

- *Molding Methods and Materials*, American Foundrymen's Society, 1962
- C.F. Walton and T.J. Opar, Ed., *Iron Casting Handbook*, Iron Castings Society, 1981

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## Aggregate Molding Materials

Thomas S. Piwonka, University of Alabama

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## Introduction

THE CASTING PROCESS involves the pouring of molten metal into a mold; therefore, the mold material and molding method must be selected with care. Most castings are made in sand molds because metallic molds wear out too quickly to be economical for ferrous metals production. For low and medium production runs, the lower tooling costs of sand molding give it an overwhelming cost advantage over permanent molds or die casting.

Selection of the molding material and its bonding system depends on the type of metal being poured, the type of casting being made, the availability of molding aggregates, the mold and core making equipment owned by the foundry, and the quality requirements of the customer. A thorough understanding of all of these factors is necessary to optimize the molding system used in the foundry.

This article will discuss the various materials used to produce molds and cores for sand casting. These materials include sands, clays, additions to sand mixes, and plastics. The principles that explain how these materials are bonded together are discussed in the articles "Bonds Formed in Molding Aggregates" and "Resin Binder Processes" in this Section. Additional information on the preparation, mulling, handling, and reclamation of sands is available in the article "Sand Processing" in this Volume.

## Sands

The refractory molds used in casting consist of a particulate refractory material (sand) that is bonded together to hold its shape during pouring. Although various sands can be used, the following basic requirements apply to each (Ref 1):

- Dimensional and thermal stability at elevated temperatures
- Suitable particle size and shape
- Chemically unreactive with molten metals
- Not readily wetted by molten metals
- Freedom from volatiles that produce gas upon heating
- Economical availability
- Consistent cleanliness, composition, and pH
- Compatibility with binder systems

Many minerals possess some of these features, but few have them all.

### *Silica Sands*

Most green sand molds consist of silica sands bonded with a bentonite-water mixture. (The term green means that the mold, which is tempered with water, is not dried or baked.) The composition, size, size distribution, purity, and shape of the sand are important to the success of the moldmaking operation.

Sands are sometimes referred to as natural or synthetic. Natural sands contain enough naturally occurring clays that they can be mixed with water and used for sand molding. Synthetic sands have been washed to remove clay and other impurities, carefully screened and classified to give a desired size distribution, and then rebled with clays and other materials to produce an optimized sand for the casting being produced. Because of the demands of modern high-pressure

molding machines and the necessity to exercise close control over every aspect of casting production, most foundries use only synthetic sands.

**Composition.** Foundry sands are composed almost entirely of silica ( $\text{SiO}_2$ ) in the form of quartz. Some impurities may be present, such as ilmenite ( $\text{FeO-TiO}_2$ ), magnetite ( $\text{Fe}_3\text{O}_4$ ), or olivine, which is composed of magnesium and ferrous orthosilicate [ $(\text{Mg,Fe})\text{SiO}_4$ ]. Silica sand is used primarily because it is readily available and inexpensive. However, its various shortcomings as a foundry sand necessitate the addition of other materials to the sand mix to produce satisfactory castings, as described later in this article.

Quartz undergoes a series of crystallographic transitions as it is heated. The first, at  $573^\circ\text{C}$  ( $1064^\circ\text{F}$ ), is accompanied by expansion, which can cause mold spalling. Above  $870^\circ\text{C}$  ( $1598^\circ\text{F}$ ), quartz transforms to tridymite, and the sand may actually contract upon heating. At still higher temperatures ( $> 1470^\circ\text{C}$ , or  $2678^\circ\text{F}$ ), tridymite transforms to cristobalite.

In addition, silica reacts with molten iron to form a slag-type compound, which can cause burn-in, or the formation of a rough layer of sand and metal that adheres to the casting surface. However, because these problems with silica can be alleviated by proper additions to the sand mix, silica remains the most widely used molding aggregate.

**Shape and Distribution of Sand Grains.** The size, size distribution, and shape of the sand grains are important in controlling the quality of the mold. Most mold aggregates are mixtures of new sand and reclaimed sand, which contain not only reclaimed molding sand but also core sands. In determining the size, shape, and distribution of the sand grains, it is important to realize that the grain shape contributes to the amount of sand surface area and that the grain size distribution controls the permeability of the mold.

As the sand surface area increases, the amount of bonding material (normally clay and water) must increase if the sand is to be properly bonded. Thus, a change in surface area, perhaps due to a change in sand shape or the percentage of core sand being reclaimed, will result in a corresponding change in the amount of bond required.

Rounded grains have a low surface-area-to-volume ratio and are therefore preferred for making cores because they require the least amount of binder. However, when they are recycled into the molding sand system, their shape can be a disadvantage if the molding system normally uses a high percentage of clay and water to facilitate rapid, automatic molding. This is because rounded grains require less binder than the rest of the system sand.

Angular sands have the greatest surface area (except for sands that fracture easily and produce a large percentage of small grains and fines) and therefore require more mulling, bond, and moisture. The angularity of a sand increases with use because the sand is broken down by thermal and mechanical shock.

The subangular-to-round classification is most commonly used, and it affords a compromise if shape becomes a factor in the sand system. However, control of grain size distribution is more important than control of grain shape. The grain size distribution, which includes the base sand size distribution plus the distribution of broken grains and fines from both molding sand and core sands, controls both the surface area and the packing density or porosity of the mold.

The porosity of the mold controls its permeability, which is the ability of the mold to allow gases generated during pouring to escape through the mold. The highest porosity will result from grains that are all approximately the same size. As the size distribution broadens, there are more grains that are small enough to fill the spaces between large grains. As grains break down through repeated recycling, there are more and more of the smaller grains, and the porosity of the mold decreases.

However, if the porosity of the mold is too great, metal may penetrate the sand grains and cause a burn-in defect. Therefore, it is necessary to balance the base sand distribution and continue to screen the sand and use dust collectors during recycling to remove fines and to determine the proper bond addition. Most foundries in the United States use the American Foundrymen's Society (AFS) grain fineness number as a general indication of sand fineness. The AFS grain fineness number of sand is approximately the number of openings per inch of a given sieve that would just pass the sample if its grains were of uniform size, that is, the weighted average of the sizes of grains in the sample. It is approximately proportional to the surface area per unit weight of sand exclusive of clay.

The AFS grain fineness number is determined by taking the percentage of sand retained on each of a series of standard screens, multiplying each by a multiplier, adding the total, and then dividing by the total percentage of sand retained on

the sieves (Ref 2). Table 1 lists the series of sieves used to run the standard AFS standard sieve analysis. A typical calculation of the AFS fineness number, which includes the multiplier factor, is given in Table 2.

**Table 1 Screen scale sieves equivalent**

USA series No.	Tyler screen scale sieves, openings per lineal inch	Sieve opening, mm	Sieve opening, $\mu\text{m}$	Sieve opening, in., ratio $\sqrt{2}$ , or 1.414	Permissible variation in average opening, $\pm\text{mm}$	Wire diameter, mm
6	6	3.35	3350	...	0.11	1.23
8 <sup>(a)</sup>	8 <sup>(a)</sup>	2.36	2360	0.0937	0.08	1.00
12	10	1.70	1700	0.0661	0.06	0.810
16 <sup>(a)</sup>	14 <sup>(a)</sup>	1.18	1180	0.0469	0.045	0.650
20	20	0.850	850	0.0331	0.035	0.510
30	28	0.600	600	0.0234	0.025	0.390
40	35	0.425	425	0.0165	0.019	0.290
50	48	0.300	300	0.0117	0.014	0.215
70	65	0.212	212	0.0083	0.010	0.152
100	100	0.150	150	0.0059	0.008	0.110
140	150	0.106	106	0.0041	0.006	0.076
200	200	0.075	75	0.0029	0.005	0.053
270	270	0.053	53	0.0021	0.004	0.037

Note: A fixed ratio exists between the different sizes of the screen scale. This fixed ratio between the different sizes of the screen scale has been taken as 1.414, or the square root of 2 ( $\sqrt{2}$ ). For example, using the USA series equivalent No. 200 as the starting sieve, the width of each successive opening is exactly 1.414 times the opening in the previous sieve. The area or surface of each successive opening in the scale is double that of the next finer sieve or one-half that of the next coarser sieve. That is, the widths of the successive openings have a constant ratio of 1.414, and the areas of the successive openings have a constant ratio of  $\sqrt{2}$ . This fixed ratio is very convenient; by skipping every other screen, a fixed ratio of width of 2 to 1 exists. Source: Ref 2

(a) These sieves are not normally used for testing foundry sands.

**Table 2 Typical calculation of AFS grain fineness number**

Size of sample: 50 g; AFS clay content: 5.9 g, or 11.8%; sand grains: 44.1 g, or 88.2%

USA sieve series No.	Amount of 50 g sample retained on sieve		Multiplier	Product
	g	%		
6	none	0.0	3	<b>0</b>
12	none	0.0	5	<b>0</b>
20	none	0.0	10	<b>0</b>
30	none	0.0	20	<b>0</b>
40	0.20	0.4	30	<b>12</b>
50	0.65	1.3	40	<b>52</b>
70	1.20	2.4	50	<b>120</b>
100	2.25	4.5	70	<b>315</b>
140	8.55	17.1	100	<b>1710</b>
200	11.05	22.1	140	<b>3094</b>
270	10.90	21.8	200	<b>4360</b>
Pan	9.30	18.6	300	<b>5580</b>
Total	44.10	88.2		15,243

It is important to understand that various grain distributions and grain shape classifications can result in similar grain fineness numbers. Table 3 provides a sample sieve analysis demonstrating that two sands assigned the same AFS grain fineness number can have very different grain size distributions.

**Table 3 Similarity in AFS grain fineness number of two sand samples with different grain size distributions**

USA sieve No.	Percentage retained

	<b>Sand A</b>	Sand B
6	0.0	<b>0.0</b>
12	0.0	<b>0.0</b>
20	0.0	<b>0.0</b>
30	1.0	<b>0.0</b>
40	24.0	<b>1.0</b>
50	22.0	<b>24.0</b>
70	16.0	<b>41.0</b>
100	17.0	<b>24.0</b>
140	14.0	<b>7.0</b>
200	4.0	<b>2.0</b>
270	1.7	<b>0.0</b>
Pan	0.3	<b>1.0</b>
<b>Total</b>	<b>100.0</b>	100.0
<b>AFS grain fineness No</b>	<b>60.0</b>	<b>60.0</b>

Source: Ref 2

Preparation of Sands. The production of sand for the foundry industry requires a series of mining and refining steps to yield pure, consistent sands (Ref 3). The actual production flow sheets vary with the source of the sand, but in general they include mining, one or more scalping operations to remove roots and pebbles, and then repeated washing and desliming operations to remove naturally occurring clays. The sand is screened and/or classified and then prepared for shipment to the foundry.

### *Zircon*

Zircon is zirconium silicate ( $ZrSiO_4$ ). It is highly refractory and possesses excellent foundry characteristics (Ref 2). Its primary advantages are a very low thermal expansion, high thermal conductivity and bulk density (which gives it a chilling rate about four times that of quartz), and very low reactivity with molten metal. Zircon requires less binder than other sands because its grains are rounded. The very high dimensional and thermal stabilities exhibited by zircon are the reasons it is widely used in steel foundries and investment foundries making high-temperature alloy components.

## *Olivine*

Olivine minerals (so called because of their characteristic green color) are a solid solution of forsterite ( $Mg_2SiO_4$ ) and fayalite ( $Fe_2SiO_4$ ). Their physical properties vary with their chemical compositions; therefore, the composition of the olivine used must be specified to control the reproducibility of the sand mixture. Care must be taken to calcine the olivine sand before use to decompose the serpentine content, which contains water (Ref 4).

The specific heat of olivine is similar to that of silica (Ref 5), but its thermal expansion is far less. Therefore, olivine is used for steel casting to control mold dimensions. Olivine is somewhat less durable than silica (Ref 1), and it is an angular sand.

## *Chromite*

Chromite ( $FeCr_2O_4$ ), a black, angular sand, is highly refractory and chemically unreactive, and it has good thermal stability and excellent chilling properties (Ref 1). However, it has twice the thermal expansion of zircon sand, and it often contains hydrous impurities that cause pinholing and gas defects in castings. It is necessary to specify the calcium oxide (CaO) and silicon dioxide ( $SiO_2$ ) limits in chromite sand to avoid sintering reactions and reactions with molten metal that cause burn-in (Ref 4).

## *Aluminum Silicates*

Aluminum silicate ( $Al_2SiO_5$ ) occurs in three common forms: kyanite, sillimanite, and andalusite. All break down at high temperatures to form mullite and silica (Ref 1). Therefore, aluminum silicates for foundry use are produced by calcining these minerals. Depending on the sintering cycle, the silica may be present as cristobalite or as amorphous silica. The grains are highly angular. These materials have high refractoriness, low thermal expansion, and high resistance to thermal shock. They are widely used in precision investment foundries, often in combination with zircon.

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1. T.E. Garnar, Jr., *AFS Cast Met. Res. J.*, Vol 2, June 1978, p 45
2. Particle Size Distribution of Foundry Sand Mixtures, in *Mold and Core Test Handbook*, American Foundrymen's Society, 1978, p 4-1 to 4-14
3. F.P. Goettman, *Trans. AFS*, Vol 83, 1975, p 15
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## Clays

Bonds in green sand molds are produced by the interaction of clay and water. Each of the various clays has different properties, as described below.

### *Bentonites*

The most common clays used in bonding green sand molds are bentonites, which are forms of montmorillonite or hydrated aluminum silicate. Montmorillonite is built up of alternating tetrahedra of silicon atoms surrounded by oxygen atoms, and aluminum atoms surrounded by oxygen atoms, as shown in Fig. 1. This is a layered structure, and it produces clay particles that are flat plates. Water is adsorbed on the surfaces of these plates, and this causes bentonite to expand in the presence of water and to contract when dried.

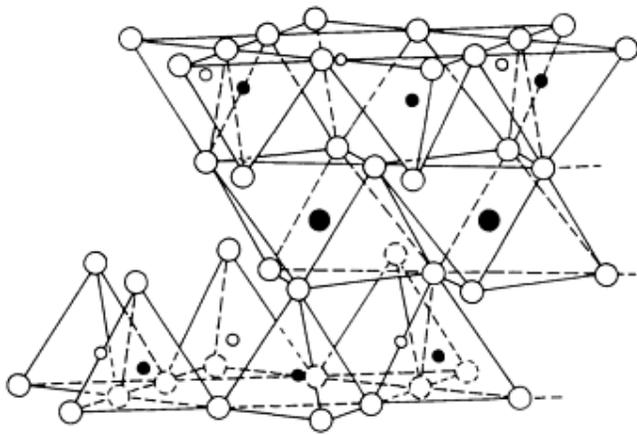


Fig. 1 Structure of montmorillonite. Large closed circles are aluminum, magnesium, sodium, or calcium. Small closed circles are silicon. Large open circles are hydroxyls. Small open circles are oxygen.

There are two forms of bentonite: Western (sodium) and Southern (calcium). Both are used in foundry sands, but they have somewhat different properties.

**Western Bentonite.** In Western bentonite, some of the aluminum atoms are replaced by sodium atoms. This gives the clay a net negative charge, which increases its activity and its ability to adsorb water. Western bentonite imparts high green and dry strengths to molding sand, and it has advantages for use with ferrous alloys, as follows.

First, Western bentonite develops a high degree of plasticity, toughness, and deformation, along with providing good lubricity when mulled thoroughly with water. Molding sand bonded with plasticized Western bentonite squeezed uniformly around a pattern produces excellent mold strengths.

Second, because of its ability to swell with water additions to as much as 13 times its original volume, Western bentonite is an excellent agent between the sand grains after compaction in the mold. It therefore plays an important role

in reducing sand expansion defects.

Finally, Western bentonite has a high degree of durability. This characteristic allows it to be reused many times in a system sand with the least amount of rebonding additions.

In using Western bentonite, it is important to control the clay/water ratio. Failure to do so can result in stiff, tough, difficult-to-mold sand with poor shakeout characteristics. Although these conditions can be alleviated by adding other materials to the molding sand, control of the mixture is preferable.

**Southern Bentonite.** In Southern bentonites, some of the aluminum atoms are replaced by calcium atoms. Again, this increases the ion exchange capability of the clay. Southern bentonite is a lower-swelling clay, and it differs from Western bentonite in the following ways:

- It develops a higher green compressive strength with less mulling time
- Its dry compressive strength is about 30 to 40% lower
- Its hot compressive strength is lower, which improves shakeout characteristics
- A Southern bentonite bonded sand flows more easily than Western bentonite and can be squeezed to higher densities with less pressure; it is therefore better for use with complex patterns containing crevices and pockets

Use of Southern bentonite also requires good control of the clay-water mixture. Southern bentonite requires less water than Western bentonite and is less durable.

In practice, it is common to blend Western and Southern bentonites together to optimize the sand properties for the type of casting, the molding equipment, and the metal being poured. Examples of the effect of mixing bentonites on various sand properties are shown in Fig. 2. At high temperatures, bentonites lose their adsorbed water and therefore their capacity for bonding. The superior high-temperature properties of Western bentonite are due to the fact that it retains water to higher temperatures than Southern bentonite (Ref 6). However, if the sand mix is heated to more than 600 °C (1110 °F), water is driven out of the clay crystal structure. This loss is irreversible, and the clay must be discarded.

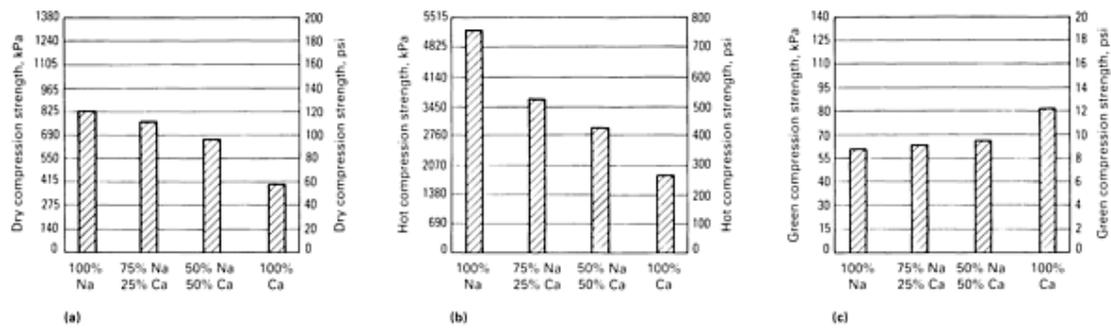


Fig. 2 Effect of blending sodium and calcium bentonites on molding sand properties. (a) Dry compression strength. (b) Hot compression strength at 900 °C (1650 °F). (c) Green compression strength

### Fireclay

Fireclay consists essentially of kaolinite, a hydrous aluminum silicate that is usually combined with bentonites in molding sand. It is highly refractory, but has low plasticity. It improves the hot strength of the mold and allows the water content to be varied over greater ranges. Because of its high hot strength potential, it is used for large castings. It is also used to improve sieve analysis by creating fines whenever the system does not have an optimum wide sieve distribution of the base sand. However, because of its low durability, its use is generally limited. In addition, the need for fireclay can usually be eliminated through close control of sand mixes and materials.

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### Reference cited in this section

6. F. Hofmann, *Trans. AFS*, Vol 93, 1985, p 377

### Other Additions to Sand Mixes

As noted above, silica sand, although inexpensive, has some shortcomings as a molding sand. If done properly, the addition of other materials can alleviate these deficiencies.

**Carbonaceous Additions.** Carbon is added to the mold to provide a reducing atmosphere and a gas film during pouring that protects against oxidation of the metal and reduces burn-in. Carbon can be added in the form of seacoal (finely ground bituminous coal), asphalt, gilsonite (a naturally occurring asphaltite), or proprietary petroleum products. Seacoal changes to coke at high temperatures expanding three times as it does so; this action fills voids at the mold/metal interface. Too much carbon in the mold gives smoke, fumes, and gas defects, and the use of asphalt products must be controlled closely because their overuse waterproofs the sand.

The addition of carbonaceous materials will give improved surface finish to castings. Best results are achieved with such materials as seacoal and pitch, which volatilize and deposit a pyrolytic (lustrous) carbon layer on sand at the casting surface (Ref 7).

Cellulose is added to control sand expansion and to broaden the allowable water content range. It is usually added in the form of wood flour, or ground cereal husks or nut shells. Cellulose reduces hot compressive strength and provides good collapsibility, thus improving shakeout. At high temperatures, it forms soot (an amorphous form of carbon), which deposits at the mold/metal interface and resists wetting by metal or slags. It also improves the flowability of the sand during molding. Excessive amounts generate smoke and fumes and can cause gas defects. In addition, if present when the clay content drops too low, defects such as cuts, washes, and mold inclusions will occur in the castings.

Cereals, which include corn flour, dextrin, and other starches, are adhesive when wetted and therefore act as a binder. They stiffen the sand and improve its ability to draw deep pockets. However, use of cereals makes shakeout more difficult, and excessive quantities make the sand tough and can cause the sand to form balls in the muller. Because cereals are volatile, they can cause gas defects in castings if used improperly.

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7. I. Bindernagel, A. Kolorz, and K. Orths, *Trans. AFS*, Vol 83, 1975, p 557

## Plastics

Plastic materials, or resins, are widely used in metal casting as binders for sand, particularly for cores of all sizes and production volumes, and for low-volume high-accuracy molding. Generally, these materials fall into three categories:

- Those composed of liquid polymeric binders that cross link and set up in the presence of a catalyst (thus transforming from a liquid to a solid)
- Those composed of two reactants that form a solid polymeric structure in the presence of a catalyst
- Those that are heat activated

Fluid-to-solid transition plastics are primarily furfuryl alcohol-base binders that are cured with acid catalysts. The polymers coat the sand when in the liquid form and are mixed with the liquid catalyst just before being placed in the core box. Alternatively, the catalyst can be delivered to the mix as a gas once the sand mix is in the core box.

Reaction-based plastics include phenolics (phenol/aldehyde), oil/urethanes, phenolic/polymeric isocyanates, and polyol/isocyanate systems. Curing catalysts include esters, amines, and acids, which can be delivered to the core mix either as liquids or gases.

Heat-activated plastics are primarily thermoplastics or thermosetting resins such as novolacs, furans (furfuryl alcohols), phenols, and linseed oils. They are applied as dry powders to the sand, and the mix is heated, at which time the powders melt, flow over the sand, and then undergo a thermosetting reaction. Alternatively, they may consist of two liquids that react to form a solid in the presence of heat.

Most binder systems are proprietary. The major ingredients are often mixed with non-reactive materials to control the reaction rate. The reactants are often dissolved in solvents to facilitate handling. Although various materials and schemes are used to form organic bonds in mold and core making, the technology rests on only a few compounds.

The presence of so many different systems allows casting producers to tailor the bonding system to the particular application. However, selection of the bonding system requires care. Care must also be taken in controlling process parameters because the systems are sensitive to variations in temperature and humidity. Consideration must also be given to environmental issues in the selection of the system because some organic systems emit noxious odors and fumes. More detailed information on organic binders can be found in the article "Resin Binder Processes" in this Volume.

## References

1. T.E. Garnar, Jr., *AFS Cast Met. Res. J.*, Vol 2, June 1978, p 45
2. Particle Size Distribution of Foundry Sand Mixtures, in *Mold and Core Test Handbook*, American Foundrymen's Society, 1978, p 4-1 to 4-14
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6. F. Hofmann, *Trans. AFS*, Vol 93, 1985, p 377
7. I. Bindernagel, A. Kolorz, and K. Orths, *Trans. AFS*, Vol 83, 1975, p 557

### Introduction

MOLDING AGGREGATES must be held together, or bonded, to form a mold. By far the most common types of bonds are those formed from sand, clay, and additives. These materials are described in the previous article "Aggregate Molding Materials" in this Section. Organic bonds, described briefly here and in detail in the following article "Resin Binder Processes," also have a substantial part of the market for core making.

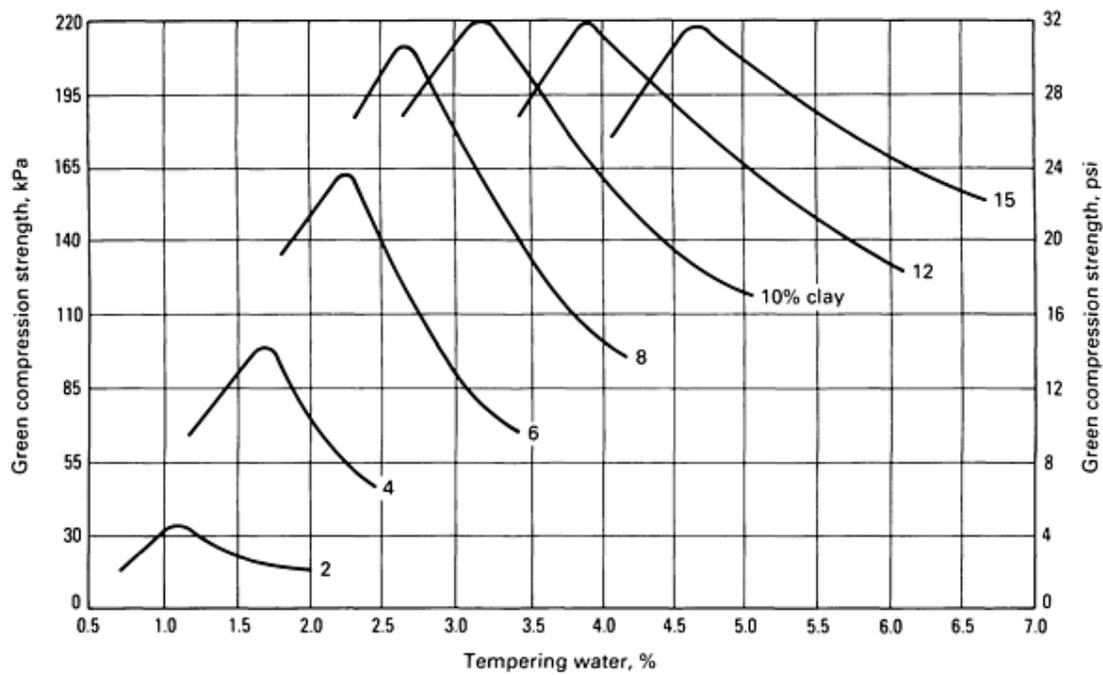
### Silica-Base Bonds

Because of the abundance and low cost of clays, green sand molds are normally clay bonded, but various forms of silica can also be used in bonding molding aggregates.

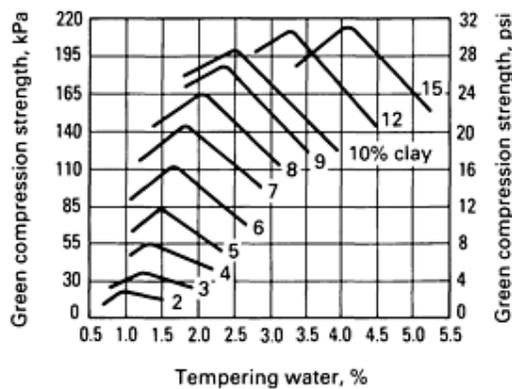
Clay-Water Bonds. As noted in the article "Aggregate Molding Materials," bentonites are not electrically neutral and can therefore attract water molecules between the clay plates. Water is also adsorbed on the quartz surfaces. Thus, there is a network of water adsorbed on sand and clay particles that is set up throughout the molding sand. If the clay covers each sand grain entirely, then clay-water bridges form between grains (Ref 1). In the case in which the clay coverage is nonuniform, similar bridges are formed.

The clay-water bond can also be explained in terms of the specific surface area of the clay, the type and strength of the water bond at the clay surface, and the hydration envelopes of the adsorbed cations (Ref 2, 3). Clay particles hold adsorbed cations on their surfaces. The bonding of cations on clay particles is weak, and ion exchange is possible in the presence of appropriate electrolytes. Therefore, clay particles and ions are surrounded by electric force fields that direct the water dipoles (the water is polarized at the clay surface) and bind the water network. The field strength decreases with increased distance from the surface of the clay, so that the dipoles closest to the clay surface are bonded most strongly. Beyond the distance at which the force field is effective, the water behaves as a liquid and has no bonding action.

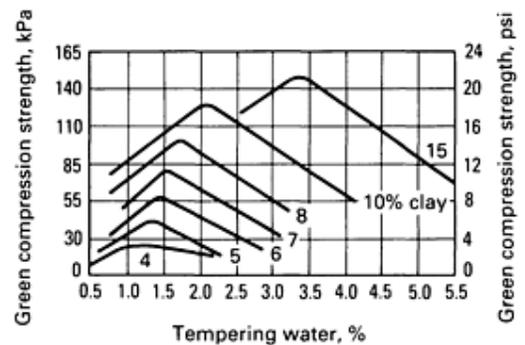
There is an ideal water content at which all of the water is polarized and active in the bonding process (because the water added to activate the clay bond is called temper water, this is known as the temper point). Above this water content, some of the water will exist as liquid water, which is not involved in bonding. Below this value, there is insufficient water to develop the bond fully. At the temper point, the green strength of the sand is at its maximum, and additions of water beyond this point decrease the strength of the sand/clay/water mixture. The effect of this can be seen quite clearly in Fig. 1.



(a)



(b)



(c)

Fig. 1 Variation of mold properties with water content. (a) Southern bentonite. (b) Western bentonite. (c) Kaolinite. Source: Ref 1

Colloidal silica bonds are used in investment casting. Colloidal silica particles are about 4 to 40 nm in diameter and form a sol in water. Their stability is determined by surface charge, pH, particle size, concentration, and electrolyte content (Ref 4). The silica is spherical and amorphous, and it contains a small amount of a radical, such as a hydroxide, to impart a negative charge to each particle so that they repel each other and do not settle out. When water evaporates from these sols (as happens when the mold layers are dried), the silica particles are forced close enough together for hydroxyl groups to condense, splitting out the water and forming siloxane bonds between the aggregates (Ref 5).

The molds made from colloidal silica are dried in air and have enough strength to retain their shapes. However, they must be fired at an elevated temperature ( $>815\text{ }^{\circ}\text{C}$ , or  $1500\text{ }^{\circ}\text{F}$ ) to develop a strong silica ceramic bond. Each mold system has an optimum silica content for maximum mold strength. More detailed information on colloidal silica bonds can be found in the article "Investment Casting" in this Volume.

Ethyl Silicate. An alternate silica bond can be produced from hydrolyzed ethyl silicates. These are precipitation bonds, such as (Ref 4):

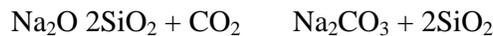


The precipitated silicate bond is a gel that comes out of suspension by a change in binder ion concentration.

Hydrolyzed ethyl silicate is manufactured by the reaction of silicon tetrachloride with ethyl alcohol. Two types of ethyl silicate are commonly available. Ethyl silicate 30, the first type, is a mixture of tetraethyl orthosilicate and polysilicates containing about 28% silica. Ethyl silicate 40, the second type, is a mixture of branched silicate polymers containing about 40% silica.

Slurries formed from these ethyl silicates and mold aggregates, such as fused silica or zircon, are very sensitive to changes in pH. The slurries are normally kept at a pH of around 3. To gel them around a pattern, they are exposed to ammonia vapor, and their pH increases to 5, where they gel. The shells are then fired, and the ethyl alcohol evaporates or burns off, causing the silica binders to condense and form the silica bond. Ethyl silicate molds have an advantage over colloidal silica in that they do not require long drying times between dips and can be used for monolithic block molds. However, the mold strength of these molds is much less than that of colloidal silicate bonded molds because of the fine craze cracking that occurs during firing. On the other hand, this fine network of cracks is also responsible for the high dimensional reproducibility of castings made in block molds. Additional information on ethyl silicate molds can be found in the article "Investment Casting" in this Volume.

Sodium Silicate Bonds. The sodium silicate process is another method of forming a bond made up of a silicate polymer. In this case, carbon dioxide is used to precipitate sodium from what is essentially silicic acid containing large quantities of colloidal sodium. The reaction is:



Continued gassing gives:



This shows that continued gassing dehydrates the amorphous silica gel and increases the strength of the mold (Ref 6).

Sodium silicate molds are widely used for large cores and castings where there is a premium on mold hardness and dimensional control. The bond breaks down easily at high temperatures and therefore facilitates shakeout. The silicate-bonded sand, after pouring and shakeout, can be reclaimed by mechanical means, and up to 60% of the reclaimed sand can be reused. Wet reclamation of silicate sand systems is also possible. Additional information on sodium silicate molds can be found in the article "Sand Molding" (see the section "Bonded Sand Molds") in this Volume.

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1. R.F. Grim and F.L. Cuthbert, Engineering Experiment Station Bulletin 357, University of Illinois, 1945
2. G.A. Smiernow, E.L. Doheny, and J.G. Kay, *Trans. AFS*, Vol 88, 1980, p 659
3. D. Boenisch, *Tonindustrie Zeitung*, Vol 86, 1962, p 237
4. W.F. Wales, *Trans. AFS*, Vol 81, 1973, p 249
5. R.L. Rusher, *AFS Cast Met. Res. J.*, Dec 1974, p 149
6. J. Gotheridge, *Trans. AFS*, Vol 87, 1979, p 669

#### Phosphoric Acid Bonds

Phosphoric acid bonds are used in both ferrous and nonferrous precision casting to produce monolithic molds. They are a reaction-type bond with the general form:



where  $M$  is an oxide frit or mixture of frits. The pH must be controlled carefully and kept acidic (Ref 4). The powdered metal oxide hardener is dry blended with the sand, and the liquified phosphoric acid is then incorporated. The coated sand is compacted into core or pattern boxes and allowed to harden chemically before removal. A similar procedure for producing phosphate bonds is described in the article "Sand Molding" (see the section "Bonded Sand Molds") in this Volume.

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#### Reference cited in this section

4. W.F. Wales, *Trans. AFS*, Vol 81, 1973, p 249

#### Organic Bonds

Organic bonds are used in resin-bonded sand systems. These systems vary widely. The sand is coated with two reactants that form a resin upon the application of heat or a chemical catalyst. The resin is a solid plastic that coats the sand so that it holds its shape during pouring. A thorough review of organically bonded systems can be found in the following article, "Resin Binder Processes," in this Section.

#### References

1. R.F. Grim and F.L. Cuthbert, Engineering Experiment Station Bulletin 357, University of Illinois, 1945
2. G.A. Smiernow, E.L. Doheny, and J.G. Kay, *Trans. AFS*, Vol 88, 1980, p 659
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#### Resin Binder Processes

James J. Archibald and Richard L. Smith, Ashland Chemical Company

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#### Introduction

THE FOUNDRY INDUSTRY uses a variety of procedures for casting metal parts. These include such processes as permanent mold casting, centrifugal casting, evaporative pattern casting, and sand casting, all of which are described in the Section "Molding and Casting Processes" in this Volume. In sand casting, molds and cores are used. Cores are required for hollow castings and must be removed after the metal has solidified.

Binders were developed to strengthen the cores, which are the most fragile part of a mold assembly. Although the use of binders in mold production is increasing, most sand casting employs green sand molds, which are made of sand, clay, and additives (green sand molding is described in the section "Bonded Sand Molds" in the article "Sand Molding" in this Volume).

Inorganic binders, such as clay or cement, are materials that have long been used in the production of foundry molds and cores. This article is limited to organic resin-base binders for sand molding. In practice, these binders are mixed with sand, the mixes are compressed into the desired shape of the mold or core, and the binders are hardened, that is, cured, by

chemical or thermal reactions to fixate the shapes. Typically, 0.7 to 4.0 parts (usually 1 to 2 parts) of binder are added to 100 parts of sand.

## Acknowledgements

The authors would like to acknowledge the Technical and Research Departments of Ashland Chemical's Foundry Products Division for their help in preparing this article.

This article was adapted with permission from P.R. Carey *et al.*, Updating Resin Binder Processes--Part I through IX, *Foundry Mgmt. Technol.*, Feb 1986.

## Classification of Resin Binder Processes

Although a wide variety of resin binder processes are currently used, they can be classified into the following categories:

- No-bake binder systems
- Heat-cured binder systems
- Cold box binder systems

In the no-bake and cold box processes, the binder is cured at room temperature; in the shell molding, hot box, and oven-bake processes, heat cures are applied. Selection of the process and type of binder depends on the size and number of cores or molds required, production rates, and equipment. Properties of the various binder systems are described below and compared in Tables 1, 2, and 3. Figure 1 summarizes the trends in resin binder usage in the foundry industry.

**Table 1 A comparison of properties of no-bake binder systems**

Parameter	Process <sup>(a)</sup>							
	Acid catalyzed		Ester cured		Oil urethane	Phenolic urethane	Polyisocyanate	Alumina phosphate
	Furan	Phenolic	Alkaline/phenolic	Silicate				
Relative tensile strength	H	M	L	M	H	M	M	<b>M</b>
Rate of gas evolution	L	M	L	L	M	H	H	<b>L</b>
Thermal plasticity	L	M	M	H	L	L	L	<b>L</b>
Ease of shakeout	G	F	G	P	P	G	E	<b>G</b>
Humidity resistance	F	F	E	P	G	G	G	<b>P</b>
Strip time, min <sup>(b)</sup>	3-45	2-45	3-60	5-60	2-180	1-40	2-20	<b>30-60</b>
Optimum (sand) temperature, °C (°F)	27 (80)	27 (80)	27 (80)	24 (75)	32 (90)	27 (80)	27 (80)	<b>32 (90)</b>

Clay and fines resistance	P	P	P	F	F	P	P	F
Flowability	G	F	F	F	F	G	G	F
Pouring smoke	M	M	L	N	H	M	M	N
Erosion resistance	E	E	E	G	F	G	P <sup>(c)</sup>	G
<b>Metals not recommended</b>	<sup>(c)</sup>	...	...	...	...	<sup>(d)</sup>	<sup>(e)</sup>	...

(a) H, high; M, medium; L, low N; none; E, excellent; G, good; F, fair; P, poor.

(b) Rapid strip times required special mixing equipment.

(c) Use minimum N<sub>2</sub> levels for steel.

(d) Iron oxide required for steel.

(e) Use with nonferrous metals

**Table 2 Comparison of properties of the heat-cured binder systems**

Parameter	Process <sup>(a)</sup>				
	Shell process	Hot box		Warm box	Oven bake (core oil)
		Furan	Phenolic		
Relative tensile strength	H	H	H	H	M
Rate of gas evolution	M	H	H	M	M
Thermal plasticity	M	L	M	L	M
Ease of shakeout	F	G	F	G	G
Humidity resistance	E	F	G	G	G
Cure speed	H	H	M	H	L

Resistance to overcure	G	F	F	F	<b>P</b>
Optimum core pattern temperature, °C (°F)	260 (500)	260 (500)	260 (500)	175 (350)	<b>205 (400)</b>
Clay and fines resistance	F	P	P	P	<b>F</b>
Flowability	E	G	F	G	<b>F</b>
Bench life of mixed sand	E	F	F	F	<b>G</b>
Pouring smoke	M	M	M	M	<b>M</b>
<b>Metals not recommended</b>	N	<sup>(b)</sup>	<b>Steel</b>	<sup>(b)</sup>	<sup>(c)</sup>

(a) H, high; M, medium; L, low; N, none; E, excellent; G, good; F, fair; P, poor.

(b) Use minimum N<sub>2</sub> levels for steel.

(c) Iron oxide required for steel

**Table 3 Comparison of properties for cold box binder systems**

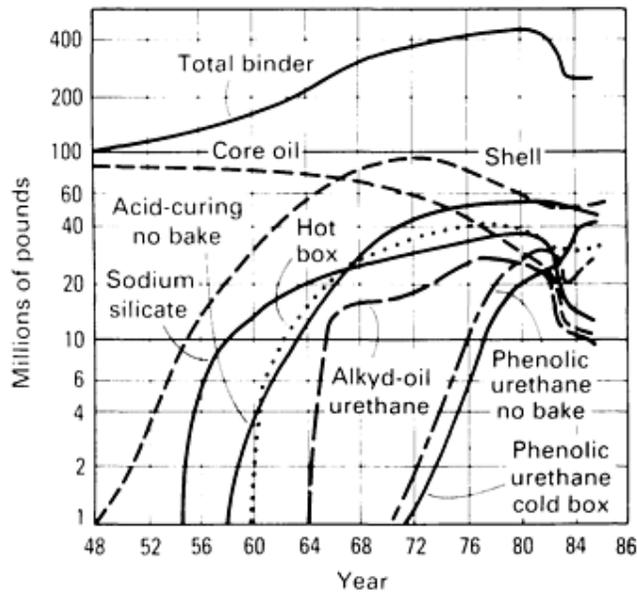
Parameter	Process <sup>(a)</sup>				
	Phenolic urethane	SO <sub>2</sub> process (furan/SO <sub>2</sub> )	FRC process acrylic/epoxy	Phenolic ester	Sodium Silicate CO <sub>2</sub>
Relative tensile strength	H	M	H	L	<b>L</b>
Rate of gas evolution	H	L	H	L	<b>M</b>
Thermal plasticity	L	N	L	L	<b>H</b>
Ease of shakeout	G	E	G	G	<b>P</b>
Moisture resistance	M	H	M	M	<b>L</b>
Curing speed	H	H	H	M	<b>M</b>
Resistance to overcure	G	G	G	G	<b>P</b>

Optimum temperature, °C (°F)	24 (75)	32 (90)	24 (75)	24 (75)	<b>24 (75)</b>
Clay and fines resistance	P	P	P	P	<b>F</b>
Flowability	G	G	E	F	<b>P</b>
Bench life of mixed sand	F	G	E	F	<b>F</b>
Pouring smoke	H	L	M	L	<b>N</b>
Erosion resistance	G	E	F	E	<b>G</b>
Veining resistance	F	F	G	G	<b>F</b>
<b>Metals not recommended</b>	<sup>(b)</sup>	...	<sup>(c)</sup>	...	...

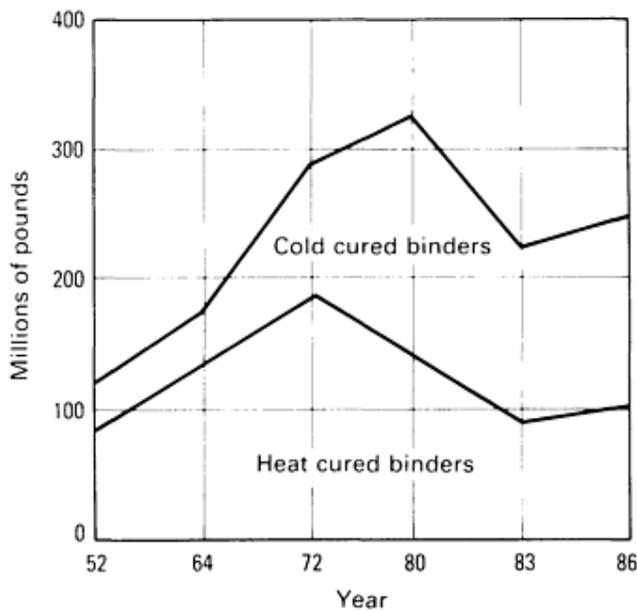
(a) H, high; M, medium; L, low; N, none; E, excellent; G, good; F, fair; P, poor.

(b) Iron oxide required for steel.

(c) Binder selection available for type of alloy



(a)



(b)

Fig. 1 Market status of resin binder processes. (a) Trends in foundry sand binder consumption showing great variations in volume. These variations have been accompanied by machinery changes. The 1985 figures are extrapolated. (b) Heat cured versus cold cured binders (U.S. foundry consumption). Source: Ashland Chemical Company

### No-Bake Processes

A no-bake process is based on the ambient-temperature cure of two or more binder components after they are combined on sand. Curing of the binder system begins immediately after all components are combined. For a period of time after initial mixing, the sand mix is workable and flowable to allow the filling of the core/mold pattern. After an additional time period, the sand mix cures to the point where it can be removed from the box. The time difference between filling

and stripping of the box can range from a few minutes to several hours, depending on the binder system used, curing agent and amount, sand type, and sand temperature.

**Furan Acid Catalyzed No-Bake.** Furfuryl alcohol is the basic raw material used in furan no-bake binders. Furan binders can be modified with urea, formaldehyde, phenol, and a variety of other reactive or non-reactive additives.

The great variety of furan binders available provides widely differing performance characteristics for use in various foundry applications. Water content may be as high as 15% and nitrogen content as high as 10% in resins modified with urea. In addition, zero-nitrogen and zero-water binders are available. The choice of a specific binder depends on the type of metal to be cast and the sand performance properties required. The amount of furan no-bake binders used ranges between 0.9 and 2.0% based on sand weight. Acid catalyst levels vary between 20 and 50% based on the weight of the binder. The speed of the curing reaction can be adjusted by changing the catalyst type or percentage, given that the sand type and temperature are constant. The furan no-bake curing mechanism is shown in Fig. 2.

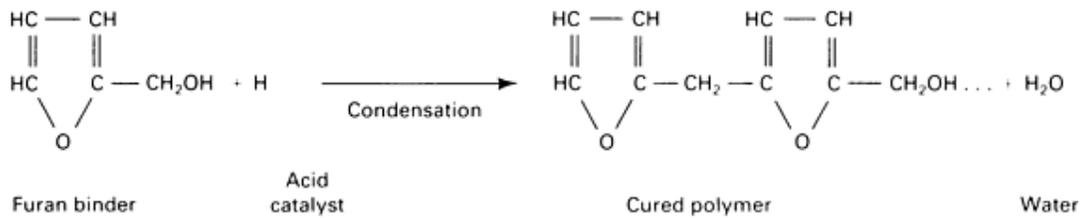


Fig. 2 The furan acid-catalyzed no-bake curing mechanism

Furan no-bake binders provide high dimensional accuracy and a high degree of resistance to sand/metal interface casting defects, yet they decompose readily after the metal has solidified, providing excellent shakeout. Furan no-bake binders also exhibit high tensile strength, along with the excellent hot strength needed for flaskless no-bake molding. They often run sand-to-metal ratios of as low as 2:1.

**Phenolic Acid Catalyzed No-Bake.** Phenolic resins are condensation reaction products of phenol(s) and aldehyde(s). Phenolic no-bake resins are those formed from phenol/formaldehyde where the phenol/formaldehyde molar ratio is less than 1. Again, as with furan no-bakes, these resins can be modified with reactive or nonreactive additives.

These resins are clear to dark brown in appearance, and their viscosities range from medium to high. Sand mixes made with these resins have adequate flowability for the filling of mold patterns or core boxes. Resins of this type contain free phenol and free formaldehyde. Phenol and formaldehyde odors can be expected during sand-mixing operations.

One disadvantage of acid-cured phenolic no-bake resins is their relatively poor storage stability. Phenolic binders are usually not stored for more than 6 months. Phenolic resole resins contain numerous reactive methylol groups, and these are generally involved in auto-polymerization reactions at ambient or slightly elevated temperatures. The storage period can be considerably longer during the winter months if the temperature of storage remains at 20 °C (70 °F) or lower. The viscosity advances as the binder ages.

The catalyst needed for the phenolic no-bake resin is a strong sulfonic acid type. Phosphoric acids will not cure phenolic resins at the rate required for most no-bake foundry applications.

The phenolic no-bake reaction mechanism is:



The catalyst initiates further condensation of the resin and advances the cross-linking reaction. The condensation reactions produce water which results in a dilution effect on the acid catalyst that tends to slow the rate of cure. Because of this effect, it is necessary to use strong acid catalysts to ensure an acceptable rate of cure and good deep set properties.

Ester-Cured Alkaline Phenolic No-Bake. The ester-cured phenolic binder system is a two-part binder system consisting of a water-soluble alkaline phenolic resin and liquid ester co-reactants. The reaction mechanism is:

Alkaline phenolic resin + Ester co-reactant  
→ Suspected unstable intermediate  
→ Splits to form:  
Polymerized phenolic resin  
Alkaline salts and alcohol

A secondary reaction is thought to occur when the partially polymerized resin contacts heat during the pouring operation, yielding an extremely rigid structure.

The viscosity of the ester-cured phenolic is similar to that of the acid-catalyzed phenolic no-bakes. It has a shelf life of 4 to 6 months at 20 °C (70 °F). Typically, 1.5 to 2.0% binder based on sand and 20 to 25% co-reactant based on the resin are used to coat washed and dried silica sand in most core and molding operations.

Both the resin and co-reactant are water soluble, permitting easy cleanup. Physical strength of the cured sand is not as high as that of the acid-catalyzed and urethane no-bakes at comparable resin contents. However, with care in handling and transporting, good casting results can be obtained. The distinct advantages of the ester-cured phenolic no-bake systems are the reduction of veining in iron castings and excellent erosion resistance.

Silicate/Ester-Catalyzed No-Bake. This no-bake system consists of the sodium silicate binder and a liquid organic ester that functions as the hardening agent. High-ratio binders with SiO<sub>2</sub>:Na<sub>2</sub>O contents of 2.5 to 3.2:1 are employed for this process, and mixtures usually contain 3 to 4% binder. The ester hardeners are materials such as glycerol diacetate and triacetate, or ethylene glycol diacetate; they are low-viscosity liquids with either a sweet or acetic acid-like smell. The normal addition rate for the ester hardener is 10 to 15% based on the weight of sodium silicate and should be added to the sand prior to the addition of the silicate binder.

The curing rate depends on the SiO<sub>2</sub>:Na<sub>2</sub>O ratio of the silicate binder and the composition of the ester hardener. Suppliers produce blends of ester hardeners giving work times that are controllable from several minutes to 1 h or longer. The hardening reaction, involving the formation of silica gel from the sodium silicate, is a cold process, and no heat or gas is produced. When added to a sand mixture containing the alkaline sodium silicate, the organic esters hydrolyze at a controlled rate, reacting with sodium silicate to form a silica gel that bonds the aggregate. A simplified version of this curing mechanism is:

Sodium silicate (Na<sub>2</sub>SiO<sub>3</sub>) + Liquid ester hardener → Cured polymer

Mixed sand must be used before hardening begins. Material that has exceeded the useful work time and feels dry or powdery should be discarded. The use of sand past the useful bench life will result in the production of weak, friable molds and cores that can result in penetration defects.

Curing takes several hours to complete after stripping. Large molds may need 16 to 24 h. Strengths can be higher than those of CO<sub>2</sub>-cured molds, and shelf life is better. Although shakeout is easier than with CO<sub>2</sub>-silicate systems, it is not as good as the other no-bake processes outlined in this article.

Odor and gaseous emission levels are low during mixing, pouring, cooling, and shakeout, but depend on the extent of organic additives in the mix. Casting defects such as veining and expansion are minimal. Burn-on and penetration are generally more severe than for the other no-bake systems and can be controlled by sand additives and a wash practice.

Oil urethane no-bake resins (also known as oil-urethane, alkyd-urethane, alkyd-oil-urethane, or polyester-urethane) are three-component systems that consist of Part A, an alkyd oil type resin; Part B, a liquid amine/metallic catalyst; and Part C, a polymeric methyl di-isocyanate (MDI) (the urethane component).

The three-part system uses the Part B catalyst to achieve a predictable work/strip time. It can be made into a two-part system by preblending Parts A and B when the amount of the Part B catalyst added to the resin controls the work/strip

time. Part A can also be modified for better coating action, improved performance in temperature extremes, or better strippability.

Part A is normally used at 1 to 2% of sand weight. The Part B catalyst, whether added as a separate component or preblended with Part A, is 2 to 10% by weight of Part A. The Part C isocyanate is always 18 to 20% by weight of Part A.

Although the oil urethane no-bake system is easy to use, the curing mechanisms are difficult to understand because there are two separate curing stages and two curing mechanisms. When the three components are mixed together on the sand, the polyisocyanate (Part C) quickly begins to cross-link with the alkyd oil resin (Part A) at a rate controlled by the urethane catalyst component of Part B, as shown in Fig. 3. This action produces a urethane coating on the sand with enough bonded sand strength to strip the pattern and handle the core or mold.

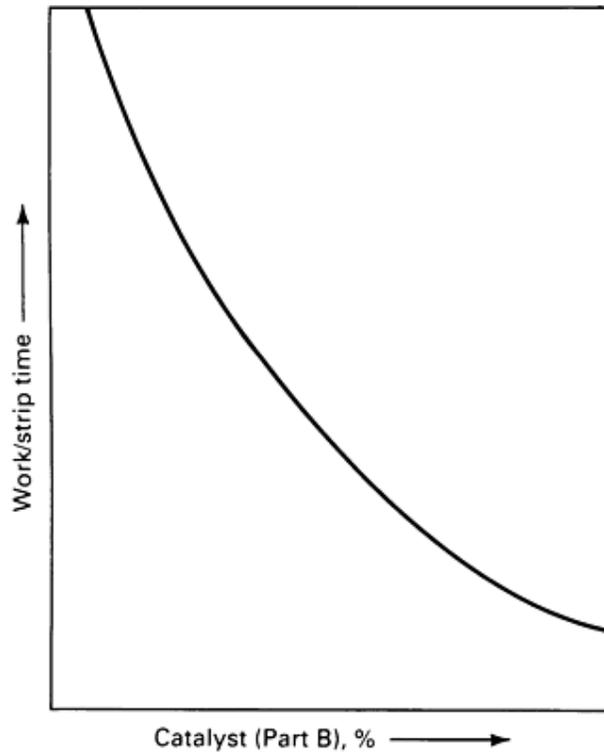
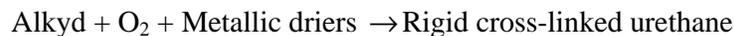
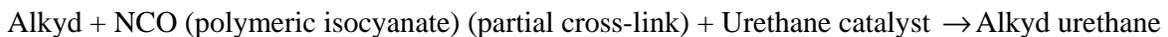


Fig. 3 Effect of increasing oil urethane system (Part B) (catalyst) on work time and strip time

The other stage of the curing reaction is similar to a paint-drying mechanism in which oxygen combines with the alkyd-oil resin component and nearly polymerizes it fully at room temperature to form a tough urethane bond. The metallic driers present in the Part B catalyst accelerate the oxygenation or drying (slowly at room temperature or quickly at 150 to 205 °C, or 300 to 400 °F), but because the full cure is oxygen dependent, section size and shape, along with temperature, determine how long it takes to attain a complete cure.

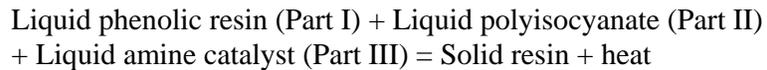
The alkyd-oil urethane mechanism is a two-stage process involving:



For maximum cure and ultimate casting properties, the mold or core should be heated to about 150 °C (300 °F) in a forced air oven for 1 h.

The oil urethane no-bake system, with its unique two-stage cure, results in unmatched stripping characteristics and provides foundrymen with a good method of producing large cores and molds that require long work and strip times.

The phenolic urethane no-bake (PUN) binder system has three parts. Part I is a phenol formaldehyde resin dissolved in a special blend of solvents. Part II is a polymeric MDI-type isocyanate, again dissolved in solvents. Part III is an amine catalyst that, depending on strength and amount, regulates the speed of the reaction between Parts I and II. The chemical reaction between Part I and Part II forms a urethane bond and no other by-products. For this reason and because air is not required for setting, the PUN system does not present the problems with through-cure or deep-set found in other no-bake systems. A simplified version of the curing mechanism for phenolic urethane no-bake systems is:



Phenolic urethane no-bake binders are widely used for the production of both ferrous and nonferrous castings and can be successfully used for high-production operations or jobbing shops because of their chemical reaction time and ease of operation.

Although many types of mixers can be used with PUN binders, zero-retention high-speed continuous mixers are the most widely used. Because the mixing takes place rapidly, the fast strip times (as fast as 30 s) of the PUN system can be utilized in practice. No mixed sand is retained in the mixer to harden after it is shut off. Further, the mixers can be coordinated with pattern movement, sand compaction, stripping operations, and mold or core finishing and storage to create a simple manual or fully automated no-bake loop.

Total binder level for the PUN system is 0.7 to 2% based on the weight of sand. It is common to offset the ratio of Part I to Part II at 55:45 or 60:40. The third-part catalyst level is based on the weight of Part I. Depending on the catalyst type and strip time required 0.4 to 8% catalyst (based on Part I) is normally added.

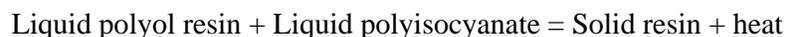
Compaction of the mixed sand can be accomplished by vibration, ramming, and tucking. The good flowability of PUN sand mixes allows good density with minimum effort. Because the PUN system cures very rapidly, the time required for the compacted pattern to reach rollover and strip must coincide with the setup or cure time of the sand mix.

For certain ferrous applications (most commonly steels), the addition of 2 to 3% iron oxide to the sand mix can improve casting surface finish. This addition is also beneficial in reducing lustrous carbon defects by promoting a less reducing mold atmosphere. The PUN resin system contains about 3.0 to 3.8% N (which is about 0.04% based on sand). To reduce the chance of nitrogen-related casting defects, the Part I to Part II ratio can be offset 60:40 in favor of the Part I because substantially all the nitrogen is in Part II. It has also been shown that as little as 0.25% red iron oxide is effective in suppressing the ferrous casting subsurface porosity associated with nitrogen in the melt and/or evolved from the PUN binder.

The polyol-isocyanate system was developed in the late 1970s for aluminum, magnesium, and other light-alloy foundries. Previously, the binder systems used in light-alloy foundries were the same as those used for the ferrous casting industry. The lower pouring temperatures associated with light alloys are not sufficient to decompose most no-bake binders, and removal of cores from castings is difficult. The polyol-isocyanate system was developed to provide improved shakeout.

The nonferrous binders are similar to the PUN system described previously. Part I is a special polyol designed for good thermal breakdown dissolved in solvents. Part II is a polymeric MDI-type isocyanate, again dissolved in solvents. Part II is an amine catalyst that can be used to regulate cure speed.

The chemical curing reaction of the polyol-isocyanate system is as follows:



In practice, polyol-isocyanate binders are used in much the same way as the PUN binders they evolved from. One difference is that the system does not require a catalyst. Several phenol formaldehyde (Part I) resins are available that

provide strip times from 8 min to over 1 h. For maximum control, however, an amine (Part III) catalyst can be used to regulate strip times to as fast as 3 min.

For light-alloy applications, binder levels range from 0.7 to 1.5% based on sand. Part I and Part II should be used at a 50:50 ratio for best results. Reactivity, strengths, and work-time-to-strip-time ratio are affected by the same variables as the PUN binders. Because of the fast thermal breakdown of the binder (Fig. 4), the polyol-urethane system is not recommended for ferrous castings.

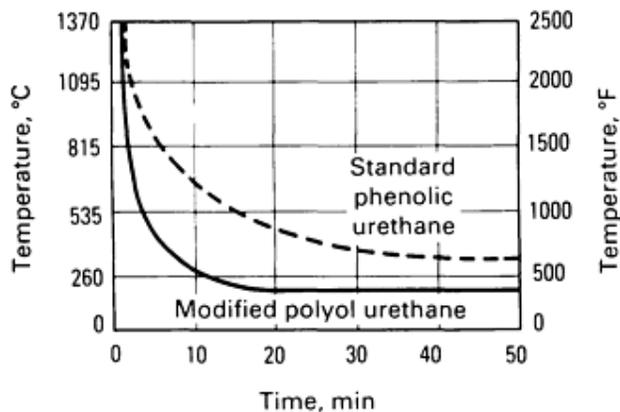


Fig. 4 Collapsibility of polyol urethane compared to that of phenolic urethane

Alumina-Phosphate No-Bake. Alumina-phosphate binders consist of an acidic, water-soluble alumina-phosphate liquid binder and a free-flowing powdered metal oxide hardener. Although this system is classified as a no-bake process (Table 1), both of its parts are inorganic; all other no-bake systems are organic or, in the case of silicate/ester systems, inorganic and organic. More detailed information on phosphate-bonded systems can be found in the article "Sand Molding" in this Volume (see the section "Bonded Sand Molds").

## No-Bake Processes

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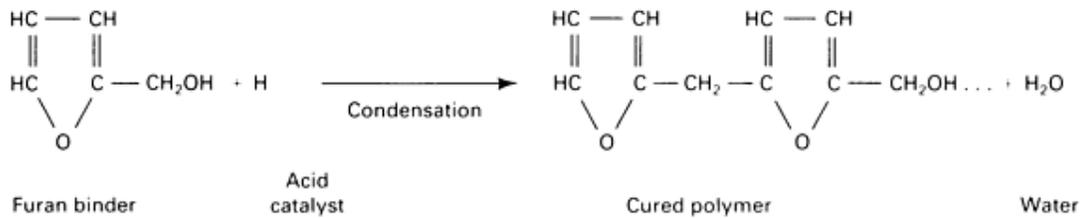


Fig. 2 The furan acid-catalyzed no-bake curing mechanism

Furan no-bake binders provide high dimensional accuracy and a high degree of resistance to sand/metal interface casting defects, yet they decompose readily after the metal has solidified, providing excellent shakeout. Furan no-bake binders also exhibit high tensile strength, along with the excellent hot strength needed for flaskless no-bake molding. They often run sand-to-metal ratios of as low as 2:1.

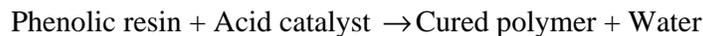
**Phenolic Acid Catalyzed No-Bake.** Phenolic resins are condensation reaction products of phenol(s) and aldehyde(s). Phenolic no-bake resins are those formed from phenol/formaldehyde where the phenol/formaldehyde molar ratio is less than 1. Again, as with furan no-bakes, these resins can be modified with reactive or nonreactive additives.

These resins are clear to dark brown in appearance, and their viscosities range from medium to high. Sand mixes made with these resins have adequate flowability for the filling of mold patterns or core boxes. Resins of this type contain free phenol and free formaldehyde. Phenol and formaldehyde odors can be expected during sand-mixing operations.

One disadvantage of acid-cured phenolic no-bake resins is their relatively poor storage stability. Phenolic binders are usually not stored for more than 6 months. Phenolic resole resins contain numerous reactive methylol groups, and these are generally involved in auto-polymerization reactions at ambient or slightly elevated temperatures. The storage period can be considerably longer during the winter months if the temperature of storage remains at 20 °C (70 °F) or lower. The viscosity advances as the binder ages.

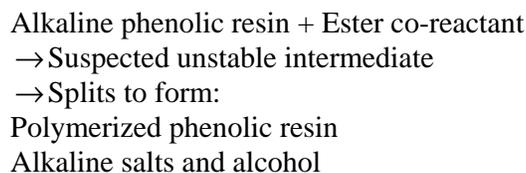
The catalyst needed for the phenolic no-bake resin is a strong sulfonic acid type. Phosphoric acids will not cure phenolic resins at the rate required for most no-bake foundry applications.

The phenolic no-bake reaction mechanism is:



The catalyst initiates further condensation of the resin and advances the cross-linking reaction. The condensation reactions produce water which results in a dilution effect on the acid catalyst that tends to slow the rate of cure. Because of this effect, it is necessary to use strong acid catalysts to ensure an acceptable rate of cure and good deep set properties.

**Ester-Cured Alkaline Phenolic No-Bake.** The ester-cured phenolic binder system is a two-part binder system consisting of a water-soluble alkaline phenolic resin and liquid ester co-reactants. The reaction mechanism is:



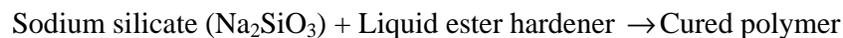
A secondary reaction is thought to occur when the partially polymerized resin contacts heat during the pouring operation, yielding an extremely rigid structure.

The viscosity of the ester-cured phenolic is similar to that of the acid-catalyzed phenolic no-bakes. It has a shelf life of 4 to 6 months at 20 °C (70 °F). Typically, 1.5 to 2.0% binder based on sand and 20 to 25% co-reactant based on the resin are used to coat washed and dried silica sand in most core and molding operations.

Both the resin and co-reactant are water soluble, permitting easy cleanup. Physical strength of the cured sand is not as high as that of the acid-catalyzed and urethane no-bakes at comparable resin contents. However, with care in handling and transporting, good casting results can be obtained. The distinct advantages of the ester-cured phenolic no-bake systems are the reduction of veining in iron castings and excellent erosion resistance.

**Silicate/Ester-Catalyzed No-Bake.** This no-bake system consists of the sodium silicate binder and a liquid organic ester that functions as the hardening agent. High-ratio binders with  $\text{SiO}_2:\text{Na}_2\text{O}$  contents of 2.5 to 3.2:1 are employed for this process, and mixtures usually contain 3 to 4% binder. The ester hardeners are materials such as glycerol diacetate and triacetate, or ethylene glycol diacetate; they are low-viscosity liquids with either a sweet or acetic acid-like smell. The normal addition rate for the ester hardener is 10 to 15% based on the weight of sodium silicate and should be added to the sand prior to the addition of the silicate binder.

The curing rate depends on the  $\text{SiO}_2:\text{Na}_2\text{O}$  ratio of the silicate binder and the composition of the ester hardener. Suppliers produce blends of ester hardeners giving work times that are controllable from several minutes to 1 h or longer. The hardening reaction, involving the formation of silica gel from the sodium silicate, is a cold process, and no heat or gas is produced. When added to a sand mixture containing the alkaline sodium silicate, the organic esters hydrolyze at a controlled rate, reacting with sodium silicate to form a silica gel that bonds the aggregate. A simplified version of this curing mechanism is:



Mixed sand must be used before hardening begins. Material that has exceeded the useful work time and feels dry or powdery should be discarded. The use of sand past the useful bench life will result in the production of weak, friable molds and cores that can result in penetration defects.

Curing takes several hours to complete after stripping. Large molds may need 16 to 24 h. Strengths can be higher than those of  $\text{CO}_2$ -cured molds, and shelf life is better. Although shakeout is easier than with  $\text{CO}_2$ -silicate systems, it is not as good as the other no-bake processes outlined in this article.

Odor and gaseous emission levels are low during mixing, pouring, cooling, and shakeout, but depend on the extent of organic additives in the mix. Casting defects such as veining and expansion are minimal. Burn-on and penetration are generally more severe than for the other no-bake systems and can be controlled by sand additives and a wash practice.

Oil urethane no-bake resins (also known as oil-urethane, alkyd-urethane, alkyd-oil-urethane, or polyester-urethane) are three-component systems that consist of Part A, an alkyd oil type resin; Part B, a liquid amine/metallic catalyst; and Part C, a polymeric methyl di-isocyanate (MDI) (the urethane component).

The three-part system uses the Part B catalyst to achieve a predictable work/strip time. It can be made into a two-part system by preblending Parts A and B when the amount of the Part B catalyst added to the resin controls the work/strip time. Part A can also be modified for better coating action, improved performance in temperature extremes, or better strippability.

Part A is normally used at 1 to 2% of sand weight. The Part B catalyst, whether added as a separate component or preblended with Part A, is 2 to 10% by weight of Part A. The Part C isocyanate is always 18 to 20% by weight of Part A.

Although the oil urethane no-bake system is easy to use, the curing mechanisms are difficult to understand because there are two separate curing stages and two curing mechanisms. When the three components are mixed together on the sand, the polyisocyanate (Part C) quickly begins to cross-link with the alkyd oil resin (Part A) at a rate controlled by the urethane catalyst component of Part B, as shown in Fig. 3. This action produces a urethane coating on the sand with enough bonded sand strength to strip the pattern and handle the core or mold.

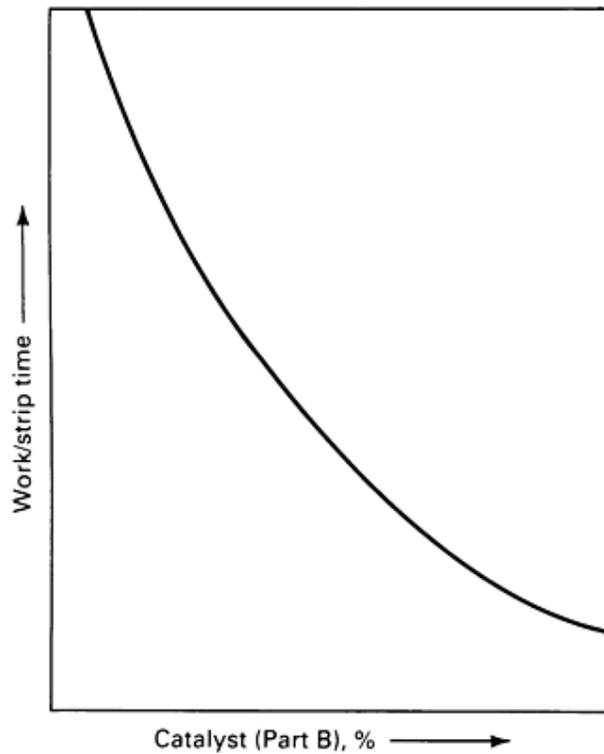
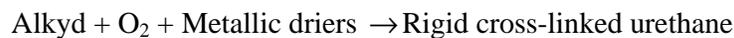


Fig. 3 Effect of increasing oil urethane system (Part B) (catalyst) on work time and strip time

The other stage of the curing reaction is similar to a paint-drying mechanism in which oxygen combines with the alkyd-oil resin component and nearly polymerizes it fully at room temperature to form a tough urethane bond. The metallic driers present in the Part B catalyst accelerate the oxygenation or drying (slowly at room temperature or quickly at 150 to 205 °C, or 300 to 400 °F), but because the full cure is oxygen dependent, section size and shape, along with temperature, determine how long it takes to attain a complete cure.

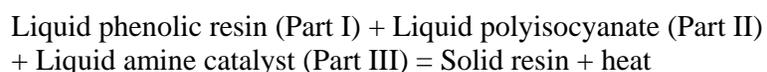
The alkyd-oil urethane mechanism is a two-stage process involving:



For maximum cure and ultimate casting properties, the mold or core should be heated to about 150 °C (300 °F) in a forced air oven for 1 h.

The oil urethane no-bake system, with its unique two-stage cure, results in unmatched stripping characteristics and provides foundrymen with a good method of producing large cores and molds that require long work and strip times.

The phenolic urethane no-bake (PUN) binder system has three parts. Part I is a phenol formaldehyde resin dissolved in a special blend of solvents. Part II is a polymeric MDI-type isocyanate, again dissolved in solvents. Part III is an amine catalyst that, depending on strength and amount, regulates the speed of the reaction between Parts I and II. The chemical reaction between Part I and Part II forms a urethane bond and no other by-products. For this reason and because air is not required for setting, the PUN system does not present the problems with through-cure or deep-set found in other no-bake systems. A simplified version of the curing mechanism for phenolic urethane no-bake systems is:



Phenolic urethane no-bake binders are widely used for the production of both ferrous and nonferrous castings and can be successfully used for high-production operations or jobbing shops because of their chemical reaction time and ease of operation.

Although many types of mixers can be used with PUN binders, zero-retention high-speed continuous mixers are the most widely used. Because the mixing takes place rapidly, the fast strip times (as fast as 30 s) of the PUN system can be utilized in practice. No mixed sand is retained in the mixer to harden after it is shut off. Further, the mixers can be coordinated with pattern movement, sand compaction, stripping operations, and mold or core finishing and storage to create a simple manual or fully automated no-bake loop.

Total binder level for the PUN system is 0.7 to 2% based on the weight of sand. It is common to offset the ratio of Part I to Part II at 55:45 or 60:40. The third-part catalyst level is based on the weight of Part I. Depending on the catalyst type and strip time required 0.4 to 8% catalyst (based on Part I) is normally added.

Compaction of the mixed sand can be accomplished by vibration, ramming, and tucking. The good flowability of PUN sand mixes allows good density with minimum effort. Because the PUN system cures very rapidly, the time required for the compacted pattern to reach rollover and strip must coincide with the setup or cure time of the sand mix.

For certain ferrous applications (most commonly steels), the addition of 2 to 3% iron oxide to the sand mix can improve casting surface finish. This addition is also beneficial in reducing lustrous carbon defects by promoting a less reducing mold atmosphere. The PUN resin system contains about 3.0 to 3.8% N (which is about 0.04% based on sand). To reduce the chance of nitrogen-related casting defects, the Part I to Part II ratio can be offset 60:40 in favor of the Part I because substantially all the nitrogen is in Part II. It has also been shown that as little as 0.25% red iron oxide is effective in suppressing the ferrous casting subsurface porosity associated with nitrogen in the melt and/or evolved from the PUN binder.

The polyol-isocyanate system was developed in the late 1970s for aluminum, magnesium, and other light-alloy foundries. Previously, the binder systems used in light-alloy foundries were the same as those used for the ferrous casting industry. The lower pouring temperatures associated with light alloys are not sufficient to decompose most no-bake binders, and removal of cores from castings is difficult. The polyol-isocyanate system was developed to provide improved shakeout.

The nonferrous binders are similar to the PUN system described previously. Part I is a special polyol designed for good thermal breakdown dissolved in solvents. Part II is a polymeric MDI-type isocyanate, again dissolved in solvents. Part II is an amine catalyst that can be used to regulate cure speed.

The chemical curing reaction of the polyolisocyanate system is as follows:



In practice, polyol-isocyanate binders are used in much the same way as the PUN binders they evolved from. One difference is that the system does not require a catalyst. Several phenol formaldehyde (Part I) resins are available that provide strip times from 8 min to over 1 h. For maximum control, however, an amine (Part III) catalyst can be used to regulate strip times to as fast as 3 min.

For light-alloy applications, binder levels range from 0.7 to 1.5% based on sand. Part I and Part II should be used at a 50:50 ratio for best results. Reactivity, strengths, and work-time-to-strip-time ratio are affected by the same variables as the PUN binders. Because of the fast thermal breakdown of the binder (Fig. 4), the polyol-urethane system is not recommended for ferrous castings.

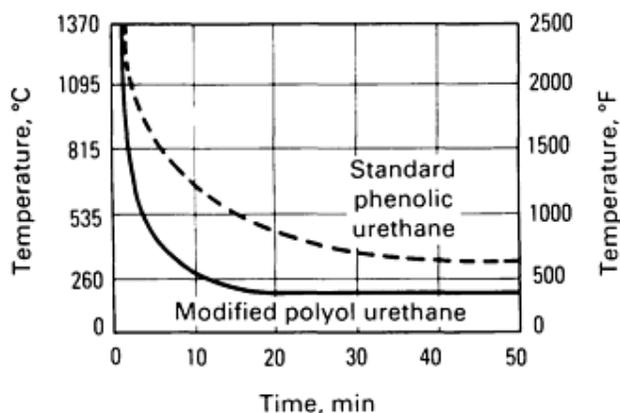


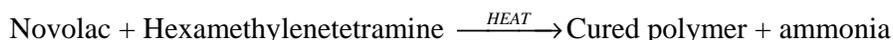
Fig. 4 Collapsibility of polyol urethane compared to that of phenolic urethane

Alumina-Phosphate No-Bake. Alumina-phosphate binders consist of an acidic, water-soluble alumina-phosphate liquid binder and a free-flowing powdered metal oxide hardener. Although this system is classified as a no-bake process (Table 1), both of its parts are inorganic; all other no-bake systems are organic or, in the case of silicate/ester systems, inorganic and organic. More detailed information on phosphate-bonded systems can be found in the article "Sand Molding" in this Volume (see the section "Bonded Sand Molds").

## Shell Process

In the shell process, also referred to as the Croning process, the sand grains are coated with phenolic novolac resins and hexamethylenetetramine. In warm coating, dissolved or liquid resins are used, but in hot coating, solid novolac resins are used. The coated, dry, free-flowing sand is compressed and cured in a heated mold at 150 to 280 °C (300 to 535 °F) for 10 to 30 s. Sands prepared by warm coating cure fast and exhibit excellent properties. Hot-coated sands are generally more free flowing with less tendency toward caking or blocking in storage.

Novolac Shell-Molding Binders. Novolacs are thermoplastic, brittle, solid phenolic resins that do not cross-link without the help of a cross-linking agent. Novolac compositions can, however, be cured to insoluble cross-linked products by using hexamethylenetetramine or a resole phenolic resin as a hardener. A simplified version of the Novolac curing mechanism is:



Phenol-formaldehyde novolac resins are the primary resins used for precoating shell process sand. These resins are available as powder, flakes, or granules or as solvent- or waterborne solutions. A lubricant, usually calcium stearate (4 to 6% of resin weight) is added during the resin production or the coating process to improve flowability and release properties. Hexamethylenetetramine, 10 to 17% based on resin weight, is used as a cross-linking agent.

Producing Cores and Molds. The shell-resin curing mechanism involves the transition from one type of solid plastic to another--thermoplastic to thermosetting. This physical conversion must be completed during a brief period of the shell cycle before the heat (necessary to cure the resin) begins to decompose the binder. Pattern temperatures are typically 205 to 315 °C (400 to 600 °F). Operating within the ideal temperature range provides a good shell thickness, optimum resin flow, and minimal surface decomposition. Higher pattern temperatures of 275 to 315 °C (525 to 600 °F) are often successfully used to make small cores, because the shell cycle is short enough that little surface definition is lost by decomposition of the resin at the pattern interface during the relatively brief cure cycle generally needed.

Various additives are used during the coating operation for specific purposes. They include iron oxide to prevent thermal cracking, to provide chill, and to minimize gas-related defects.

The shell process has some advantages over other processes. The better blowability and superior flowability of the lubricant-containing shell sand permits intricate cores to be blown and offers excellent surface reproduction in shell molding. Because the bench life of the coated shell sand is indefinite, machines do not require the removal of process sand at the end of a production period.

Storage life of cured cores or molds is excellent. A variety of sands are usable with the process, and nearly all metals and alloys have been successfully cast using shell sand for cores and molds.

## Hot Box and Warm Box Processes

In the hot box and warm box processes, the binder-sand mixture is wet. A liquid thermosetting binder and a latent acid catalyst are mixed with dry sand and blown into a heated core box. The curing temperature depends on the process. Upon heating, the catalyst releases acid, which induces rapid cure; therefore, the core can be removed within 10 to 30 s. After the cores are removed from the pattern, the cure is complete as a result of the exothermic chemical reaction and the heat absorbed by the core. Although many hot box cores require postcuring in an oven to complete the cure, warm box cures require no postbake oven curing.

**Hot Box Binders.** Conventional hot box resins are classified simply as furan or phenolic types. The furan types contain furfuryl alcohol, the phenolic types are based on phenol, and the furan-modified phenolic has both. All conventional hot box binders contain urea and formaldehyde. The furan hot box resin has a fast cure compared to that of the phenolic-type system and can therefore be ejected faster from the core box. Furan resin also provides superior shakeout and presents fewer disposal problems because of the lack of phenol. Typical resin content is 1.5 to 2.0%.

A simplified hot box reaction mechanism is:



Catalyst selection is based on the acid demand value and other chemical properties of the sand. Sand temperature changes of 1 °C (20 °F) and/or variations of  $\pm 5$  units in the acid demand value of the sand require a catalyst adjustment to maintain optimum performance. When a liquid catalyst is used, many operations have winter and summer grades that can be mixed together during seasonal transitions. Both chloride and nitrate catalysts are used. The chloride catalyst is the more reactive. Therefore, the chloride is the winter grade, and the nitrate the summer grade.

Hot box resins have a limited shelf life and increase in viscosity with storage. If possible, containers should be stored out of the sun in a cool place and used on a first-in-first-out basis. Hot box catalysts have indefinite storage lives.

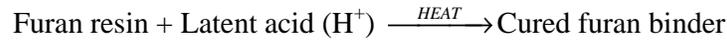
Pattern temperature should not vary more than 28 °C (50 °F). Measurements should be made at the highest and lowest points across the pattern. Most production shops run hot box pattern temperatures of 230 to 290 °C (450 to 550 °F), but the ideal temperature is between 220 and 245 °C (425 and 475 °F). The most common mistake made with the hot box process is to run too high a pattern temperature, which causes poor core surfaces. This condition results in a friable core finish that is especially detrimental to thin-section cores.

The color of the core surface shows how thoroughly the core is cured and is a good curing guideline. The surface should be slightly yellow or very light-brown--not dark brown or black. Overall, the phenolic and furan hot box resins are extensively used in the automotive industry for producing intricate cores and molds that require good tensile strengths for low cost gray iron castings.

**Warm Box Binders.** The warm box resin is a minimum-water (<5%) furfuryl alcohol-type resin (furfuryl alcohol content: ~70%) that is formulated for a nitrogen content of less than 2.5%. Because the resin/sand mix exhibits a high degree of rigid thermoset properties when fully cured, little or no post strip distortion or sagging occurs. High hot and cold tensile properties are characteristic of warm box sands and generally permit a binder level between 0.8 to 1.8%, or 20% less than the conventional hot box resin content.

Warm box catalysts are copper salts based primarily on aromatic sulfonic acids in an aqueous methanol solution. The catalyst amount used is 20 to 35%, based on resin weight. These catalysts are unusual in that they impart an excellent latent property (unreactive at room temperature) to the binder system, but still form strong acids when heated. They promote a thorough curing action at temperatures at approximately 65 °C (150 °F) or higher.

A simplified warm box curing reaction mechanism is:



The binder components remain stable when mixed together in the proper ratios in sand until activated by heat, which decomposes the catalyst and releases the acid that causes the resin to polymerize.

The pattern temperatures used range from 150 to 230 °C (300 to 450 °F). The optimum temperature of 190 °C (375 °F) is about 55 °C (100 °F) below the operating temperature for hot box binders. Low resin and catalyst viscosity combine to produce a flowable sand mix. Castings produced with warm box binders exhibit casting features that are very similar to those of a furan no-bake system. Good dimensional accuracy and excellent erosion resistance are observed with warm box binders.

## Oven-Bake Processes/Core-Oil Binders

Core-oil binder is used in combination with a water-activated cereal to produce a coated sand mix that has green strength. Green strength permits the wet sand mix to be blown or hand rammed into a simple vented, relatively low-cost core box at room temperature and to retain its shape when removed from the pattern.

The uncured plasticlike cores are generally placed on a flat board or a dryer plate (a supporting structure to maintain the shape of the core) for oven drying. This process translates into a fast method of producing cores or molds. Except for the subsequent drying operations, the cores are in effect made almost as fast as they are blown.

Types of Core Oil. A binder system that uses water and cereal to develop green strength and then cures or dries in a hot, forced air oven is normally referred to as a core-oil process. Several types of binders fall into this category. Linseed or vegetable oil binders account for most of the volume, but urea formaldehyde and resole phenolic resins are also used. The sand-coating procedure, sand formulation, coremaking techniques, and general foundry procedures are chemically different, but are similar for all types of core-oil processes.

Urea formaldehyde is noted for its excellent shakeout and is used in aluminum foundries and shops that operate dielectric curing ovens instead of the hot, forced air ovens. Because of its high nitrogen content and low hot strength, urea formaldehyde has found rather limited application outside of nonferrous shops.

Additives. Core mixes generally contain 1% or less cereal, based on sand weight. The cereal is kept to a minimum because it generates gas. Normally, when more green strength is required for core stripping and/or handling, the cereal is mulled along with the water for a longer time.

Small additions of Southern and/or Western bentonite (up to  $\frac{1}{2}$  % based on sand weight) to cereal have also proved useful for developing green strength. An additional benefit is that bentonite evolves far less gas than cereal does.

Water is added to the mix to activate the cereal and to create green strength. The amount must be controlled to develop optimum properties, as indicated in Table 4. Baked strength, green strength, and baking rate are influenced by moisture content. A 2% water addition gives optimum results.

**Table 4 Effects of moisture on core-oil sand mixes**

1% cereal, 1% oil, 90 min bake at 200 °C (400 °F), AFS 62 GPN silica sand

Property	Percentage of moisture							
	0	0.5	1.0	1.5	2.0	3.0	4.0	5.0
Green strength, kPa (psi)	1.4	3.4	6.2	8.9	9.6	7.6	6.9	<b>6.2</b>

	(0.2)	(0.5)	(0.9)	(1.3)	(1.4)	(1.1)	(1.0)	<b>(0.9)</b>
Tensile strength, kPa (psi)	1205	1450	1825	2275	2480	2345	2135	<b>1725</b>
	(175)	(210)	(265)	(330)	(360)	(340)	(310)	<b>(250)</b>
Percentage baked	100	100	100	100	100	97	88	<b>78</b>
<b>Scratch hardness index</b>	<b>60</b>	<b>71</b>	<b>82</b>	<b>92</b>	<b>96</b>	<b>95</b>	<b>90</b>	<b>88</b>

Operational Considerations. A number of points are essential for effective use of core-oil systems:

- *Basic Mix.* A standard core-oil mix contains about 1% cereal, 1 to 3.5% water, 1% binder, and 0.1% of a flowability/release agent
- *Mixing Order.* As indicated in Table 5, the sequence of additions to the muller has a significant effect on core properties. The best order of addition to the sand clearly is (1) cereal and dry additives, (2) water, (3) oil, and (4) flowability/release agent
- *Oven Drying.* Forced hot air is the principal means of curing core-oil binders. Heat causes the binder in the core-oil sand mix to cross-link and provide strength. The proper combination of oven temperature, drying humidity, and time determines the final strength, dimensional stability, and surface finish of the core

**Table 5 Sequence of muller additions to core-oil sands**

1% cereal, 1% oil, 1.5% water, 90 min bake at 200 °C (400 °F), silica sand

Property	Percentage of moisture						
	All at once	1. Cereal 2. Oil 3. Water	1. Cereal 2. Water 3. Oil	1. Oil 2. Cereal 3. Water	1. Oil 2. Water 3. Cereal	1. Water 2. Oil 3. Cereal	1. Water 2. Cereal 3. Water
Green strength, kPa (psi)	6.9	2.0	10.3	3.4	4.1	3.4	<b>7.6</b>
	(1.0)	(0.3)	(1.5)	(0.5)	(0.6)	(0.5)	<b>(1.1)</b>
Tensile strength, kPa (psi)	1930	1345	2495	1725	1450	1380	<b>2275</b>
	(280)	(195)	(362)	(250)	(210)	(200)	<b>(330)</b>

It is important to note that mixing cores produced by other binder processes in the same drying oven with uncured core-oil cores usually weakens the non-core-oil cores because of the steam evolved from the water used in the core-oil process

## Cold Box Processes

The term cold box process implies the room-temperature cure of a binder-sand mixture accelerated by a vapor or gas catalyst that is passed through the sand. Several different cold box systems are currently used, employing different binders and gas or vapor catalysts—for example, triethylamine or dimethylethylamine for phenolic urethane binders, sulfur dioxide for furan and acrylic epoxy binders, methyl formate for ester-cured alkaline phenolic binders, and carbon dioxide for silicate binders.

Phenolic Urethane Cold Box (PUCB). The process uses a three-part binder system consisting of a phenolic resin (Part I), a polymeric isocyanate (Part II), and a tertiary amine vapor catalyst (Part III). Sand is coated with the Part I and Part II components and compacted into a pattern at room temperature. The tertiary amine catalyst is introduced through vents in the pattern to harden the contained sand mix. The catalyst gas cycle is followed by an air purge cycle that forces the amine gas through the sand mass and removes residual amine from the hardened core. It is recommended that the exhaust from the core box be scrubbed chemically to remove the amine.

The reactive component of the PUCB Part I is phenolic resin. It is dissolved in solvents to yield a low-viscosity resin solution to facilitate coating the sand and blending it with the second component. Part II is a polymeric MDI-type isocyanate that again is blended with solvents to form a low-viscosity resin solution. The hydroxyl groups provided by the phenolic resin in Part I react with the isocyanate groups in Part II in the presence of the amine catalyst to form the solid urethane resin. It is this urethane polymer that bonds the sand grains together and gives the PUCB process its unique properties.

A simplified curing reaction mechanism for the PUCB process is:



The urethane reaction does not produce water or any other by-product. The system contains 3 to 4% N, which is introduced from the Part II polymeric isocyanate component. The organic resins and solvents in the PUCB system make it high in carbon content, which contributes to the formation of lustrous carbon and a reducing mold atmosphere during casting.

The PUCB process can be used with all of the sands commonly used for coremaking in the foundry industry. Some consideration must be given, however, to the effects of sand temperature, chemistry, and moisture content on the resin performance of PUCB. The ideal sand temperature is 20 to 25 °C (70 to 80 °F). Lower temperature can reduce mixing efficiency and increase cure times. Higher sand temperatures reduce gassing cycles and the amount of catalyst required, but shorten the usable life of the coated sand mix.

A maximum sand moisture content of 0.2% is acceptable for the PUCB process at room temperature (~20 °C, or 70 °F), but when the sand temperature rises to 30 °C (90 °F), the moisture content of the sand must be kept at less than 0.1% for the process to function properly.

All types of popular sand-mixing equipment can be used with the PUCB process. A sand delivery system that causes the least amount of aeration is best. Typically, 1.5% total binder, consisting of equal parts of Part I and Part II components, is used on a washed and dried sand for ferrous castings. Many foundries prefer to offset the ratio and use slightly more Part I for various technical reasons. For the casting of aluminum, magnesium, and other low pouring temperature alloys, binder levels of 1% and less are used to facilitate shakeout.

The volatile liquid tertiary amines commonly used to cure the PUCB binders are triethylamine or dimethylethylamine. Various designs of generators vaporize and blend these amines with carrier gas and deliver them to the core machine. The best generators provide a consistently high concentration of amine to facilitate fast, predictable cure cycles.

The exhaust from the core box is delivered to a chemical scrubber, and the amine is removed by reacting it with dilute sulfuric acid to form an amine sulfate salt. In larger foundry operations, concentrated liquor from the scrubber has been recycled through chemical processing to convert it back into usable amine, thus providing economic and ecological advantages.

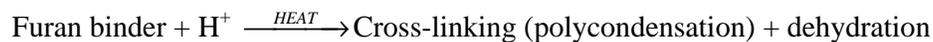
Certain sand additives can be used with the PUCB system to eliminate specific casting defects. Veining in ferrous and brass castings can be substantially reduced by the addition of 1 to 2% proprietary clay-sugar blends or 1 to 3% iron oxide.

Black and red iron oxide additions of 2 to 3% are recommended for steel castings. Red iron oxide at levels as low as 0.25% can be effective in eliminating binder-induced subsurface pinhole porosity in alloys prone to those defects.

**SO<sub>2</sub> Process (Furan/SO<sub>2</sub>).** The sulfur dioxide (SO<sub>2</sub>) process can be described as a rapid-curing, gas-activated, furan no-bake. Various furfuryl alcohol-base resins, blended with an adhesion promoter, are used to coat the sand in the range of 0.9 to 1.5%. Organic hydroperoxides at 30 to 50% by weight of the resin are added to the sand mixture and/or blended with the resin. Methanol-diluted silane (5 to 10%, based on resin weight) is used to increase strength, to improve shelf life, and to increase humidity resistance.

Once the sand is in place, SO<sub>2</sub> gas is introduced. It reacts with the peroxide and water in the furan resin, causing an *in situ* formation of a complex group of acids that cures the furan binder.

The simplified curing reaction mechanism for the SO<sub>2</sub> process is:



The curing reaction begins when the SO<sub>2</sub> first contacts the peroxide and continues even after removal from the pattern. As the catalyzed furan/SO<sub>2</sub> resin bonded sand ages, the water of condensation resulting from the furan polymerization continues to dissipate from the still-curing sand until the reaction is complete. Upon curing, the sand changes from a light color to dark green or black.

The recommended sand temperature for the SO<sub>2</sub> process is 25 to 40 °C (80 to 100 °F). Lower temperatures reduce cure speed and may produce partially cured cores. Higher temperatures promote evaporation of solvents and reduce mixed-sand bench life. Hot purging with air at 95 °C (200 °F) is required to achieve optimum cure.

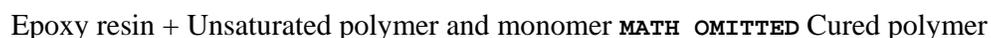
The SO<sub>2</sub> process develops approximately 20 to 50% of its overall tensile strength upon ejection from the core box. It then builds strength rapidly to 85 to 95% of overall tensile strength after about 1 h. Bench life of the mixed sand is 12 to 24 h. In typical core blowing operations, relatively low blow pressures of 275 to 415 kPa (40 to 60 psi) are possible because excellent flowability is characteristic of the system.

The free radical cure (FRC) process includes all acrylic and acrylic-epoxy functional binders. The binders are cured using an organic hydroperoxide and SO<sub>2</sub>. A variety of acrylic-epoxy binders have been developed for both ferrous and nonferrous applications, ranging from 100% acrylic binders to approximately 30:70 ratios of acrylic-epoxy blends. Sand performance and casting properties are influenced by the ratio of acrylic to epoxy functional components present in the binder system.

*Acrylic binders* are based on acrylic functional components. When combined with small amounts of organic hydroperoxides, acrylic binders can be cured through the application of a wide range of concentrations of sulfur dioxide with inert gas carriers such as nitrogen (1 to 100% SO<sub>2</sub>).

Acrylic binders are primarily used in light-metal applications because of their good shakeout properties; however, they have specific applications in ferrous metals where veining defects are troublesome with other binder systems. When acrylic binders are used in ferrous applications, a refractory coating and nonturbulent gating design are recommended to reduce the threat of erosion.

*Acrylic-epoxy binders* are blends of acrylic and epoxy functional components. The acrylic-epoxy binder systems offer alternatives to existing cold box systems. The process utilizes a two-part liquid binder system consisting of (1) an unsaturated resin and/or monomer and (2) an organic hydroperoxide with an epoxy resin. The mixed sand, once exposed to SO<sub>2</sub> gas, yields a cured polymer. A simplified version of this reaction mechanism is:



Varying the acrylic-epoxy composition influences such core- and moldmaking properties as rigidity, cure speed, SO<sub>2</sub> consumption, humidity resistance, tensile and transverse strengths, and core release. In addition, casting properties such as veining resistance, shakeout, erosion resistance, and surface finish can be influenced by changing the acrylic-epoxy composition.

The FRC process employs a variety of binder systems, including specific systems for ferrous and nonferrous casting applications. Binder levels range from 0.6 to 1.8%, depending on the type of sand used and the type of metal poured.

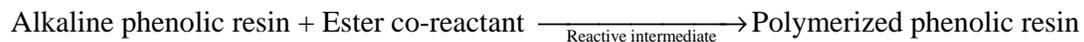
Because the FRC process components do not react until SO<sub>2</sub> is introduced to the pattern, the prepared sand mix has an extremely long bench life when compared to other cold box and hot box binder systems. This feature minimizes waste sand, provides for consistent flowability, and, most important, decreases the machine downtime because sand magazines, hoppers, and mixers do not have to be cleaned on a daily basis.

Tooling and equipment requirements are similar to those of the other cold box processes. Gassing units used for the phenolic-urethane or the SO<sub>2</sub> process are replaced or simply converted for use with the FRC system. Substitutions of caustic solutions for acid solutions are made in the wet scrubbers when the FRC process replaces the phenolic urethane system.

*Disposal of SO<sub>2</sub> Gas.* Scrubbing of the gas is accomplished with a wet scrubbing unit that utilizes a shower of water and a sodium hydroxide. A 5 to 10% solution of sodium hydroxide at a pH of 8 to 14 provides efficient neutralization of the SO<sub>2</sub> and prevents the by-product (sodium sulfite) from precipitating out of solution. Higher sodium hydroxide concentrations will cause precipitation of the neutralized product. Stoichiometrically, 0.58 kg (1.27 lb) of sodium hydroxide is required to neutralize 0.45 kg (1.0 lb) of SO<sub>2</sub>.

Casting dimensional accuracy and resistance to veining of ferrous and nonferrous metals are influenced by the thermal expansion of sand and by the hot distortion characteristics of the binder system. The antiveining feature of specific FRC binders has eliminated the need for specialty sands, sand additives, and special slurry applications in iron and steel castings. Further, the lack of nitrogen and the absence of water minimize the nitrogen and/or hydrogen pinholing porosity formation often associated with cold box systems containing water or nitrogen.

The phenolic ester cold box (PECB) process was introduced to the foundry industry in 1984. A two-part system, it consists of a water-soluble alkaline phenolic resole resin and a volatile ester vapor co-reactant. Sand is coated with the phenolic resin and blown into the core box. The liquid ester coreactant is vaporized and injected as gas through the sand mix. The theoretical reaction is as follows:



Because the ester is consumed in the curing reaction, purging of excess ester vapor can be accomplished with the minimum volume of purge air. However, purge air helps to distribute the ester vapor throughout the sand mix.

Methyl formate is the preferred ester for curing the phenolic resin because it is volatile and vaporized more easily than other esters. Methyl formate is readily available and relatively inexpensive.

The alkaline-phenolic binder is a low-viscosity (0.1 to 0.2 Pa · s) liquid at typically 50 to 60% solids in aqueous solution. The system contains less than 0.1% N and produces a less reducing mold atmosphere than the cold box binder systems.

The PECB system is affected by the physical characteristics of the sand, such as grain fineness, grain shape, and screen distribution. The best strengths are achieved with high-purity, washed and dried, round-grain silica sands. Because of the alkaline nature of the resin, however, it is not very sensitive to sand acid demand value. The fact that it is a water-soluble aqueous resin makes the system less sensitive to moisture, and it can tolerate up to 0.3% water in the sand.

The PECB system can be mixed using conventional mullers and continuous mixers. Binder levels vary, depending on sand type, but 1.75 to 2.5% resin is typically used with washed and dried silica sands. For sufficient handling strength, somewhat higher binder levels are required than for other gas-cured organic binder systems.

Methyl formate is volatilized in generating equipment designed especially for the PECB process. Because the methyl formate is not a catalyst, but a co-reactant of the system, the generating equipment must be capable of delivering a large volume of highly concentrated vapor to promote cure.

Stoichiometrically, about 15% methyl formate based on phenolic resin is required to harden the binder/sand mixture. In practice, the methyl formate requirement ranges from 30 to 80% and is largely dependent on venting and negative exhaust on the tooling. Lower gassing pressures and longer curing times promote the most efficient use of the ester co-reactant.

Despite the low handling strengths characteristic of the PECB system, castings made from all alloys show good surface finish. The erosion resistance and veining resistance of the PECB system are better than those of the phenolic urethane and phenolic hot box systems. A coating is recommended to control penetration defects. The PECB system does not usually require sand mix additives such as iron oxides or sugars to reduce veining and to control nitrogen defects. Because of the alkaline nature of the PECB sand, care must be taken so that it does not contaminate sand systems that are sensitive to pH change, especially if the reclaimed sand is used for other binder processes.

Sodium Silicate/CO<sub>2</sub> System. This system consists of liquid sodium silicate and CO<sub>2</sub> gas, and it is an inorganic system. Silicate binders are odorless, nonflammable, suitable for all types of work (high production to large molds), applicable to all types of aggregates, produce no noxious gases upon mixing/molding/coring, and produce a minimum of volatile emissions at pouring/cooling/shakeout. More detailed information on sodium silicate/CO<sub>2</sub> systems can be found in the article "Sand Molding" in this Volume (see the section "Bonded Sand Molds").

## Sand Molding

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### Introduction

SAND MOLDING (CASTING) is one of the most versatile of metal-forming processes, providing tremendous freedom of design in terms of size, shape, and product quality. Sand molding processes are classified according to the way in which the sand is held (bonded). For the purposes of this Handbook, sand molding processes have been categorized as:

- *Resin Binder Processes.* These organically bonded systems include no-bake binders, heat-cured binders (the Shell process and warm box, hot box, and oven-bake processes), and cold box binders. Each of these systems is described in the articles "Resin Binder Processes" and "Coremaking" in this Volume
- *Bonded sand molds* are based on inorganic bonds and include such processes as green sand molding, dry sand molding, skin dried molds, and loam molding, sodium silicate-carbon dioxide systems, and phosphate bonded molds
- *Unbonded Sand Molds.* With unbonded sand molding processes, dry, unbonded, free-flowing sand surrounds the pattern. Lost foam processing, which uses expandable polystyrene patterns, and vacuum molding, are examples of unbonded sand molds. Lost foam molds for large castings are sometimes backed up with a no-bake binder system

This article will describe the latter two categories. More information on sand molding equipment and processing can be found in the article "Sand Processing" in this Volume.

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### *Bonded Sand Molds*

Patrick O'Meara, Internet Foundries Inc.; Larson E. Wile, Consultant; James J. Archibald and Richard L. Smith, Ashland Chemical Company; Thomas S. Piwonka, University of Alabama

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According to the American Foundrymen's Society (AFS), approximately 90% of all castings produced annually in the United States are processed by sand molding (Ref 1). This section will review a number of sand molding methods that use bonded sand (see classification system described above) with emphasis on green sand molds, the most widely used molding method for small-to-medium castings in all metals.

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### Reference cited in this section

1. E.J. Sikora, Evaporative Casting Using Expendable Polystyrene Patterns and Unbonded Sand Casting Techniques, *Trans. AFS*, Vol 86, 1978, p 65

### Green Sand Molds

The phrase green sand refers to the fact that the medium has been tempered with water for use in the production of molds (temper water, which is the water added to activate clay/water bonds in green sand molds, is described in the article "Bonds Formed in Molding Aggregates" in this Volume). As will be described below, the control of a green sand process requires an understanding of the interaction of the various parameters normally measured in a system sand.

### *Process Control Requirements*

A realistic approach to sand control is to target those system variables with which actual control can be implemented and realized. Put in more simple terms, one must control those system parameters that are directly affected by actions taken on the foundry floor. Clay and water are the primary additives of a system sand. The functions they perform are measured by determining the clay content and the percent of compactability of the prepared sand. Seacoal, cellulose, and starches may also be added to the sand. These organic components of the system sand are normally measured by the percent volatile and/or the total combustible test.

The percent volatile test measures the volatile content of the system sand at a specified temperature, usually 650 °C (1200 °F). The total combustible test is conducted by burning the samples of system sand at an elevated temperature, normally 1010 °C (1850 °F). Detailed procedures for these tests can be found in the *AFS Mold and Core Test Handbook*.

The remaining parameters measured on a system sand, such as green strength and permeability are secondary controls. They should be tracked using trend line analysis techniques. This type of analysis allows the monitoring of the variable in question over an extended time so that subtle changes in the magnitude of the variable can be detected. Significant changes in these secondary parameters indicate equipment problems, changes in raw material quality or consistency, and/or changes in product mix being made in the system sand.

### *Sand Systems*

**Types of Sand.** Sand for green sand molding is composed of various ingredients, each with a specific purpose. The most basic of these ingredients is the base sand itself. The most predominant type of base sand is silica sand. It is classified in two categories: naturally bonded and synthetic sand.

The naturally bonded sand (or bank sand, as it is sometimes called) contains clay-base contaminants. These naturally occurring clays are the result of sedimentation deposits produced during the formation of the sand deposit. The use of this type of sand as a green sand molding medium is determined by the type of metal being cast, economics, casting quality, and the degree of consistency demanded by the final product.

Synthetic sand is composed of base sand grains of various grain distributions. Bonding agents are added to these base sands to produce the desired molding characteristics. The major base sand in this category is silica, although zircon, olivine, and chromite are used for special applications.

**Controlling Sand Properties.** Sand grain structure is a very important characteristic in the selection of a base sand. The selection dictates the ultimate mold permeability and density, and both of these parameters are critical to the production of quality castings.

When molten metal is introduced into a green sand mold, gases and steam are generated as a result of the thermal decomposition of the binder and other additives or contaminants that are present. If the permeability of the mold is not sufficient to allow the escape of the generated gases, mold pressures will increase, impeding the flow of molten metal, or even causing the metal to be blown from the mold. Thus, the selection of a base sand that provides adequate mold porosity is very important.

Because resistance to gas flow increases as the size of the pores (voids) between the sand grains decreases, the minimum porosity required is determined by the volume of the gas generated within the mold cavity. In like turn, the selection of the base sand is determined by the total amount of gas produced within the mold cavity, as well as by surface finish requirements.

The fact that gas is generated within the mold cavity is not always a disadvantage. Pressures within the mold from the generation of gases help prevent metal penetration into the sand. This minimizes burned-on sand grains and resulting problems associated with cleaning and machining the casting. Thus, a balance between mold permeability and gas generation must be maintained. For example, if mold permeability is low because of the fineness of the base sand, the

sand additives should be those conducive to the production of a low volume gas. On the other hand, if permeability is high, it is advantageous to select materials that yield higher levels of gas.

Permeability is controlled by the amount and size of the voids between densely packed sand grains. The size of the voids is determined by the size, size distribution, shape, and packing pattern of the grains. Figure 1 illustrates two sizes of rounded sand grains. Figure 2 shows that the voids in a mold face are large for a coarse sand and small for a fine sand, although the total void area per cubic unit of volume is almost the same for both sands. However, these distribution criteria also govern the dimensional stability of the base sand.

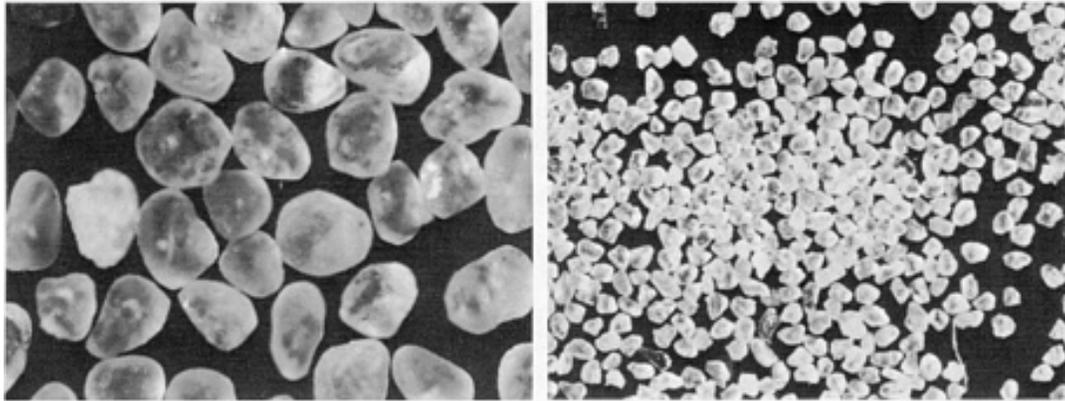


Fig. 1 Two sizes of rounded sand grains. 35 $\times$ .

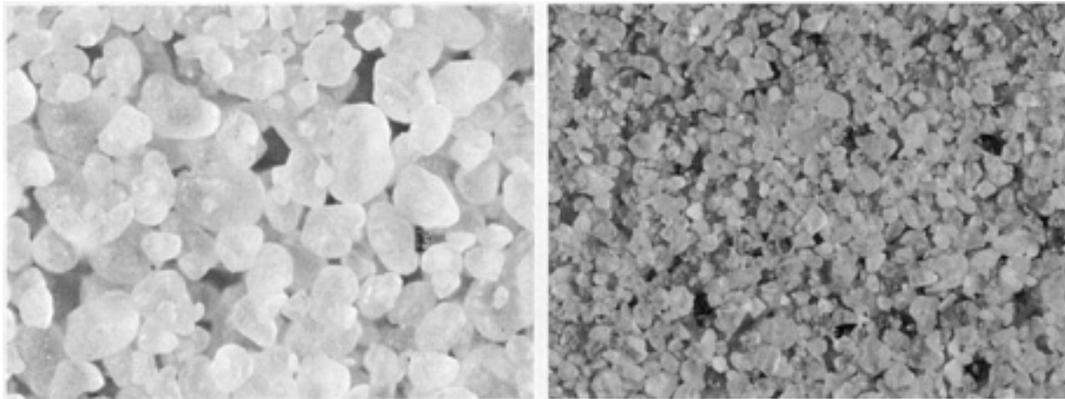


Fig. 2 Sizes of pores in faces of molds made from coarse sand and from fine sand. 35 $\times$ .

A green sand mold must withstand the erosion caused by the metal impinging on and flowing over the sand surface. If the individual sand grains are not held firmly in place during metal flow, the result will be loose sand grains that will wash into the casting cavity and cause a defective casting. Sand grains are held in place by a combination of two mechanisms: a wedging action in which the sand grains are mechanically locked to adjacent grains, and the clay-water bond established between the grains. The combined action of these two mechanisms forms the basis of the sand strength developed in the mold cavity. The best sand condition for optimum mold strength and density development is produced by sand grains that show a normal distribution over four or more adjacent screen sizes.

As molten metal is introduced into the mold cavity, heat is transferred from the molten metal to the adjacent sand grains, causing the sand grains to expand. Between 425 and 600 °C (800 and 1110 °F), silica undergoes a phase change from alpha to beta, which is accompanied by a rapid increase in volumetric size (Fig. 3). Each sand grain must be allowed to expand, or the mold surface will be altered or destroyed, with resultant loss in casting quality. Therefore, the silica sand

grains must not be compacted so densely or rammed so tightly that they are unable to expand without disrupting the mold surface.

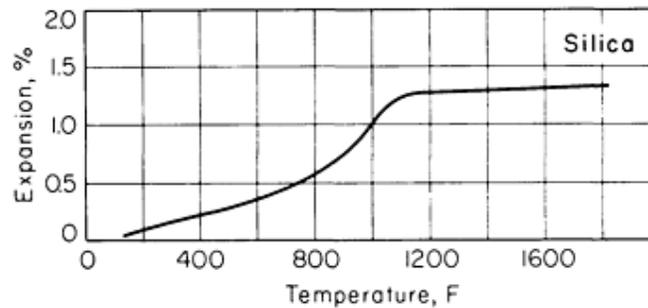


Fig. 3 The effect of temperature on the expansion of silica.

Four methods for optimizing the dimensional stability of the base sand are:

- Selection of a base sand aggregate suitable for a dimensionally stable mold surface. Generally, this will be a four-screen sand, although three-screen sands may be used for certain castings
- Addition of carbonaceous additives such as seacoals and cellulose to the green sand system. The thermal decomposition of these additives creates voids, which allow for the expansion of the silica sand grains
- Increasing clay content to develop higher green strengths, which tend to produce more stable molds
- Controlling the mold density produced by the molding equipment

If it is necessary to use a mold material with less thermal expansion than silica, alternate materials such as zircon, olivine, chromite, or calcined clay may be chosen. Zircon and chromite have the additional advantage of possessing higher heat transfer capabilities. Calcined clay is sometimes used in the production of very large castings in dry sand molds because of its extremely low thermal expansion.

The sand-to-metal ratio for a given mold influences the required pore or void size. The amount of heat transferred to the sand is a function of pouring temperature, volume of metal poured, and amount of time the sand is exposed to the elevated temperatures. These same conditions dictate the volume of gas generated for a given sand formulation. Therefore, for large, heavy castings with high pouring temperatures, a sand with large pores is preferred. For small castings, a sand with smaller pores is the sand of choice.

Finer sands with smaller pores may have reduced ability to allow the decomposition gases to escape. However, they do improve the surface finish and enhance the reproduction of pattern detail. Sand of a single mesh size distribution provides the best venting action, but affords the least protection against erosion or expansion defects. It should be noted that fine sand may require higher amounts of bonding agents (clay, water) because of the higher surface area that must be coated. This further aggravates the gas generation problems because the increased level of bonding agents generates increased amounts of gas that have to permeate the less permeable mold.

The selection of a suitable base sand is a compromise at best. The optimum selection is a multiscreen sand with adequate permeability for the metal and geometry being poured. Factored into the decision also are the economics of the raw materials and the surface finish and casting quality required.

### *Clays for Green Sand Molding*

Green sand additives can be divided into two categories, clays and carbonaceous materials. The major purpose of the clays is to function as a bonding agent to hold together the sand grains during the casting process. The carbonaceous materials aid dimensional stability of the mold, surface finish, and cleanability of the finished casting.

Types of Clay. Clays normally used in green sand molding are of three general types:

- *Montmorillonite*, or bentonite clays. These are subdivided into two general types: Western, or sodium, bentonite; and Southern, or calcium, bentonite. The two clays differ in their chemical composition as well as in their physical behavior within a system sand
- *Kaolinite*, or fireclay as it is normally called
- *Illite*, a clay not widely used. The material is derived from the decomposition of certain shale deposits

The most significant clays used in green sand operations are the bentonites. Western and Southern bentonites differ in chemical makeup and, thus, their physical characteristics also. In general, Western bentonite develops lower green strength and higher hot strength than the same amount of Southern bentonite. Southern bentonite, at the same concentration, produces higher green strength and lower hot strength. This phenomenon is sometimes confused with what is referred to as durability.

Controlling Clay Properties. All clays can be made plastic and will develop adhesive qualities when mixed with the proper amounts of water. All clays can be dried and then made plastic again by the addition of water, provided the drying temperature is not too high. However, if the temperature does become too high, they cannot be replasticized with water. It is this third condition that dictates the durability of the clay in a system sand.

All clays, regardless of type, develop both adhesive and cohesive properties when mixed with water. The amount of adhesive or cohesive property depends on the amount of water added. When the water content is low, the cohesive properties are enhanced and the clays tend to cohere, or stick to themselves, rather than adhere, or stick to the sand grains to be bonded. With high water additions, the converse is true.

In addition to having different bonding and durability characteristics, the various clays have very distinctive behavior patterns as a result of their differing physical characteristics. System sands formulated with high levels of Western bentonite have high levels of hot strength. A system sand formulated with an equivalent level of Southern bentonite will have a significantly lower hot strength. In addition, the flowability of the two sands is different because of the greater swelling tendency of the Western bentonite clays compared to that of the Southern bentonite materials. Therefore, the proper formulation of clay materials for a green sand system must take into consideration the flowability requirements as well as the shakeout requirements of the sand.

The ratio of clay to water is of critical importance in optimizing the properties of clays. The shear strength of a clay-water mixture is representative of the green strength of the compacted sand, because it is the shear strength of the films of clay coating the sand grains that bonds the sand together. This parameter is controlled by the amounts of water and clay added to the mixture and is measured by monitoring the pressure required to extrude various clay-water mixtures through a fixed orifice (Fig. 4).

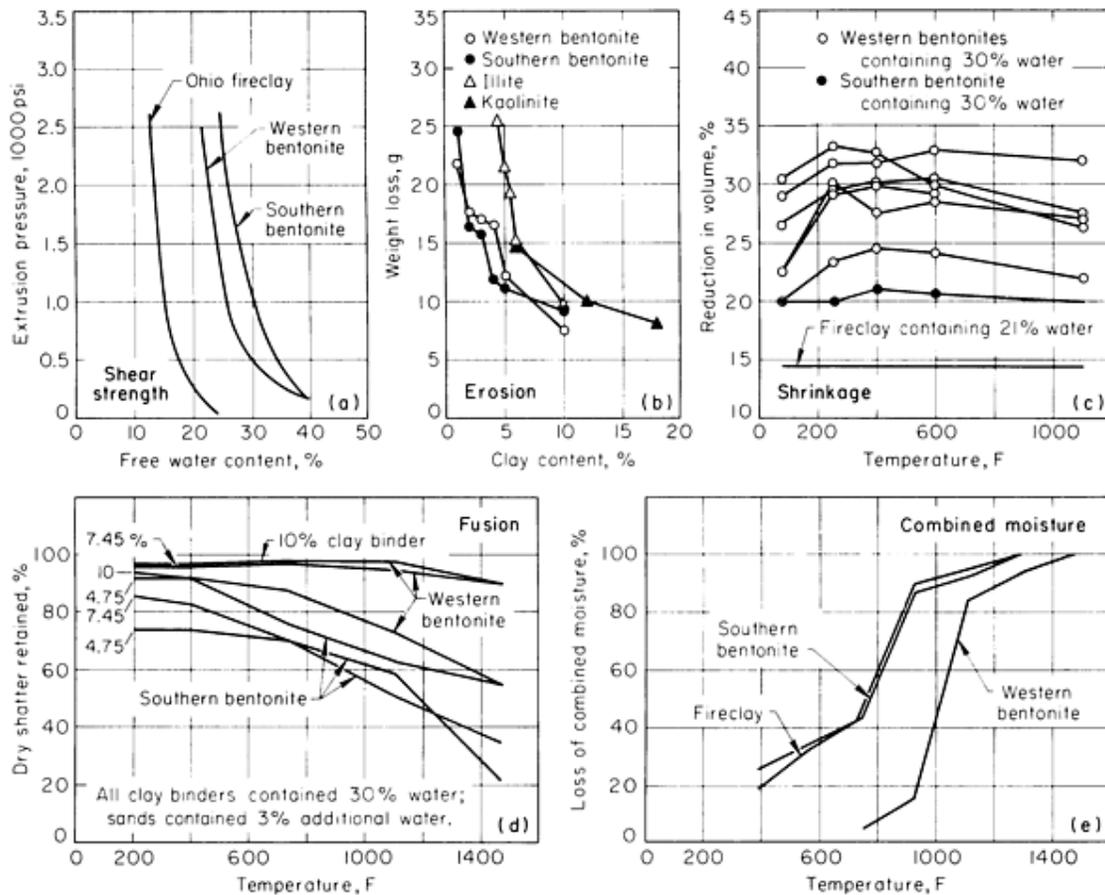


Fig. 4 The effect of several variables on the efficiency of clay used as a bonding agent in sand molds. (a) Relationship of shear strength, as measured by pressure required for extruding a continuous worm of clay through an orifice, to water content, for three clays. (b) Effect of type and quantity of clay on erosion of sand-clay mixtures. (c) Effect of temperature on shrinkage of various types of clays. (d) Effect of mold temperature during casting on fusion of clay binder. (e) Effect of temperature on loss of combined moisture in clays.

In a sand and clay mixture, water is absorbed by the clay up to its maximum capacity. Any additional water is carried as free water in the system sand and does not contribute to bonding. Therefore, high water content clay yields low shear strength. As water content is decreased, a sharp rise in shear strength occurs. The free water content in bentonite clays is normally in the range of 28 to 40%, and for fireclays it is from 15 to 20%.

While the ratio of clay to water in a sand mixture controls the ultimate strength of the sand mixture, the origin of the clay has a significant contribution on the strength potential. Clays from different geographic regions, even though they may be classified as being the same, have different strength curves. However, many of these differences are minimized by modern techniques used in the mining of the clays.

Clay quality is generally measured against the amount required to develop a specified green strength in a sand mixture. Care must be taken when evaluating a clay in this fashion because of the effects of water on strength. The term "the sticky point" defines the point of transition from predominantly cohering properties to those of adhesion. Clays selected for foundry use should have compositions near their "sticky point," or the state at which their cohesive and adhesive properties are balanced.

Once the type of clay is determined for the system sand, economic considerations must be evaluated, because the geographic location of the foundry will, in part, dictate the type, or the combination, of clays used in the operation.

Western bentonite requires a higher energy output to develop its properties than do the Southern bentonites. The fireclays contribute little to green property development, but contribute dramatically to dry and hot property development. The proper combinations of clays allow the formulation of a system sand conducive to the production of quality castings.

### *System Formulation*

Of utmost importance in controlling a green sand system is the selection and consistency of the raw materials introduced into the system sand. Acquisition of the basic raw materials should be from reputable sources only, that is, those that have ongoing quality improvement programs, including the understanding and application of statistical process control techniques. This is critical for a successful control program: Inconsistency in the raw materials used in the system results in sand variations that no amount of attention or corrective action can overcome.

Next in importance is the condition of the sand processing equipment. This includes the sand muller or mixer, sand cooling equipment, and dust collection equipment. It is important to coat the individual sand grains with a uniform thickness of the bonding agent; this governs the physical property development of the sand. The coating action, in turn, is controlled by the condition of the mixing and/or the muller equipment. Failure to monitor the equipment and to maintain it adds appreciably to variations in the sand and a loss of casting quality. More detailed information on equipment for green sand processing can be found in the article "Sand Processing" in this Volume.

Third is the identification of the critical primary and secondary control parameters. The primary control parameters for a system sand are:

- Determination of the organic components measured by the total combustible and/or percent volatile tests
- Determination of clay content measured by the methylene blue titration method
- Percent compactability of the sand controlled by the molding machine

For the majority of foundries, primary controls are limited to the system clay and the content of water and carbonaceous material (secondary control parameters are discussed below).

Actual sampling of a system sand should be accomplished as close to the point in time of use as is practical without compromising worker safety. By so doing, corrective actions can be carried out prior to the molding operation. Tests should be conducted when applicable according to standard procedures outlined in the *AFS Mold and Core Test Handbook*.

The clay content of the system sand is normally measured by the methylene blue titration method. This method of determining clay content is based on the ability of a test sample of the system sand to absorb the methylene blue dye. In this test, the dye is added to the test sample by a buret. The end point of the titration is read by the technician as a "bursting halo" when a drop of the test material is placed onto a hardened piece of filter paper with a stirring rod. The "halo" is an indication that the dye-absorbing ability of the clay has been reached. The amount of dye required to reach the end point (measured in milliliters) is compared against a known standard mixture.

Care should be exercised in the use of the methylene blue titration test because of its vulnerability to operator error. Provision should be made to obtain a test analysis of each revolution of the system sand. However, it is more important to react properly to the available test results than to be concerned with the quantity of the available test data. Clay control can be enhanced by close monitoring of clay additions. Simply knowing what goes into the sand can result in a significant reduction in system sand variations.

### *Raw Material Additions*

The sand in a green sand molding system is primarily made up of recycled, reclaimed, and reused sand. The rejuvenation of this sand is the principal function of the sand preparation system. Sand for the green sand molding system is recovered from the shakeout, cooled, cleaned, and screened. New sand is added to compensate for that which has been lost from spillage or carried away in deep pockets of the casting. Clay, water, and other additives are introduced to bring the sand mix to specification.

Maintaining Sand System Quality. Because the system sand is basically made up of recycled sand, it consists not only of mold sand, but also of core sand. The size and shape of core sand, and the binders used for core sands, are frequently quite different from those used for molding sands, and this must be considered for maintaining the sand system. Also, over time, the sand in the system breaks down as a result of mechanical attrition and thermal cycling, and therefore changes in size, size distribution, and shape. Daily variations in the product mix affect the ratio of core sand to molding sand being recycled. Raw or virgin sand additions to the system should be made to dilute the contaminating effects of residual core binders.

The introduction of additives to a system sand based on a programmed approach greatly reduces system variations. Additives are consumed at identifiable rates. Core sand dilution can be determined as well as any raw virgin sand additions. Losses due to sand carry-out, dust collection loss and material handling can be calculated or approximated. By monitoring sand system variations, a predictable quantity of bonding material can be determined and added to the system. This approach helps minimize system variations and also reduces the necessity for clay analysis as a control tool.

New or reclaimed sand additions to a system sand are of critical importance. Their most important function is to reduce the concentration of contaminants in the system sand. The origin of these contaminants may be alloy by-products or contamination from a core process. A second function is to maintain the total system volume.

All ingredients added to a system sand should be added gravimetrically. Volumetric or timed additions of dry additives are generally not consistent enough to ensure adequate control and only contribute to overall consistency problems. This applies to the addition of a new or reclaimed sand as well as to the return system sand for a batch system.

Most system sands contain additives other than clays; monitoring those additions is critical to the production of quality castings. Carbon additives are either single- or multiple-component. The relative concentration of the carbon additive must remain constant for a laboratory-derived measurement to be of any value. For example, casting finish produced in a system sand with a total combustible value of 3.50% derived from a carbon additive based totally on seacoal can differ drastically from a similar system sand with an equivalent total combustible value derived from a multiple-component carbon additive. In cases in which the benefits can be justified, the use of preblended sand additives is recommended.

Compactibility is the only physical characteristic of a system sand that a molding machine realizes, and it is of paramount importance that it be controlled within a tight band. The desired range will be specific to each foundry. The range chosen should allow optimum strength of the clay as well as adequate moisture levels to minimize sand friability while satisfying the requirements of the molding equipment. The secondary control parameters are as important as the primary, but must be looked at over a period of time. It is necessary to realize that problems develop gradually in a system sand. With this in mind, the use of trend line analysis technique as a tool to a better understanding of the effects of subtle changes in a system sand can be of significant benefit. The specific secondary tests that should be run on a system sand include green compressive strength, permeability, moisture, AFS clay, screen distribution, and AFS washed fineness tests (use the *AFS Mold and Core Test Handbook*). The mulling efficiency should be monitored and charted on an ongoing basis.

While testing a system sand is very important, of equal importance is knowledgeable and responsible review of the data and corrective actions when necessary. Routine review of all test results should include representation from all the various disciplines within the foundry.

Included in the control program for a green sand system should be routine monitoring of the dust collection system. Particular attention should be given to the screen distribution, methylene clay content test, and the total combustible level test. Deviations from normal operating levels indicate equipment malfunctions that require corrective action.

Screen distribution is important. For system sands comprised of only base sand (plus new-sand additions and core sand dilution), if the grain shape remains constant, changes in screen distribution will occur slowly, a major contributor being the condition of the dust collector system. On the other hand, in those systems that have an influx of various types of base sand from varying core processes and sand sources, changes in the base sand distribution will be more dramatic and will cause dimensional problems unless preventive measures are implemented. For these systems, screen distribution should be tested more frequently.

Influence of Molding Equipment. The type of molding equipment used is also critical in the selection of a green sand system. Green sand molding can be divided into three basic types:

- Low-density and low-pressure molding includes manually operated jolt-squeeze units. The green

compressive strengths of the sand for these units is generally in the low to mid teens (given in pounds per square inch)

- Medium-density units include automatic or semiautomatic units with rigid flasks that combine jolting action and hydraulic squeeze pressures
- High-pressure or high-density units produce molds with hardness values in the high 90s\*. These units incorporate flaskless molding technology and use hydraulic pressure and other energy sources for sand compaction

The third group, that is, the high-pressure or high-density molding methods, dominate the high-production and highly automated foundry today. This type of green sand molding lends itself to both flask and flaskless system designs. Some of the major criteria that dictate whether a system is designed as a flask or a flaskless unit is the amount of metal to be poured in each mold and the total mold area that is required. It is not within the scope of this article to deal with all the factors that influence the selection of a molding system. However, all of the systems in this category can be used for high-production repetitive work. Dimensional control of castings with these processes is quite good, and the economics of their operation have yet to be matched by any other. Unfortunately, these systems represent a significant capital investment.

As automation and production rates have increased, the capability for the precise placement of the sand on the pattern has diminished. Thus, a critical characteristic for today's high-production sands is the capability of uniformly covering the pattern surface before application of the compaction energy. Therefore, sand flowability and consistency are of utmost importance in the formulation of a system sand.

### *Sand Reclamation*

The economics of a foundry operation require sand reclamation to reduce the costs associated with new sand and the costs of landfill use, and to reduce the problems associated with the control of environmentally undesirable contaminants in the discarded sand.

In addition, tangible operational advantages result from sand reclamation. These begin with the ability to select the best sand for the casting process, knowing that most of it will be reclaimed during operation. In addition, the use of reclaimed sand reduces the number of variables that must be controlled, and provides operational consistency over a period of time. Sand grain shape and distribution and binder system bonding are more uniform, thus reducing sand defects. A properly designed sand reclamation system begins with green sand and converts it to a product very similar to new sand. Figure 5 shows the appearance of sand before casting, after molding, and after reclamation.

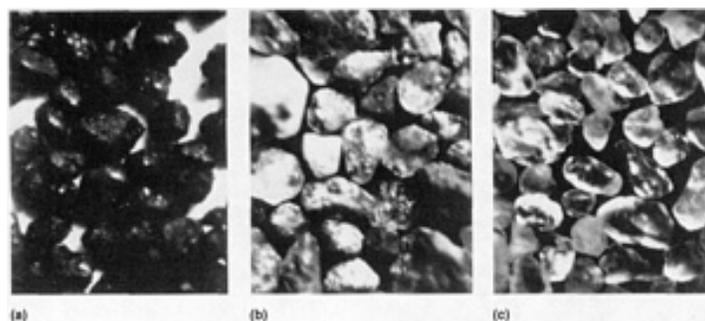


Fig. 5 Influence of sand reclamation on the appearance of green sand. (a) After molding (no reclamation). (b) After thermal reclamation. (c) New sand.

Sand reclamation begins with the removal of tramp and foreign materials, such as core rods, metal spills, slag, and paper, and the disintegration of lumps of sand. Then organic and inorganic binders are removed by attrition (scrubbing) and/or thermal methods. Dead clay is removed as fines. The sand is then brought up to specification by the addition of new sand, clay, and other sand additives.

Sand reclamation systems must be selected with regard to their cost, the specifications for the system sand, system capacity, compatibility with the sand system, metal being poured, and core mixes being used. It is important for the foundry to have a clear understanding of its needs in sand reclamation before calling in vendors. A variety of reclamation systems are described below. More detailed information can be found in the article "Sand Processing" in this Volume (see the section on "Sand Reclamation").

*Wet Washing/Scrubbing.* The cores of large castings can be removed by high-velocity jets of water. In the process, the cores are broken down into grains, and some binder is removed. Excess molding sand can be added and washed simultaneously. If the shakeout system is dry, the sand is charged into an agitator system where the solid content is held between 25 and 35%. Excess molding sand may be blended with the core knockout material. A similar system uses intensive scrubbing with a solids content of 75 to 80% and units in series. This latter method is superior because of closer and more frequent grain-to-grain contact. After washing, the sand is classified and may be used either wet (naturally drained to 4 to 5% moisture) and added to a system sand, dried for cores, or used for facing sand. Facing sand mixes derive their name from the fact that they are used in limited quantities against the face of the pattern or core box. They have properties usually different from those of the backup or system sand and contain additives not otherwise present. Facing sands are designed to perform special functions, such as providing higher green strength for lifting deep pockets, higher deformation for limited draft patterns, and special carbons that enhance skin drying.

The wet system has limitations in that only a portion of the binder, clay, and carbon is removed. The product, however, is excellent for use as a makeup sand in systems.

*Dry Scrubbing/Attrition.* This method is widely used, and there is a large variety of equipment available in price ranges and capacities adaptable to most binder systems and foundry capacities. Dry scrubbing may be divided into pneumatic, mechanical, and combined thermal-calcining/thermal-dry scrubbing systems.

*In pneumatic scrubbing,* grains of sand are agitated in streams of air normally confined in vertical steel tubes called cells. The grains of sand are propelled upward and rub and impact each other, thus removing the binder. In some systems, grains are impacted against a steel target. Banks of tubes may be used depending on capacity and degree of cleanliness desired. Retention time can be regulated, and fines are removed through dust collectors.

*In mechanical scrubbing,* the equipment available offers foundrymen a number of techniques for consideration. An impeller may be used to accelerate the sand grains at a controlled velocity in a horizontal or vertical plane against a metal plate. The sand grains impact each other and metal targets, thereby removing the binder. The speed of rotation has some control on impact energy. The binder and fines are removed by exhaust systems, and screen analysis is controlled by air gates and/or air wash separators. Additional equipment options include:

- A variety of drum types with internal baffles, impactors, and disintegrators to reduce lumps to grains and to remove binder
- Vibrating screens with a series of decks for reducing lumps to grains, with recirculating features and removal of dust and fines
- Shot-blast cleaning equipment that may be incorporated with other specially designed units to form a complete casting cleaning/sand reclamation unit
- Vibro-energy systems that use synchronous and diametric vibration. Separation of the binder from the sand grains is caused by frictional and compressive forces. One special, advantageous feature of these systems is the small number of moving parts

*Thermal-Calcining/Thermal-Dry Scrubbing Combinations.* These systems offer the best reclamation for the organic and clay-bonded systems. Grain surfaces are not smooth; they have numerous crevices and indentations. The application of heat with sufficient oxygen oxidizes the binders or burns them off. In attrition, only because there is no contact in the crevices, the binder remains. Heat offers the simplest method of reducing the encrusted grains of molding sand to pure grains. Both horizontal and vertical rotary kiln and fluidized bed systems are available.

In the horizontal rotary kiln, material is fed into one end (usually the cold one) and moved progressively through the heat zone by rotation assisted by baffles, flights, or other mechanical means. Some mechanical scrubbing also occurs. Some systems incorporate heat exchanger technology to considerably reduce the energy required. The latest technology also

includes provision for recovery of metal entrained in the sand and collection and detoxification of the process wastes for suitable nonhazardous waste disposal.

Several fluidized bed system designs are available. Some use preheating chambers and hot air recuperation. A drying compartment may also be added. Sand is introduced into the top (preheating) chamber of the reactor and is lifted by the hot air stream from below until it assumes some of the characteristics of a fluid. The hot air coming in contact with the sand grains burns the organics and calcines the clay. At the same time, some attrition takes place. A correct pressure differential must be maintained between the compartments if more than one is used in order to ensure downward flow of sand; otherwise gravity flow must be provided. Fluidizing is a very good method for cooling sand when using cool air.

**Multiple-Hearth Furnace/Vertical Shaft Furnace.** The multiple-hearth furnace consists of circular refractory hearths placed one above the other and enclosed in a refractory-lined steel shell. A vertical rotating shaft through the center of the furnace is equipped with air-cooled alloy arms containing rabble blades (plows) that stir the sand and move it in a spiral path across each hearth. Alternate hearths are "in" or "out." That is, sand is repeatedly moved outward from the center of a given hearth to the periphery, where it drops through holes to the next hearth. This action gives excellent contact between sand grains and the heated gases. Material is fed into the top of the furnace. It makes its way to the bottom in a zigzag fashion, while the hot gases rise countercurrently, burning the organic material and calcining clay, if one or both are present. Discharge can be directly from the bottom hearth into a tube cooler, or other cooling methods may be used. The units are best suited to large tonnages, that is, five tons or more. They are extremely rugged and relatively maintenance free.

Combinations of systems may also be used, for example, thermal methods followed by dry attrition scrub to remove calcined clay from molding sand or undesirable chemicals and oxides from core processes. Also, commercial centers for sand reclamation are in operation and may be used by smaller foundries.

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#### Note cited in this section

- \* Hardness in this situation refers to green surface hardness as measured by the C scale hardness tester described in the *AFS Mold and Core Test Handbook*. It should be noted that this scale is not related to the Rockwell C scale hardness indication.

## Dry Sand Molding

The essential difference between dry sand and green sand molding is that the moisture in the mold sand is removed prior to pouring the metal. Dry sand molding is more applicable to medium and large castings than to small castings. The molds are stronger and more rigid than green sand molds. They can therefore withstand more handling and resist the static pressure of molten metal, which may cause green sand molds to deform or swell. In addition, they may be exposed to the atmosphere for long periods of time without detrimental effect. Such exposure may be necessary for placing and fitting a large number of cores.

Seacoal is the most common carbon material used in green sand; pitch is the most common in dry sand. Other materials in dry sand are gilsonite, cereal (corn flour), molasses, dextrine, glutrin, and resin. These additives thermoset at the baking/drying temperature (150 to 315 °C, or 300 to 600 °F) to produce high dry strength and rigid mold walls. The base sand is normally coarser than in green sand to facilitate natural venting and mold drying.

**Dry Sand Molding Methods.** As described below, dry sand molds are made by a variety of methods.

*Large sand compaction machines* of the jolt, roll-over, and draw-type or jolt-only-type compact the sand in conjunction with tucking, hand peening, and air ramming.

*Sand Slingers.* These machines throw and compact the sand by means of centrifugal force. A variety of sizes are available. Some supplemental hand ramming may be required.

*Floor Molding.* This molding method uses larger flasks normally requiring the services of an overhead crane. The molds are made by a combination of mechanical equipment (slinger), hand peening, and pneumatic hand-operated

rammers. Sand must be placed in the flasks in layers, and care must be taken by the molder to make certain that each layer knits and adheres to the other and is of uniform hardness.

*Pit Molding.* This method is used for very large castings when flasks are impractical. Pits are normally constructed of concrete walls and sometimes floors to withstand great pressures during pouring. Because the drag part of a pit cannot be rolled over, the sand under the pattern must be rammed or bedded in, or the bottom must be constructed with dry sand cores. A bed of coke, cinders, or other means of venting the pit bottom must be provided. Once the pattern is in place, mold-making procedures are the same as those for floor molding.

**Curing Sand Mixtures.** The sand mixture for dry sand molds can be cured (hardened) by baking in an oven or using forced hot air or stoves placed in the mold.

**Mold Coating.** Dry sand molds are coated with refractory washes. Water and/or solvent carriers using graphite, silica, or zircon are the most frequently used. It is common to apply several coats. An example of a dry sand mold being coated is shown in Fig. 6.



Fig. 6 Dry sand pit mold for stationary diesel engine.

Equipment used for dry sand molding must be strong and rigid. Flasks are equipped with crossbars that normally extend to within several inches of the pattern. The molding sand is reinforced with hooks and gagers (L-shaped steel bars) that are usually coated with a clay slurry to enhance bonding to the sand. Cores may be suspended in the cope by means of threaded rods and bolts. Venting of the molds and cores is important. Drilling holes in the side walls of flasks facilitates venting. Large flasks and pit molds must be tightly secured with heavy clamps and weights to prevent run-out, which could be extremely dangerous and cause casting loss as well.

**Cooling of Castings.** Large castings should be cooled slowly in order to prevent internal stresses and/or cracking of the casting. It is sometimes possible to have the molds or cores so rigid that castings will hot tear. The use of inert filler materials placed a safe distance from the casting surface and/or the hollowing out of heavy mold sections will help to prevent such problems.

### Skin-Dried Molds

Almost all dry sand molding has been replaced by the no-bake molding (see the article "Resin Binder Processes" in this Volume). Sometimes the pattern may be faced with a no-bake sand mixture and then backed up with a green/dry sand mixture. An intermediate (between green sand and dry sand) type of molding referred to as skin drying is sometimes used. The process is similar to dry sand molding in that the same type of sand mixtures and equipment are used. After coating the surface with a refractory wash, the molds are dried to a depth of 6 to 12 mm (0.25 to 0.5 in.). Skin-dried molds have some characteristics of green sand molds and some of dry sand molds such as ease of shakeout and firm mold face, respectively.

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## Sand Molding

### Loam Molding

Loam molding is one of the oldest methods known. It requires the skill of an experienced craftsman, and is seldom used today because of the lack of these craftsmen and the advent of the no-bake systems that have a number of advantages over loam molding, especially greatly reduced production time. Loam molding is particularly adapted to medium or large castings, usually those of circular shape.

The equipment required is relatively simple. No pattern is used; however, a flask or pit may be necessary to support the finished mold. Replacing the pattern is one or more sweeps conforming to the shape of the mold/core. The sweep is attached to an upright, rotating spindle. A bed plate, a cover plate, and arbors for cores are also necessary items.

Materials for making the molds consist of:

- Soft bricks capable of absorbing water

- Molding sand that is quite coarse (sometimes referred to as gravel) and containing a high percentage of clay
- Sawdust, straw, hay, hair, or cloth clippings may be used. These materials contribute to mold strength and burn during casting, thus enhancing collapsibility (disintegration of mold/core)

The molding sand is mixed with water to which molasses may be added until a thick loam slurry resembling concrete is obtained. This mixture is used along with the bricks to build up the general shape, using the same technique that a mason would use. Once the general shape is attained, the bricks are covered with a layer of loam, and the sweep is used to form the outside surface. A layer of loam from 6 to 25 mm (0.25 to 1 in.) thick remains. The mold/core is then baked until thoroughly dry, after which a refractory coating is applied. During the drying process, numerous small cracks form on the surface of the low moisture content clay. These small cracks produce a surface that is very receptive to the refractory coating, which may be brushed, swabbed, sprayed, or actually troweled on. After application, the coating is brushed with molasses and water. A camel hair brush may be used to impart an exceptionally smooth surface. The coating must be dried prior to assembly. Loam molds impart a superior peel to castings.

Before the advent of spun cast pipe in metal molds, large-diameter pipe was made in pits (pit cast pipe). The cores for these molds were made from loam. Hay rope was wrapped around a metal mandrel and the loam slurry was applied, smoothed, and dried, after which a refractory coating was applied.

A typical screen analysis of a loam molding sand is given in Table 1. A casting made from a loam molded cope is shown in Fig. 7.

**Table 1 Typical screen analysis of a loam molding sand**

Screen No.	Percent retained
6	4.5
12	12.5
20	25.3
30	15.0
40	10.4
50	7.7
70	3.0
100	2.4
140	1.4
200	0.7

270	<b>0.6</b>
Pan (-270)	<b>1.2</b>
<b>AFS clay</b>	<b>15.3</b>

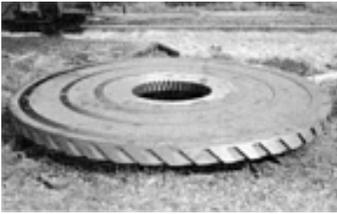


Fig. 7 Casting produced by loam molding.

## Silicate and Phosphate Bonded Molds

Sodium Silicate/CO<sub>2</sub> System. Typical silicate binders are odorless, nonflammable, suitable for all types of work (high production to large molds), and applicable to all types of aggregates. They produce no noxious gases on mixing/molding/coring and only a minimum of volatile emissions at pouring/cooling/shakeout.

The amount of silicate binder used for cores and molds varies from 3 to 6%, depending on the type of sand, grain fineness, and degree of sand contaminants. The type of metal poured and its temperature, and the amount of erosion resistance the core or mold will have to withstand are additional factors. A clean, rounded sand grain of 55 fineness requires approximately 2.5 to 3% of binder. As the sand fineness increases, the amount of binder that must be used to coat each grain increases. Thus, a sand of 120 to 140 fineness requires from 1.5 to 3.0% more binder than a sand of 55 fineness.

Either continuous-type or batch-type mixers can be used with sodium silicates. Overmixing should be avoided. Mixtures normally have a good bench life, which becomes shorter when higher-ratio silicates are used. Hoppers of mixed sand should be covered with plastic sheets or damp sacking to prevent premature hardening (crusting).

The initial tensile strength of cores gassed for 5 s with CO<sub>2</sub> varies from 255 to 310 kPa (37 to 45 psi), depending on the binder used. When the core stands, strength increases to a maximum of about 670 to 1380 kPa (100 to 200 psi) in 24 h. This increase is due to some dehydration of unreacted silicates and continued gelling of the silicate. Under normal conditions, cores and molds do not deteriorate and can be stored. An exception may occur during periods of high humidity when sand mixtures are unable to achieve maximum strength by dehydration during storage after gassing. Strength deterioration in high humidity conditions is even more prevalent when the binder formulation or the sand mixture contains organic additives such as sugars, starches, or carbohydrates. Under these conditions, a short heating cycle is necessary to obtain the desired strength. When a core is hardened by carefully controlled gassing, and further hardened by dehydration and polymerization during the subsequent 24 h, good strengths are maintained over a long storage period.

Washes may be necessary on cores and molds made by the silicate/CO<sub>2</sub> process to prevent burned-on sand and metal penetration. Alcohol-base and solvent-type washes are normally used; isopropyl alcohol is preferred to methyl alcohol because it is less toxic and has a higher boiling point. Specially prepared graphite and zircon refractory pastes, which may be diluted with alcohol or solvent in the foundry, are commercially available. Washes on cores and molds promote peel, aid collapsibility, improve casting surface finish, and aid in resisting moisture absorption during periods of high humidity. Water-base washes can be used if care is taken to dry the core thoroughly immediately after coating. This procedure must be carried out with care due to the softening effect of the water on the silicate bond.

Additives may be used in sodium silicate bonded sand mixtures to improve shakeout or collapsibility. Sugars are commonly used for this purpose; they can be compounded with the silicate binder or added separately to a sand mixture.

Small cores and molds are successfully made with core blowers or shooters combined with gassing stations operating on predetermined cycles and automatically controlled. For these applications, CO<sub>2</sub> gas is injected through a hollow pattern or double-wall corebox, or by means of a mandrel in a core, or through a hood covering the box.

Larger cores can be cured by means of lance pipes of about 5 mm ( $\frac{3}{16}$  in.) in diameter that are open at the lower end. Using a rod, holes are made about 150 mm (6 in.) apart; the lance is inserted into each hole successively, and the gas is

applied for 10 to 15 s at about 170 kPa (25 psig). The gas permeates and cures an area of sand having about a 75 mm (3 in.) radius around the hole. Large cores and molds may be gassed using specially designed, gasketed covers or hoods that fit over the flask or box. It is important to place vents properly to ensure the flow of gas through all parts of the mass.

Coreboxes and patterns may be made of wood, metal, or plastic and should be washed regularly to prevent sticking problems caused by a buildup of sodium silicate.

The silicate-bonded sand, after pouring and shakeout, may be reclaimed by mechanical means; up to 60% of the reclaimed sand can be reused. Wet reclamation of the silicate sand system is possible, but requires a significant amount of water to scrub the sand. Recently, new methods of attrition reclamation combined with low-temperature thermal methods have shown some promise (see the discussion on sand reclamation in this article).

**Phosphate-Bonded Molds.** This inorganic binder system, which consists of an acidic, water-soluble, liquid phosphate binder and a powdered metal oxide hardener, was designed to comply with air quality control regulations. Because its components are inorganic, fumes, smoke, and odor are reduced at pouring and shakeout. The phosphate no-bake binder system has shakeout properties superior to those of the silicate/ ester catalyzed no-bake systems described in the article "Resin Binder Processes" in this Volume. The bonded sand can be reclaimed easily by either shot blast or dry-attrition reclamation units.

The hardener component is an odorless, free-flowing powder. It must be kept dry; in contact with water, it slowly undergoes a mildly alkaline hydration reaction that alters its chemical reactivity and physical state. Under normal ambient conditions, the material is not hygroscopic. Flow properties of the powdered hardener are good. Standard powder feeding equipment can be used to disperse the hardener into sand mixers.

Curing characteristics of the phosphate no-bake binder system depend on the ratio of hardener to binder. Varying the level of hardener can typically control strip times from 25 min to more than 1 h. Recommended phosphoric acid-base binder levels are from 2.5 to 3.0% for molds and 3.5 to 4.0% for core production. The hardener level should be kept within 18 to 33% of the binder weight for best results.

Sand type also affects cure speed. Strongly alkaline sands such as olivine tend to accelerate the cure rate. Zircon forms an extremely strong and stable bond with phosphate binders, and as a result shakeout is more difficult.

High-quality defect-free castings can be produced using the phosphate binder system for molds and cores with a variety of metals, including gray and ductile irons and various steels. Erosion resistance of both washed and unwashed molds is excellent. Veining resistance is good on unwashed surfaces and can be controlled with the proper coating selection.

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### *Unbonded Sand Molds*

Murray Patz, Lost Foam Technologies, Inc.; Thomas S. Piwonka, University of Alabama

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Casting processes that use unbonded sand molds are viable alternatives to conventional green sand molding processes. This section will review lost foam casting and vacuum molding both of which offer considerable advantages. A brief description is also provided for the magnetic molding process, which borrows from lost foam technology. Additional information on these processes can be found in Ref 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12.

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## Lost Foam Casting \*\*

The lost foam casting process originated in 1958 when H. F. Shroyer was granted a patent for the cavity-less casting method using a polystyrene foam pattern imbedded in traditional green sand, which was not removed before pouring of the metal (patent 2,830,343). The polystyrene foam pattern left in the sand mold is decomposed by the molten metal. The metal replaces the foam pattern, exactly duplicating all of the features of the pattern. Early use of the process was limited to one of a kind rough castings because the foam material used was coarse and hand fabricated and because the packed green sand mold would not allow the gases from the decomposing foam pattern to escape rapidly from the mold (the trapped gases usually resulted in porous castings).

The most significant breakthrough in the lost foam process came in 1964 with the issuance of a patent to T.R. Smith for the utilization of loose, unbonded sand as a casting media (patent 3,157,924). With this development, it was becoming clear to the foundry industry that the lost foam casting process was an emerging technology deserving of attention.

In the 1960s and 1970s, most of the lost foam casting activity took place in automotive company research facilities. Very few production castings were produced during this time. However, use of the lost foam casting process has been increasing rapidly since the expiration of the Smith patent in 1981. Currently, many casting facilities are dedicated strictly to the lost foam process.

### *Process Technique*

Because the casting is an exact representation of the polystyrene foam pattern, the first critical step in the lost foam process is to produce a high-quality foam pattern. As will be described below, surface quality, fusion, dimensional stability, and foam pattern density are key control areas.

The foam pattern is prepared for casting by attaching it to a gating system (sometimes molded as part of the pattern) of material of the same type and density. The pattern system with gating is then coated inside and out with a permeable refractory coating. Once the coating is dry, the pattern system is ready for investment into a onepiece sand flask. Investment of the pattern is achieved by positioning the pattern system in the flask, which has a 25 to 75 mm (1 to 3 in.) bed of sand in the bottom of the flask.

Once the pattern system is properly positioned, loose, unbonded sand is introduced in and around it (Fig. 8). The flask is vibrated to allow the loose sand to flow and compact in and around all areas of the pattern. A pouring basin or sprue cup is usually positioned around the exposed foam downsprue. When compaction (sand densification) is complete, the flask is moved into the pouring area, and molten metal is poured into the pouring basin (sprue cup). The metal vaporizes the foam pattern, precisely duplicating all the intricacies of the pattern (Fig. 9). The casting is then allowed to cool for approximately the same amount of time as with green sand. The flask is usually tipped over, allowing the loose sand to fall away from the casting (Fig. 10a). This sand is collected for reuse and the casting is ready for degating and cleaning (Fig. 10b).

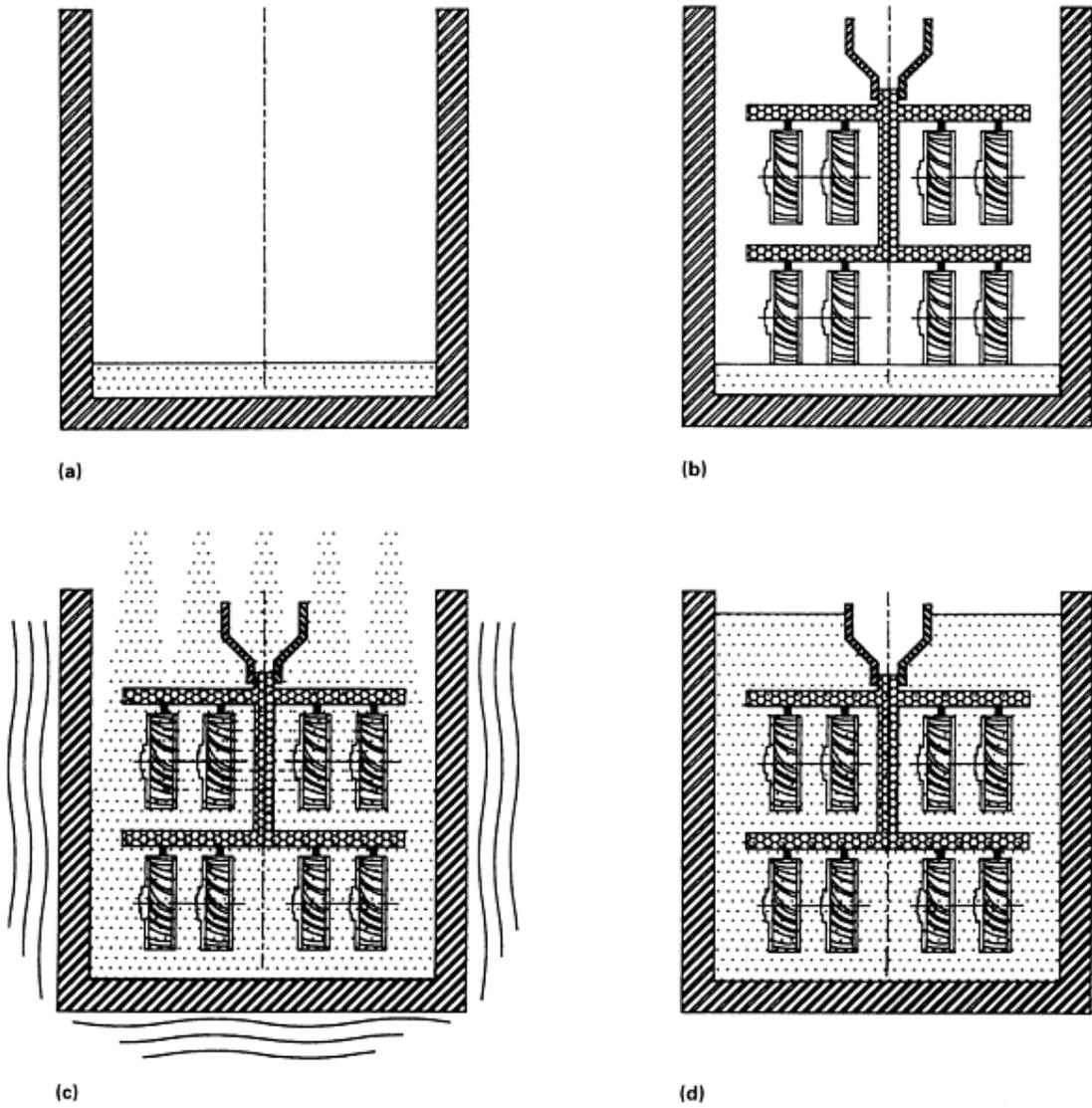


Fig. 8 Lost foam pattern system. (a) Flask that contains a 25 to 75 mm (1 to 3 in.) sand base. (b) Positioning the pattern. (c) Flask being filled with sand, which is subsequently vibratory compacted. (d) Final compact ready for pouring.

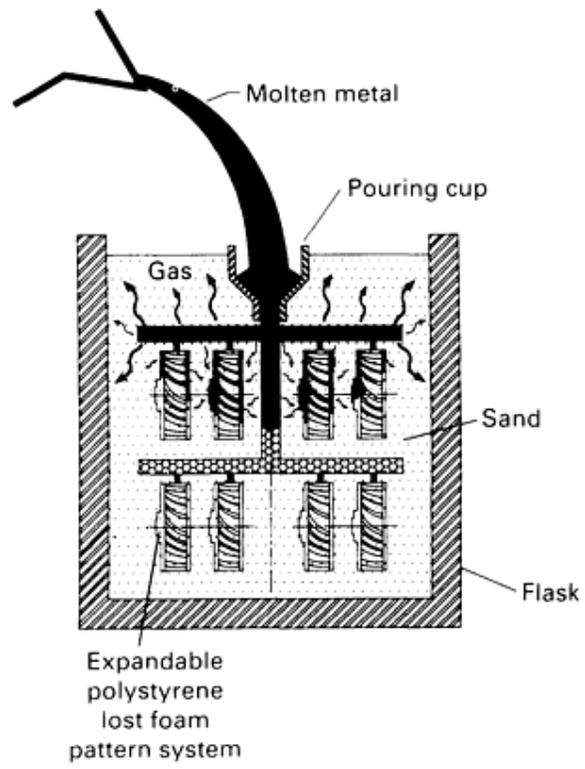


Fig. 9 Pouring of a lost foam casting.

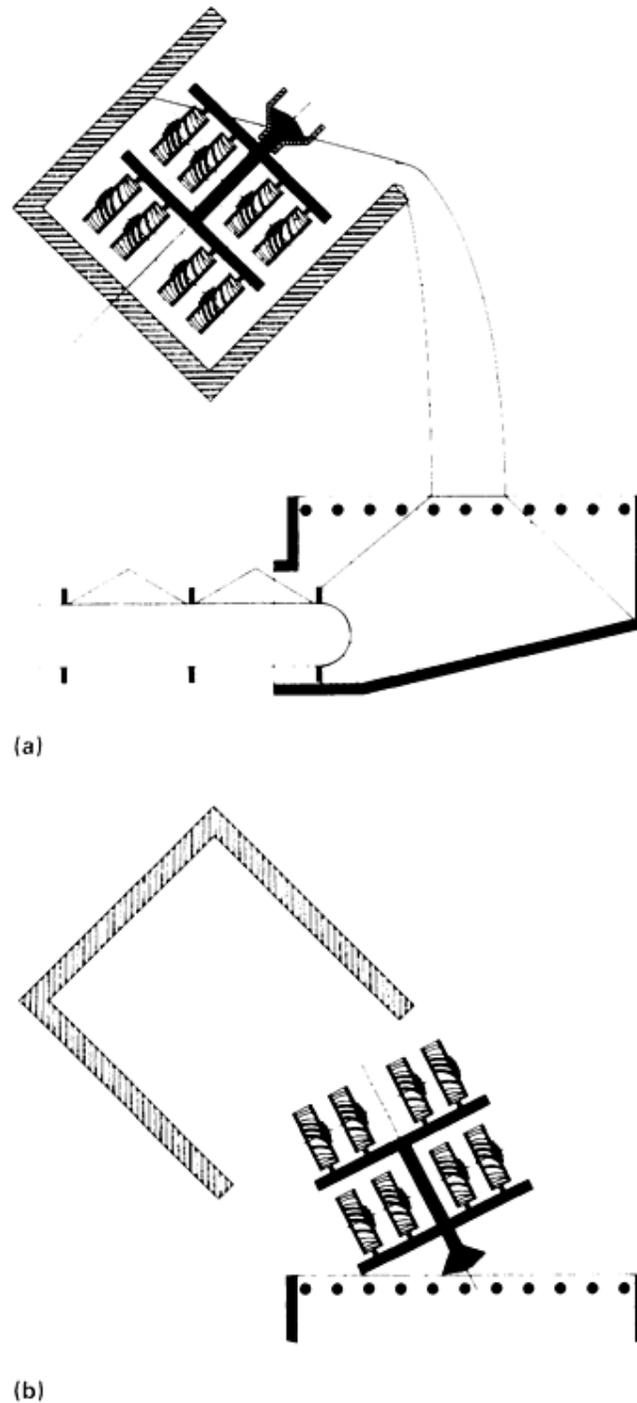


Fig. 10 Processing of completed (cooled) casting. (a) Flask is tipped, and the sand is recycled. (b) Casting is ready for degating and cleaning.

### *Processing Parameters*

The Foam Pattern. Expandable polystyrene (EPS) has been, and will probably continue to be, the preferred material for manufacturing lost foam patterns. There are other foam materials under development that show some promise, but to date their use is quite limited. There are several grades of EPS, as indicated in Table 2. Grades T and X are preferred because they give the foam pattern molder the ability to produce the smoothest surfaces and the thinnest sections possible for lost foam patterns.

**Table 2 Grades of expandable polystyrene**

Bead grades	Raw bead diameter		Diameter at 24 kg/m <sup>3</sup> (1.5 lb/ft <sup>3</sup> )		Typical use
	mm	in.	mm	in.	
A	0.83-2.0	0.033-0.078	2.5-5.9	0.097-0.231	<b>Insulation</b>
B	0.58-1.2	0.023-0.047	1.7-3.5	0.068-0.138	<b>Packaging</b>
C	0.33-0.71	0.013-0.028	1.0-2.1	0.040-0.082	<b>Cups (coffee)</b>
T	0.25-0.51	0.010-0.020	0.74-1.5	0.029-0.058	<b>Cups/lost foam</b>

Expandable polystyrene weighs approximately 640 kg/m<sup>3</sup> (40 lb/ft<sup>3</sup>) in its raw state. For the EPS to be useful in the manufacture of lost foam patterns, its bulk density must be reduced to a level between 16 and 27 kg/m<sup>3</sup> (1.0 and 1.7 lb/ft<sup>3</sup>), as indicated in Table 3. This is achieved through a process known as preexpansion. The raw EPS is introduced into a heated chamber and kept in constant motion for even distribution of heat throughout the batch of material. The plastic beads soften, and the gas within the beads expands; this increases the diameter of each individual bead and thus reduces the bulk density (a good analogy is popping corn).

**Table 3 Typical pattern density requirements for lost foam casting**

Metal	Metal pouring temperatures		EPS pattern density	
	°C	°F	kg/m <sup>3</sup>	lb/ft <sup>3</sup>
Aluminum	705-790	1300-1450	24-27	<b>1.5-1.7</b>
Brass/bronze	1040-1260	1900-2300	20-21.6	<b>1.25-1.35</b>
Gray iron	1370-1455	2500-2650	≤ 20	≤ <b>1.25</b>

The volume ratio at a finished density of 16 kg/m<sup>3</sup> (1.0 lb/ft<sup>3</sup>) is approximately 40:1. After a period of time in the preexpander, the material is discharged and weighed to check density. The density of the foam pattern for a given cast product is critical. For consistent casting results, EPS density must be controlled within ±2% of target density. This is achieved by monitoring and adjusting time and temperature in the preexpander.

Once the preexpanded EPS is discharged from the preexpander, it is placed in intermediate storage to cool and stabilize. After the stabilizing process is complete (usually 6 to 12 h, depending on the type of bead used), the preexpanded EPS is conveyed to a hopper attached to a pattern-molding press. This sequence is illustrated schematically in Fig. 11.

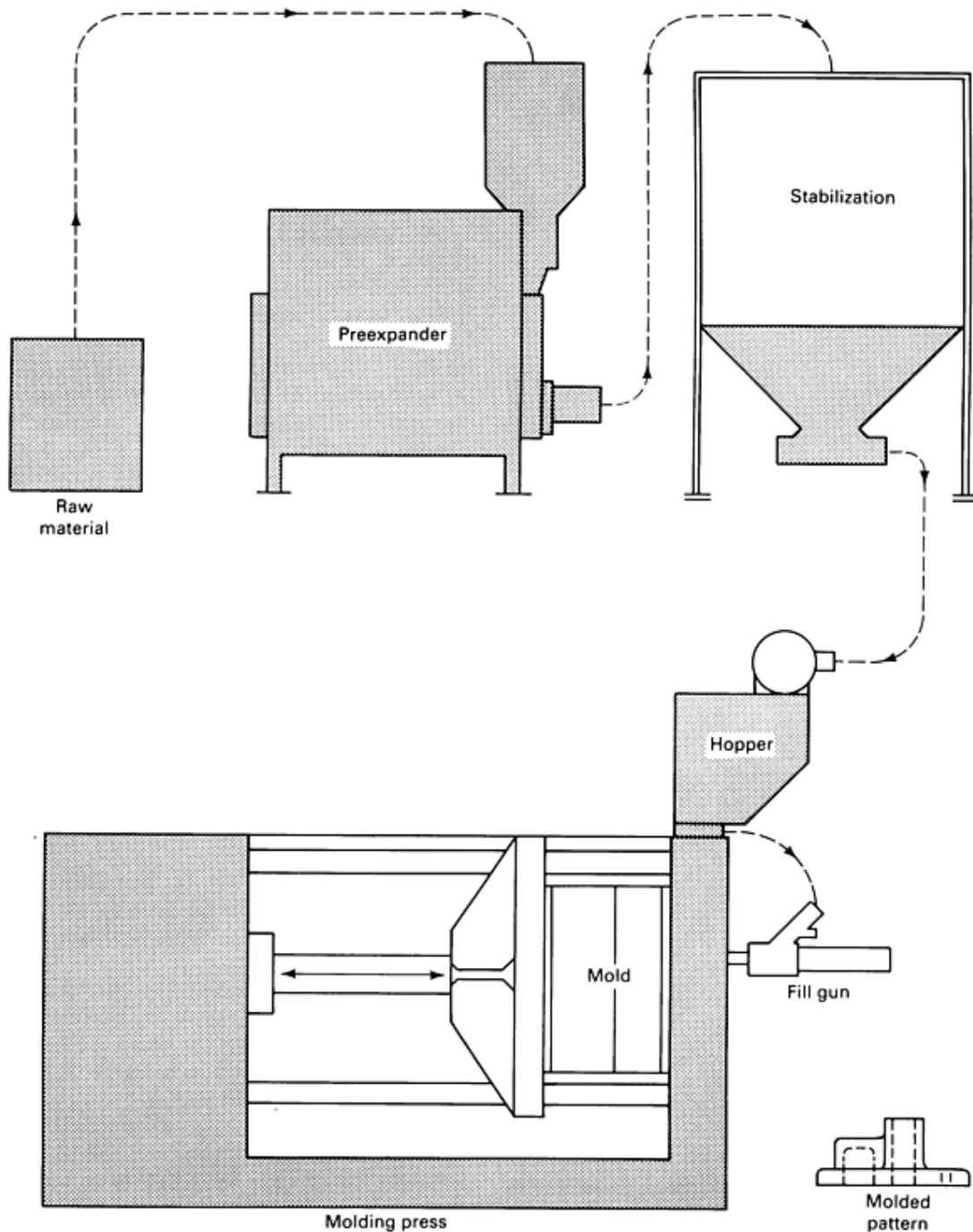


Fig. 11 Sequence of operations for producing a foam pattern.

Pattern molding for the lost foam process can be grouped into four major functions: filling, fusion, cooling, (stabilization), and ejection.

*Filling.* The preexpanded stabilized material at the desired density is fed from the hopper on the press to the mold (or pattern die). A vented fill gun is used to feed the material, as illustrated in Fig. 12.

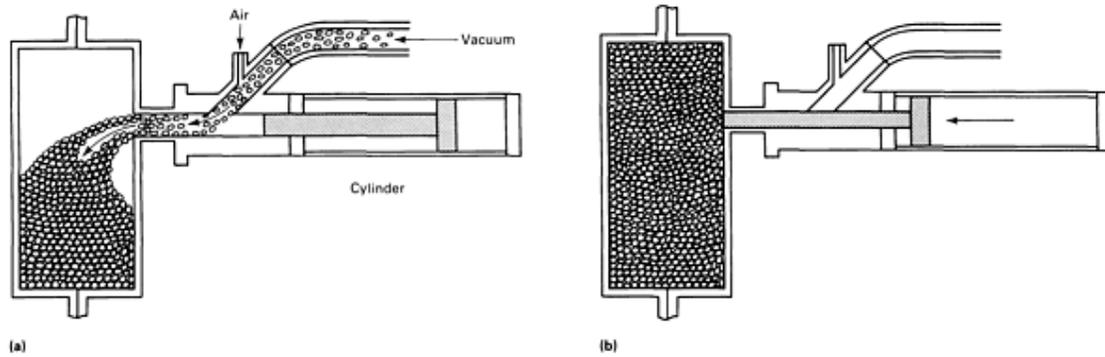


Fig. 12 Fill gun used to feed preexpanded stabilized material to molding press. (a) Open cylinder with pattern material transported by air/vacuum. (b) Cylinder closed prior to fusion.

*Fusion.* After the mold cavity is full, heat is added by passing steam through the material in the cavity; this reinitiates the expansion process and softens the material as in the preexpansion process (Fig. 13a). The material expands again, filling the air voids between the individual EPS beads and fusing the beads together into a solid mass to form the desired foam pattern.

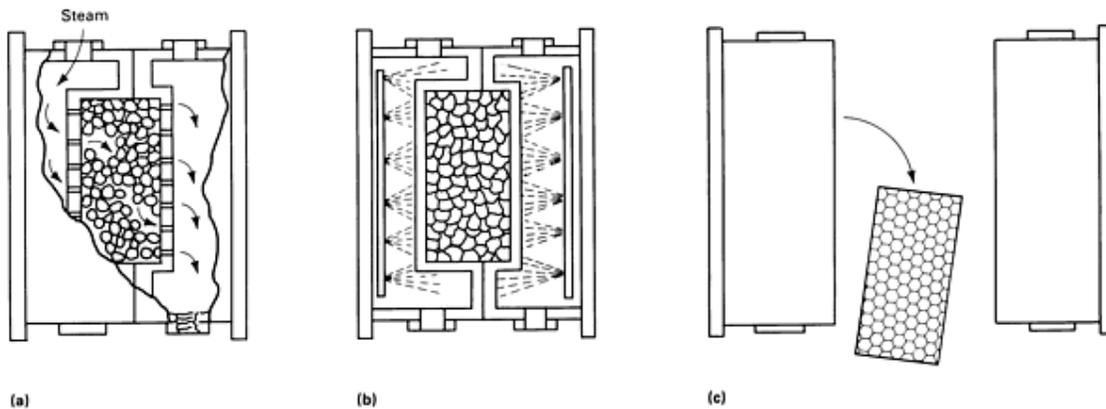


Fig. 13 Schematic showing fusion (a), cooling (b), and ejection (c) of lost foam pattern material.

*Cooling.* During the fusion portion of a molding cycle, the molded part exerts pressure against the cavity walls. If the part has not been cooled to reduce the internal pressure of the molded part, the part will continue to expand after ejection. This condition is known as postexpansion. To eliminate postexpansion, it is necessary to cool the mold cavity, thus reducing the internal pressure of the molded part to a point at which it can be ejected and still maintain its dimensional integrity. Cooling is usually accomplished by spraying water on the back of the mold wall cavity (Fig. 13b).

*Ejection.* Once the part has been cooled, the press can be opened and the part ejected (Fig. 13c). This can be done pneumatically or mechanically.

*Pattern Assembly.* Lost foam patterns typically consist of multiple pieces that must be assembled to form a completed pattern and gating system. The most widely accepted method of assembling patterns is to glue them together with a hot melt adhesive. The adhesive used is specifically formulated for the lost foam process. The temperature at which it is applied to the foam patterns is much lower than the application temperatures of other commercial hot melt adhesives. Lost foam hot melts are generally applied between 120 and 130 °C (245 and 270 °F). To ensure consistent dimensional control and adhesive joint quality, an automatic or semiautomatic gluing procedure is preferred. Figure 14 illustrates a typical pattern assembly sequence.

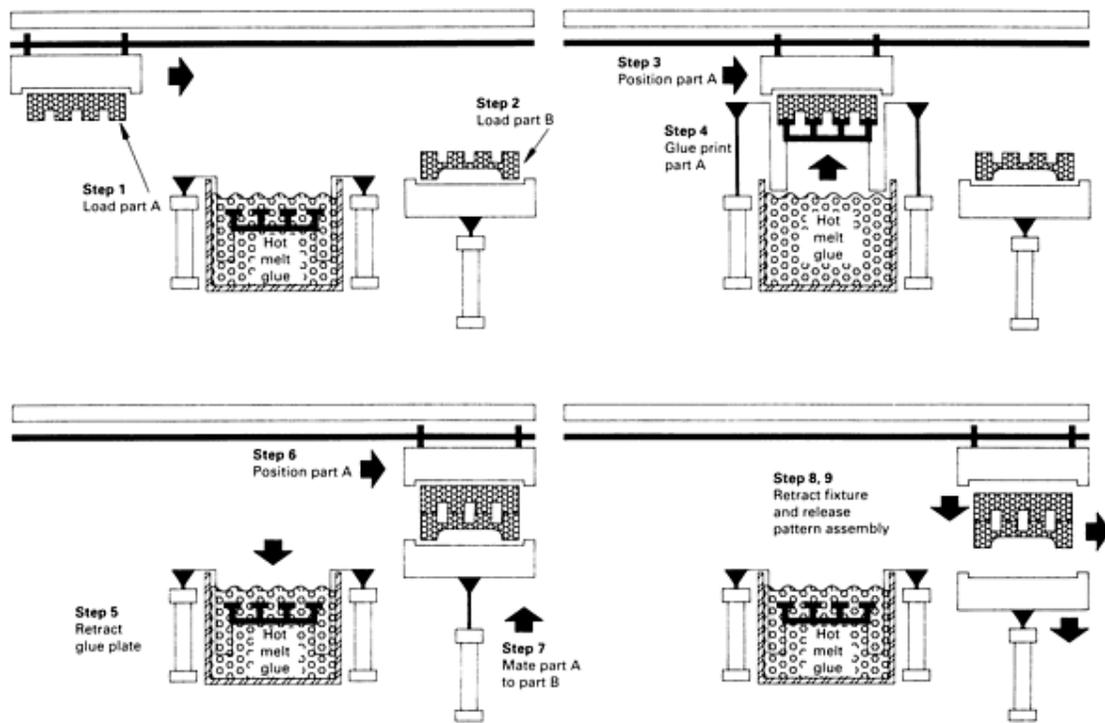


Fig. 14 Pattern assembly sequence showing nine steps performed in the pattern assembly machine.

For prototypes and short run quantities, hand-operated glue printing and assembly jigs can be used. Other methods of pattern assembly can be used in specific applications. These may include hand-applied rubber cement, liquid and contact adhesives, robotically applied airset adhesives, and foamed hot melt procedures. Whichever adhesive material is chosen, it must be suitable for use with lost foam patterns and must be compatible with the molten metal during the casting operation.

The vaporization rate and ash content of the adhesive must be approximately the same as those of the EPS pattern. The adhesive must not adversely affect the dimensional integrity of the pattern. Care must be taken to control all aspects of pattern assembly to maintain consistency. Poor assembly techniques will result in increased casting scrap and dimensional control problems. Thorough inspection of the completed foam pattern system is essential before proceeding to the next step in the process.

Coating Types. It is possible to produce a lost foam casting without using a refractory coating on the foam pattern, but for maximum process latitude, it is advantageous to coat the pattern system. This specialized coating serves two purposes. First, it provides a barrier between the smooth surface of the pattern and the coarse surface of the sand. Second, it provides controlled permeability, which allows the gaseous products created by the vaporizing foam pattern to escape through the coating and into the sand away from the cast metal (Fig. 15).

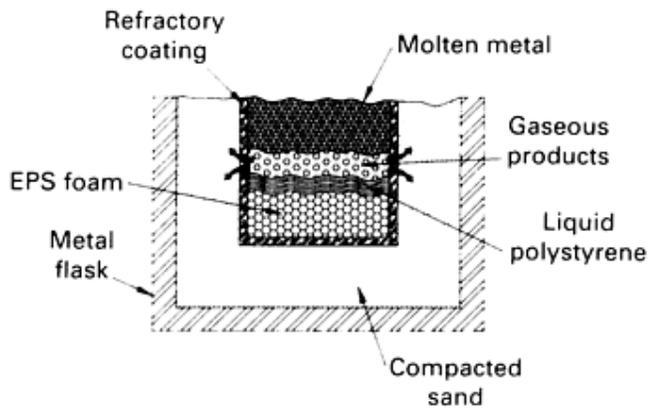


Fig. 15 Reactions taking place during a lost foam pouring operation.

Lost foam coatings are available in various permeabilities. Lower-permeability coatings are preferred in aluminum castings with high surface-area-to-volume ratios--for example, intake manifolds. Heavy-section aluminum castings and other nonferrous castings may require medium- or high-permeability coatings. Ferrous castings generally require higher permeability than nonferrous castings. Silica is the refractory of choice. Its combination of low cost and excellent heat transfer characteristics makes it attractive for use with most metals.

Zircon and olivine coatings are also available, but are not widely used. The choice of coating carrier is limited because the carrier must be compatible with the foam pattern. Hydrocarbons and chlorinated solvents will attack the EPS. Water is the most widely used carrier.

consistent production of high-quality lost foam castings. The coating, when mixed properly, can be applied to the pattern system by dipping, brushing, spraying, or flow coating.

Application of the Coating. Proper preparation and control of the coating is absolutely essential for the

Brushing, spraying, and flow coating are used on very large patterns. Dipping is the preferred method for small- and medium-size patterns. Because of the extreme difference in density between the foam pattern system and the coating slurry, large patterns are sometimes difficult to immerse.

Pattern orientation and coating fluidity must facilitate pattern coverage in blind areas. The entire pattern system must be covered inside and out with the exception of the exposed downsprue area, on which molten metal will be poured.

Foam pattern cluster systems must be handled carefully during coating and drying. The weight of the wet coating may cause the patterns to distort or break. Medium- and high-production lost foam facilities find automated coating systems very helpful in controlling the consistency of the coating.

The next step is to dry the coated pattern. This can be done at ambient conditions within 24 h, or the pattern can be force dried in a drying oven or heated room. Forced drying is done at oven temperatures of 50 to 65 °C (120 to 150 °F), along with numerous changes of air per hour and possibly dehumidification. This method of drying coated foam patterns usually takes 2 to 6 h. Microwave drying in the final stage can be used in very high production applications.

Investing the Foam Pattern in Sand. As indicated in Table 2, the coated pattern system is placed in a one-piece flask. Loose, dry, unbonded sand is introduced into the flask generally through a sand raining system. This system gently fills the flask with sand, minimizing the possibility of pattern distortion due to side movement of the sand against the pattern. During the filling of the flask, the flask is isolated from the flask conveying system and vibrated with a high-frequency compaction system either from the bottom or the side of the flask. Variable frequency and amplitude may be required to compact the sand fully in both the internal and external areas of the foam pattern system.

Sand System. The sand most commonly used is silica sand--subangular to round. Different sizes are used for different applications. Generally, AFS grain fineness number 35-3 screen distribution is used in ferrous applications, while AFS 45-3 screen distribution is used in most nonferrous systems (methods for determining sand grain fineness number are discussed in the article "Aggregate Molding Materials" in this Volume). Most sand systems, in addition to the compaction and sand fill stations, incorporate a pouring area, cooling area, dump-out area, sand return system, and sand cooler classifier system. To maintain consistent sand permeability, it is necessary to screen or separate the fine particles that accumulate. The sand must be cooled before being returned to the flask fill area. Foam pattern distortion and adhesive softening may occur if the temperature of the sand introduced in the flask is higher than 50 °C (120 °F).

Pouring a lost foam casting is much like pouring metal in other sand casting methods. The pouring basin or pour cup must remain full throughout the pour. Metal feed is controlled by the vaporization rate of the foam pattern system. A positive head of metal must be maintained (Fig. 9). Failure to do so may result in a mold collapse and scrapped castings

or a partial mold collapse, thus providing the opportunity for sand and coating inclusions in the casting. Metal temperature at the time of pouring is critical and must be controlled tighter than with most other sand casting methods.

After pouring, the castings are allowed to cool at approximately the same rate as green sand castings. The flasks are moved into the dump-out area, sand and castings are separated (Fig. 10), and the castings are ready for degating and cleaning. Conventional cleaning methods, such as sandblasting or shotblasting, can be used. Vibratory media cleaning systems may be necessary to remove the coating, which adheres to internal cast surfaces. Water quenching will greatly assist the cleaning of aluminum castings. Methods for cleaning castings are reviewed in detail in the article "Blast Cleaning of Castings" in this Volume.

### *Advantages of Lost Foam Casting*

The benefits of lost foam processing are numerous, and most are obvious to those who have witnessed the simplicity of the process. In lost foam casting, there is no mold parting line and there are no cores. One-piece flasks are readily moved.

The use of untreated, unbonded sand makes the sand system economical and easy to manage. There is less maintenance on sand handling equipment. Less sand is needed in the system, and the recycling of the sand is an ecological advantage.

These advantages lead to others that are equally desirable. Casting cleaning is greatly reduced and is sometimes eliminated except for removal of the wash coating that transfers from the pattern to the casting. Casting yield can be considerably increased by pouring into a three-dimensional flask with the castings gated to a center sprue.

Another advantage of lost foam casting is its ability to reduce the labor and the skill required in the casting process. In addition to reduced cleaning and the elimination of the need for core setting or parting line matches, handling of the flasks and castings is more readily automated with the lost foam process because locations are predictable.

A lost foam casting facility has the ability to produce a variety of castings in a continuous and timely manner. Lost foam foundries can pour diverse metals with very few changeover problems, and this adds to the versatility of the foundry. Response to customer demands can also be very rapid with this type of manufacturing system.

Further benefits of lost foam casting result from the freedom in part design offered by the process. Assembled patterns can be used to make castings that cannot be produced by any other high-production process. Part development costs can be reduced because of the ability to prototype with the foam. Product and process development can be kept in-house.

Finally, cast-in features and reduced finishing stock are usually benefits of using the lost foam process. Inserts can be cast into the metal, and bimetallic castings can be made.

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\*\* Lost foam casting is also referred to in the literature as evaporative pattern casting, evaporative foam casting, the lost pattern process, the cavity-less expanded polystyrene casting process, expanded polystyrene molding, or the full mold process.

### Magnetic Molding (Ref 12)

Magnetic molding is similar to the lost foam process in that an EPS pattern is used. However, the unbonded sand used as the mold backing aggregate is replaced with magnetic iron or steel shot that is bonded by a magnetic field. The process consists of positioning the EPS pattern in the flask and encasing it with iron particles between 0.5 and 0.1 mm (0.02 and 0.004 in.) in diameter (supported by periodic vibrating and/or tilting), then magnetizing the molding material and pouring the molten metal while the evolving gases are drawn off through the base of the flask. The magnetic field is turned off after solidification and cooling, resulting in immediate shakeout. The free-flowing magnetic shot molding material is returned to its point of origin after cooling, dedusting, and metal splash removal.

The increased heat conductivity of the molding material results in a finer grain structure in the cast metal. Other advantages include the absence of a chemical binder, reductions in dust and noise levels, full mechanization or automation of the process, and the elimination of molding activities normally used (such as ramming and jolting).

To date, most of the research on magnetic molding has been carried out in the Soviet Union and Germany on cast irons, carbon and low-alloy steels, high-chromium steels, and copper-base alloys (Ref 5, 6, 7, 8). Investigations are still being conducted to determine the influence of process variables such as vibration time, magnetic field strength, and time of application on the dimensional accuracy of the castings produced. In addition, work is required to establish more clearly the magnetic properties of the iron powder to provide accurate information on the values of magnetic field strength required for the process (Ref 4).

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#### Vacuum Molding (Ref 10, 11, 12)

The vacuum molding process, or V-process, is a sand molding process in which no binders are used. Instead, the sand is positioned between two sheets of thin plastic and is held in place by the application of a vacuum. Originally developed in Japan for the production of castings with high surface-area-to-volume ratios, the process is now licensed for use worldwide, and it has been successfully used to cast all metals that are normally cast in conventional green sand mold mixes.

Sequence of Operations. The steps in the process are shown in Fig. 16. A specially constructed pattern is built on a hollow carrier plate. The pattern contains a number of small vent holes. A thin (0.05 to 0.10 mm, or 0.002 to 0.004 in.) plastic film is then heated and stretched over the pattern and the sprue pin. A moderate vacuum (27 to 53 kPa, or 200 to 400 torr) is applied to the pattern plate, and this draws the film tightly to the pattern by suction through the vent holes.

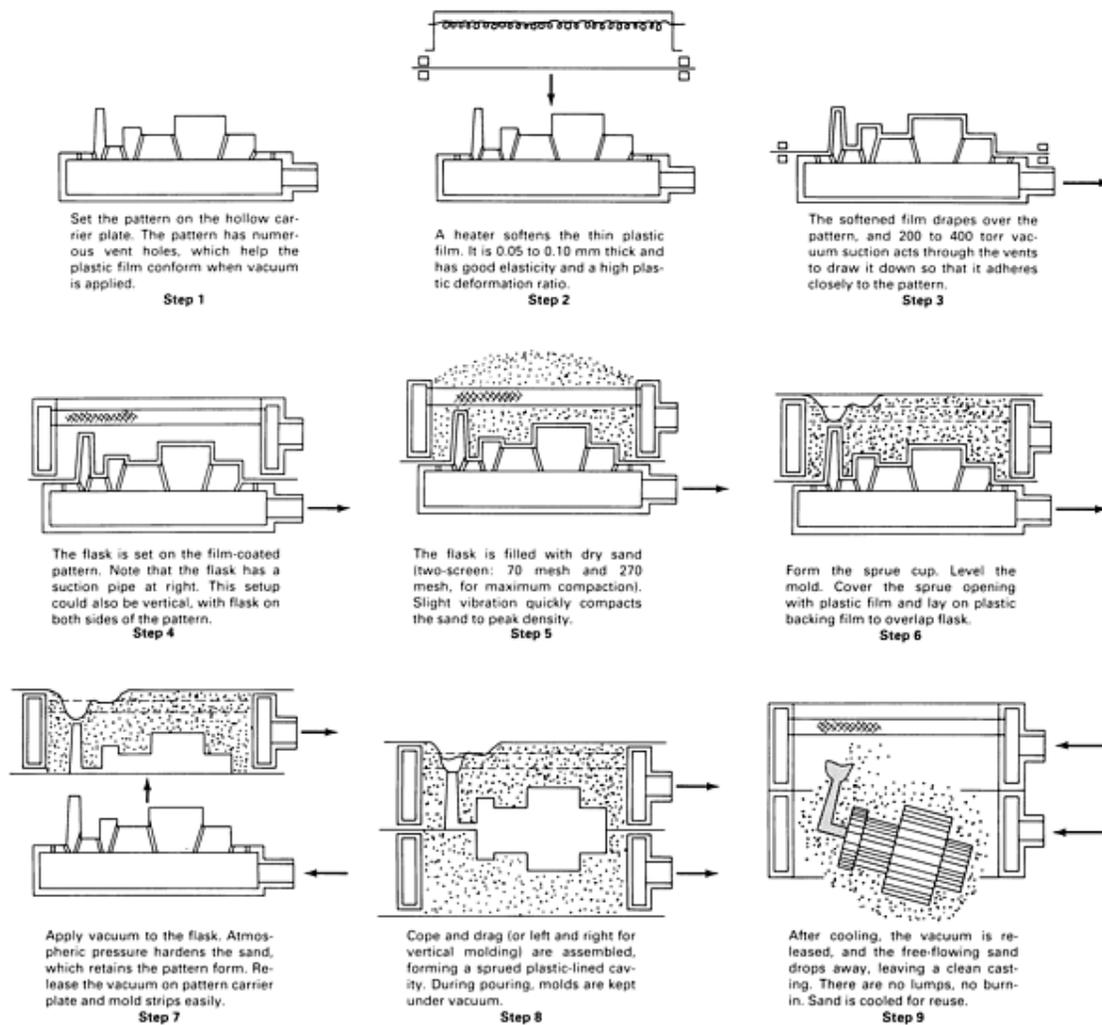


Fig. 16 Elementary sequences in producing V-process molds.

A specially constructed hollow-wall flask containing a vacuum connection is placed around the pattern, filled with sand, and vibrated at a low power level. A two-screen sand (70 and 270 mesh) is recommended for producing high-density molds. The excess sand is then struck off, and the top of the sprue pin is wiped clear of sand. A sheet of plastic film is placed over the top of the sand, and vacuum is applied to the flask. The vacuum holds the sand tightly in place, producing an extremely hard (AFS mold hardness 90+) dense mold. When the vacuum is released on the pattern carrier plate, the pattern is easily withdrawn.

Cope and drag are assembled while maintaining the vacuum, and the casting is poured. After the casting cools, the vacuum is released in the flasks, and the casting and loose sand are removed. The castings separate easily from the sand, which requires only cooling and screening for reuse.

Before pouring, the plastic that covers portions of the mold cavity that would normally be open to the atmosphere (such as the tops of risers, vents, and sprues) is removed to ensure that the mold cavity remains at atmospheric pressure during pouring in order to maintain the pressure differential between the mold and the mold cavity (otherwise the mold will collapse). Care must be taken to ensure that the gases generated during pouring exit to the atmosphere not to the sand and vacuum system.

Plastic Film Characteristics. The plastic films used for vacuum molding are thermoplastic compositions, while thermosetting resins are used as foundry sand binders (see the article "Resin Binder Processes" in this Volume). Plastics that have been evaluated for their applicability to vacuum sealing are listed in Table 4, along with some representative

properties. The most commonly used material is an ethylene-vinylacetate co-polymer (EVA) with vinylacetate contents ranging from 14 to 17%.

**Table 4 Plastic films used for the V-process**

Type of film	Density, g/cm <sup>3</sup>	Melting point	
		°C	°F
Low-density polyethylene	0.920	88-90	<b>190-194</b>
High-density polyethylene	0.960	94-97	<b>201-207</b>
Nylon	1.13	215-222	<b>419-432</b>
Polypropylene	0.90-0.91	160-170	<b>320-338</b>
Ionomer	0.93-0.94	72-75	<b>162-167</b>
EVA <sup>(a)</sup>	0.940	58	<b>136</b>
<b>Polyvinylchloride</b>	<b>1.450</b>	<b>56-90</b>	<b>133-194</b>

(a) Ethylene-vinylacetate co-polymer.

The characteristics of the plastic film must be suitable for vacuum forming so that pattern contours will be closely replicated without film shape defects (folds and creases) or rupturing, and the original sheet should be free of pinholes, tears, air bubbles, or blemishes. The important characteristics for easy shaping to pattern contour are both elastic and plastic behavior in proper balance. These properties are a function of film composition, temperature, thickness, stress, rate of loading, direction of loading, and the presence of notch inducers. More detailed information on the film characteristics and test methods used to evaluate these properties is available in Ref 10.

**Advantages.** The V-process offers a number of benefits. The lack of a binder means that fumes and dust are reduced and that no sand mixing system is necessary. No moldmaking machines are needed, and shakeout and sand reclamation are simplified. Patterns are identical to those used for green sand molding, except that vent holes must be judiciously placed around the patterns for plastic film adhesion. Pattern wear is reduced because the sand never makes contact with the pattern surface. Casting surfaces and dimensions are excellent.

The V-process is not normally used for high-production runs, because of the number of functions that must be performed; however, production rates of 60 to 100 molds per hour have been achieved. Figure 17 shows the layout for a high-speed automated vacuum molding line for the production of medium-size castings at a rate of 60 molds per hour. Vacuum molding is often used in the floor molding of relatively large patterns (flask sizes  $\geq 750 \times 750$  mm, or  $30 \times 30$  in., are typical) in jobbing foundries, where production rate is five to ten molds per hour.

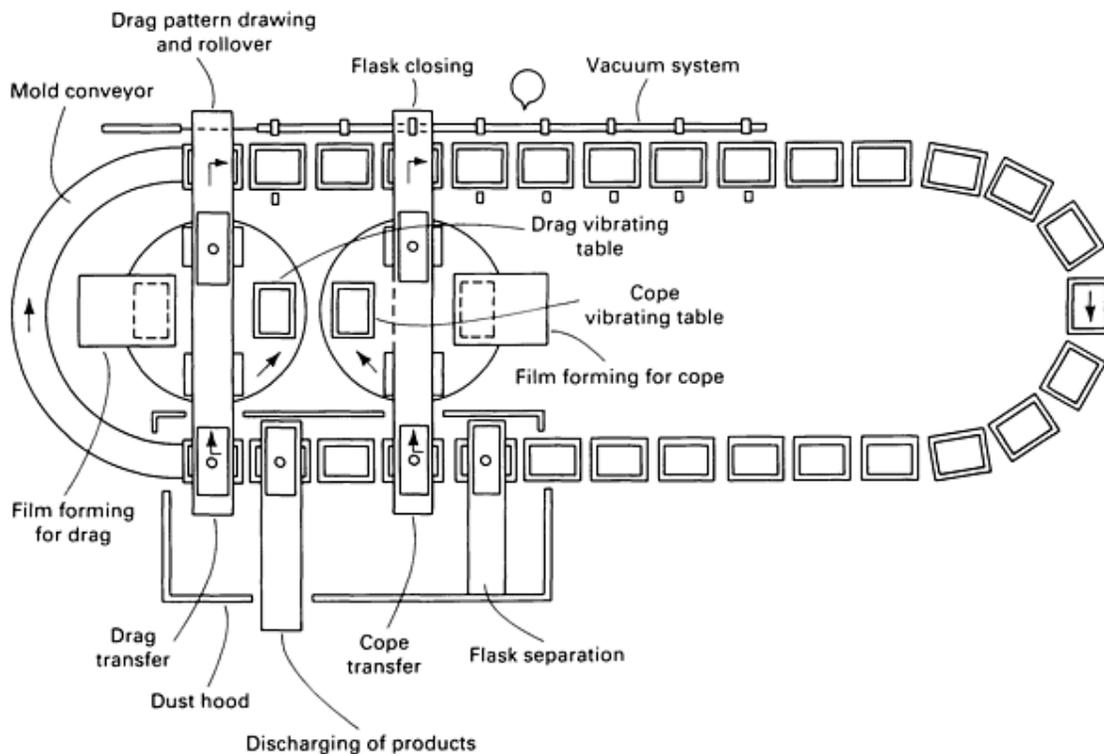


Fig. 17 High-speed automatic V-process production line. Production: 60 complete molds per hour. Flask size: 1300 × 1100 × 400 mm (50 × 40 × 15 in.). Amount of sand: 120 Mg (130 tons/h). Number of operators: 5.

As the plastic film vaporizes with a reducing gas, metal fluidity is often improved in V-process molds. However, because the molds contain no moisture, solidification rates are slower. The high mold rigidity increases riser efficiency because there is virtually no mold wall movement.

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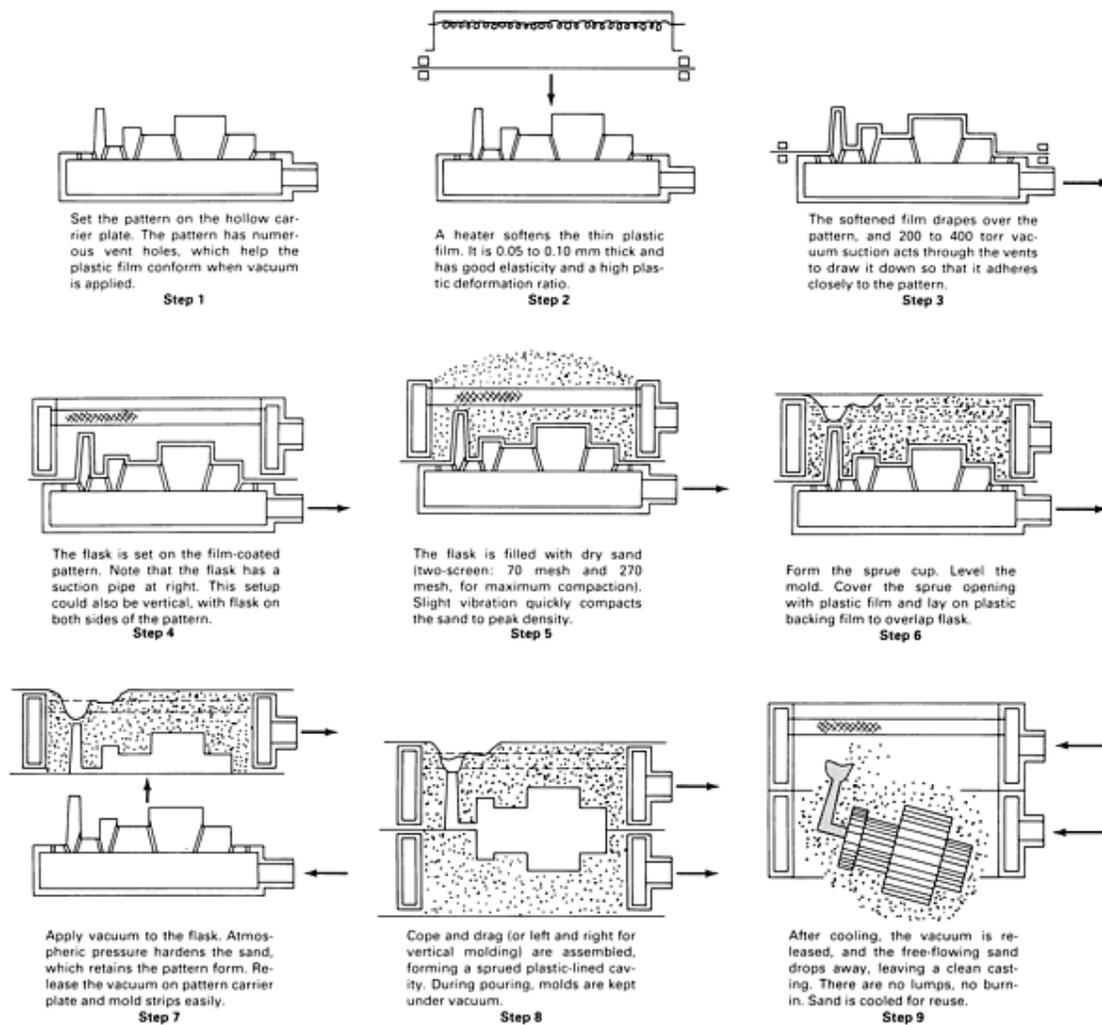


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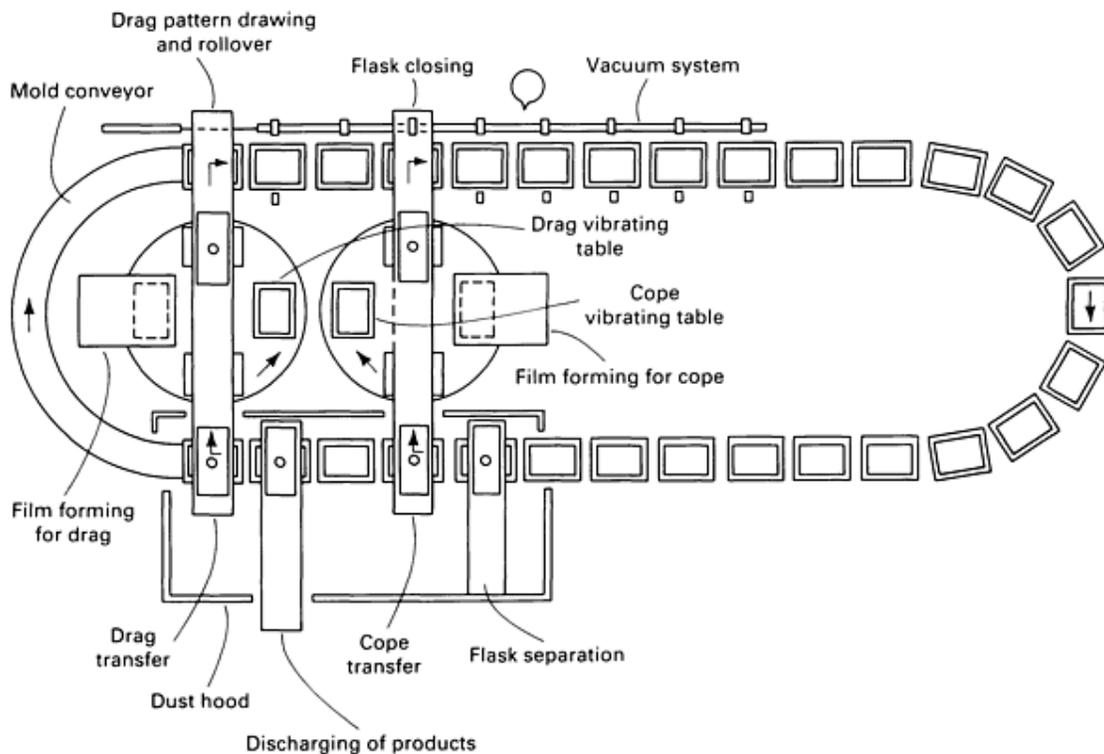


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## Coremaking

Larson E. Wile, Consultant; Ken Strausbaugh, James J. Archibald, and Richard L. Smith, Ashland Chemical Company; Thomas S. Piwonka, University of Alabama

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## Introduction

COREMAKING involves coating a refractory aggregate with binder, compacting the coated sand into the desired shape, and then curing (hardening) the compacted mass so that it can be handled. Refractory coatings are also often applied to the core surface to prevent sand-adhering defects on the casting and to yield a smoother casting finish.

## Selection of a Core System

Although a wide variety of methods and materials are used for making cores, coremaking processes are generally categorized according to curing method and binder type. Detailed information on these processes can be found in the article "Resin Binder Processes" in this Volume. The three major systems used for coremaking are listed below:

### Cold Box Processes

- Phenolic urethane/amine
- Furan/SO<sub>2</sub>
- (Acrylic/epoxy)/SO<sub>2</sub> (free radical cure process)
- Sodium silicate/CO<sub>2</sub>
- Phenolic ester

### Heat-Cured Processes

- Shell process
- Core oil (oven bake)
- Phenolic hot box
- Furan hot box
- Furan (furfuryl alcohol) warm box

### No-Bake Processes

- Furan/acid
- Phenolic/acid

- Alkaline phenolic/ester
- Silicate/ester
- Phenolic urethane/amine
- Polyol isocyanate
- Alumina phosphate

The cold- and heat-cured (heat-activated) processes lend themselves exceptionally well to medium- and high-production applications. Examples of high-production operations are foundries that cast automotive, pipe fitting, air conditioning, and refrigeration components (Fig. 1). The no-bake processes are generally used for short-run production quantities.

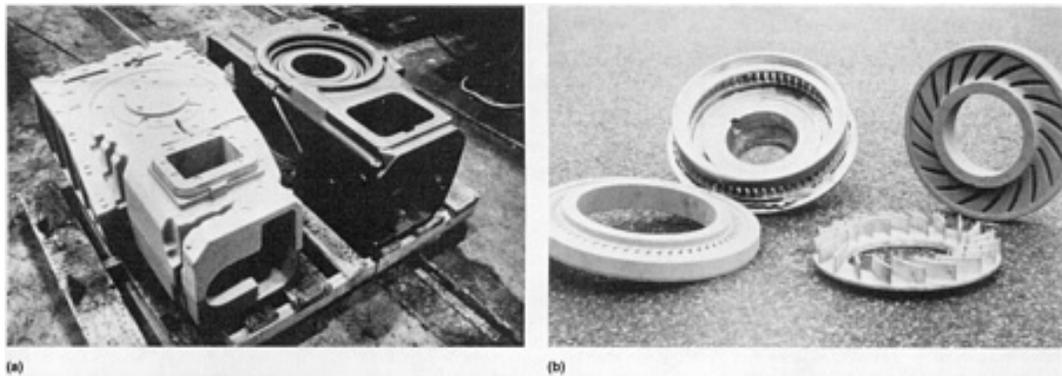


Fig. 1 Cores and corresponding castings produced by the cold box process. (a) Large transmission case and resulting gray iron casting for an agricultural equipment manufacturer. (b) Disk brake rotor and turbine cores and castings. Courtesy of Ashland Chemical Company

Both cold- and heat-activated cores are cured in the core box, thus maintaining excellent dimensional accuracy. Cold processes utilize gases that are forced through the compacted sand mixture to cure the core (Fig. 2). Heat-cured processes require the core box to be heated to 175 to 290 °C (350 to 550 °F) prior to introduction of the prepared sand. The no-bake process uses binder systems that consist of chemicals that, when mixed together in sand, cure without the introduction of an external agent, such as heat. The process is well suited to the fabrication of larger cores.

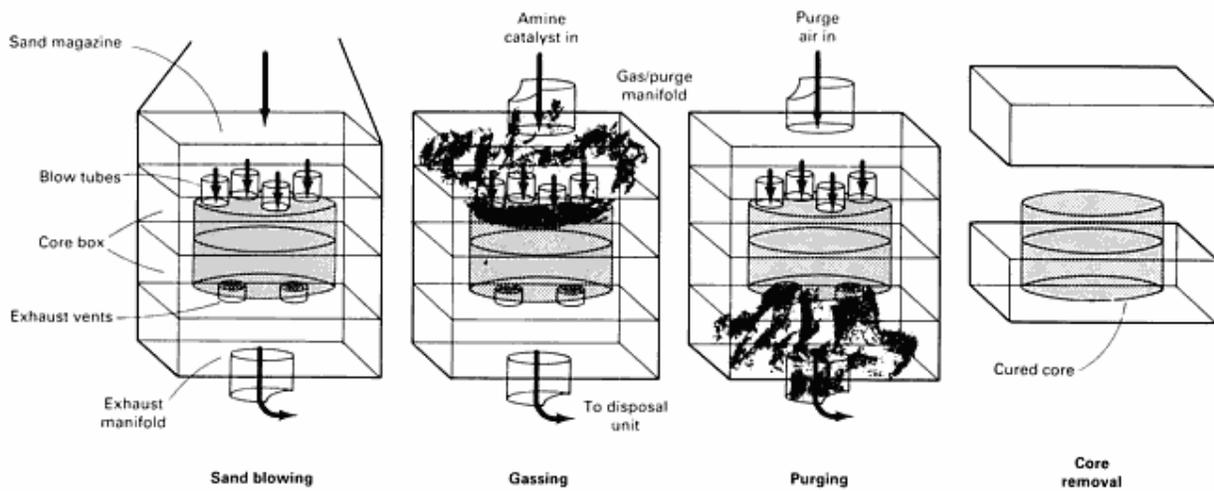


Fig. 2 The cold box coremaking process. The wet sand mix, prepared by mixing sand with the two-component liquid resin binder, is blown into the core box. The core box is then situated between an upper gas input

manifold and a lower gas exhaust manifold. The catalyst gas enters the core box through the blow ports or vents and passes through the core, causing almost instantaneous hardening of the resin-coated sand. The core is ready for ejection from the core box after purging with clean air for a few seconds. After the catalyst gas passes through the core, it leaves the core box through vents into the exhaust manifold. From the gas exhaust manifold, the catalyst gas is piped to an appropriate disposal unit.

In the core-oil (oven-bake) process, sand is mixed with corn flour and/or clay and water along with the binder to give sufficient strength to the mass of sand so that it can be immediately removed from the core box onto core plates. The cores are then hardened by baking at 200 to 260 °C (400 to 500 °F). The oven-bake process does not require complicated curing equipment, and materials are inexpensive; but dimensional accuracy is more difficult to maintain.

The type of metal to be poured must be considered in selecting a core process. For example, steel and certain high-alloy cast irons are sensitive to urea because of the tendency to form gas defects due to the amount of nitrogen present. In making aluminum castings, the pouring temperature may not be high enough to break down the binder system adequately for easy removal from the castings. Although silicate cores usually collapse sufficiently when used with aluminum and steel, their use in cast iron may be a problem because of a secondary bond that forms at iron-pouring temperatures. Cores for magnesium castings require inhibitors that must be compatible with the binder system.

Wood, plastic, and metal core boxes can be used with the cold processes, while only metal can be used with the heat-activated systems. However, once a system is established, metal core boxes and machines designed for one type of heat-activated process can usually be used for alternate heat-activated processes. The same is true for cold processes.

Although equipment is available for blowing or shooting core weights of up to 540 kg (1200 lb), most cores of this size and above use one of the no-bake processes. Smaller cores are usually made using cold, warm, or hot box techniques unless they have high surface-area-to-volume ratios, in which case the required equipment would be cumbersome.

Elevated temperatures accelerate chemical reactions. Summer temperatures may adversely affect some of the hot systems to the point where they actually harden prematurely. In cold systems, the silicon dioxide (SiO<sub>2</sub>) types possess the longest working times.

The core sand will eventually become system sand. Therefore, suitability for reclamation and compatibility with the sand reclamation and sand system used must be considered.

## Mixing

Sand mixing is easily accomplished for all of the processes except the oven-bake and shell processes. Special mullers are required to mix the sand and dry ingredients adequately with water and binders to develop the necessary strength to permit baking process cores to be removed from the core boxes in the uncured state.

Most shell process sands are hot coated in paddle/plow-type mixers using solid or liquid novolac resins. Cold and warm coating, both of which utilize powdered or liquid novolac resins, have declined.

With the hot coating process, a solid flake or liquid novolac resin is dispersed into a sand that has been preheated to 130 to 175 °C (265 to 350 °F). Hardener (contents ranging from 10 to 17% based on the weight of the resin) is first dissolved in water, and this solution is added after the resin is dispersed, and a lubricant is added near the end of the cycle.

The moisture content of the sand mix will range from 1.5 to 2.5%. Immediately after the addition of the water/hardener solution, cold air is blown into the mixer to cool and dry the sand. Whatever process is selected, the coating process is carried out in a paddle-type mixer that is usually equipped with a system (fluid bed, screen, or cyclone) to cool and complete the drying of the coated sand.

Various types of blending equipment are used to disperse the binders uniformly over the sand used in the other processes. Batch or continuous mixers can be employed to coat the sand used in the cold or heat-activated processes. If a batch mixer is used, the sand and additives are weighed or volumetrically measured before being introduced into a mix. There the mixture is agitated by a revolving mixer or by vibratory motion for 20 s to 5 min. Prepared sand is then discharged and transferred to the coremaking station.

A continuous mixer is almost a necessity for a no-bake coremaking operation, but is also adequate for mixing sand for the cold or heat-activated processes, with the exception of the shell process. Sand and additives are continuously metered into a mixing trough or chamber that contains revolving mixers of various designs, and prepared sand is discharged. In the no-bake process, the sand is discharged directly into the core box, where it is immediately compacted. Prepared sand for the cold and heat-activated processes is generally discharged into a storage hopper above a coremaking machine.

## Compaction

Cores must be sufficiently dense to obtain good grain-to-grain bonding of the sand mass and to prevent metal penetration between the sand grains. Prepared sand can be hand rammed into the core box, and this is the usual procedure for no-bake cores; but mechanical methods are required for high-production operations.

Core blowing machines are commonly used to compact sand into the core boxes. Prepared sand is added to a chamber, which is then sealed except for exit ports (blow ports) that are placed directly over inlet ports (investment areas) of the core boxes. The core boxes are equipped with air relief vents. A large volume of compressed air at 275 to 700 kPa (40 to 100 psi) is suddenly introduced above the sand in the chamber, forcing the sand into the core box through the investment area. The carrier air is exhausted through the vents in the core box. The blow air is then turned off, the excess pressure in the blow chamber is exhausted, and the core boxes are disengaged from the blow ports. All these steps are generally electrically or mechanically controlled and require only seconds to complete.

## Release Agents

All core binders are sticky, but some are less so than others. It is this characteristic that requires the use of release agents/parting compounds on core boxes, regardless of the type of core box material. The desirability of having a dense core compounds the problem of core release, because binder-coated sand is packed or blown against the surface with force, which enhances sticking. In the heat-activated processes, the binder melts or softens and migrates to the heated surface.

It is necessary to start with a good core box; no amount of release agent will overcome roughness and scoring. The core box should be chromium plated if it is to be used for high production, and it should be broken in gradually. If a release agent is functioning properly, some buildup will occur; it should be removed frequently because it adversely affects core dimensions and quality. One method of removing buildup is blasting with ground walnut hulls, corn cobs, or other soft media. Solvents can also be used. Minimum amounts of release agents should be used, and when adding them during mixing, they should be added near the end of the cycle. The release agent should be chemically compatible with the binder system.

Oleic acid diluted with kerosene (usually 10:1) is used as a release agent for core-oil cores. It is added to the sand mixture and used to keep the core boxes clean. The amounts used are 125 to 250 mL/450 kg (1 pt to 1 qt/1000 lb) of sand.

Shell and other heat-cured processes use emulsified silicone release agents diluted in water. A low surface tension silicone should be used for spraying core boxes. Stearates, usually calcium, are added to shell sand during the coating process. Amounts recommended are 2 to 5%, based on resin solid weight. Small amounts of core oil or silicone emulsion can be added to hot box sand during mixing.

The no-bake and cold box processes use a wide variety of release agents. Small-to-medium size high-production core systems will normally use liquid types, which can be sprayed through jet nozzles and integrated into an automatic cycle or sprayed with a hand gun. No-bake systems normally use liquids, suspensions in liquids, or dry materials for larger cores. The suspension systems usually use a solvent carrier that evaporates readily. Materials can be sprayed, brushed, dusted, or hand rubbed onto the core boxes. Ingredients include (in many combinations) water, alcohol, chlorinated solvents, mica, talc, silicones, aluminum powder, graphite, and soybean oil (lecithin).

## Curing

Curing of the compacted mass of sand and binders varies according to the process chosen. In the cold box processes, the appropriate gas for the process (carbon dioxide, sulfur dioxide, tertiary amines, or methyl formate) is forced through the compacted sand (Fig. 2). Chemical reactions then occur that create rigid bonds between sand grains. Excess curing gas is purged from the cured core with compressed air, and the cores are removed from the core box as hardened cores.

In the heat-activated process, prepared sand is blown into a heated core box. The heat releases curing agents from latent hardeners in the sand mix, and these curing agents then cure the binder.

Time alone is required for the binders in the no-bake cores to react, and after sufficient time, generally from 30 s to 1 h, the cores are rigid enough to be removed from the boxes. Additional curing may continue for several hours.

Cores from the core-oil process are placed in ovens after stripping from the core box and are baked for 1 h or longer, depending on section thickness. They are removed from the oven when thoroughly cured and allowed to cool to ambient temperature.

## Coating

Coatings are frequently applied to cores to enhance the casting surface finish and to reduce casting defects at the mold/metal interface. Coatings accomplish this by having a higher refractory value than the sand and/or by forming an impermeable barrier between the metal and the core. Most coatings are formulated with five major components:

- Refractory materials
- Carrier system
- Suspension system
- Binder system
- Chemical modifiers

Refractory materials for coatings can be made of any of the following materials:

<b>Zirconium oxide</b>
<b>Zirconium silicate</b>
<b>Magnesium oxide</b>
<b>Olivine</b>
<b>Chromate</b>
<b>Pyrophyllite</b>
<b>Talc</b>
<b>Carbon (many forms)</b>
<b>Silicon dioxide</b>
<b>Magnesium/calcium oxide</b>

<b>Mullite (aluminum silicate)</b>
<b>Mica</b>
<b>Iron oxide</b>
<b>Magnesite</b>

These materials are blended in many combinations to make up a broad selection of proprietary coatings. Silica, alumina, and carbon are the most commonly used, and water, alcohol (isopropyl, methanol), naphtha (petroleum distillate), chlorinated solvents (inhibited 1,1,1-trichloroethane, or chlorothene NU, and methylene chloride), and aliphatic hydrocarbon are used as liquid carriers.

The carrier allows the refractory to be applied evenly to the sand mold or core. After the coating has been applied, the carrier must be removed. When the carrier is water, it can be torched or oven dried. Alcohol carriers are commonly ignited and allowed to burn off. The volatile chlorinated hydrocarbons readily air dry and require neither torching nor oven drying.

Suspension System. The function of the suspension system is to maintain the refractory material uniformly dispersed in solution. With water carriers, sodium bentonite is commonly used, while organic bentonite or bentones are generally used with alcohol and chlorinated hydrocarbon carriers.

The binder system in a coating is usually an organic resin, and it behaves similarly to the resins used to bond sands. The amount of binder used depends on the density and fineness of the refractory. It is used sparingly to avoid casting surface defects.

Chemical modifiers to the coating include surfactants to enhance wettability, antifoaming agents, and bactericides.

Coating Benefits. Most of the reasons for using coatings center around reducing casting costs by improving sand peel and reducing mold/core reaction, reducing or eliminating metal penetration (burn-in and/or burn-on), and reducing or eliminating veining. These reasons are directly associated with casting cleaning costs. Coatings are also used to reduce machining time and tool wear by having a clean smooth surface, to improve casting appearance, to facilitate handling (especially where low-strength cores may be required because of shakeout conditions), or to promote chill or increase hardness in metal (for which selenium or tellurium paste is used). Coatings should not be used indiscriminately. No coating will compensate for a poor-quality core.

Blending and Applying Coatings. All the advantages of selecting the proper coating, or wash, can be lost if it is not properly blended. Coating ingredients are available in powder, paste, slurry forms, and ready-to-use forms.

In preparing a core wash, the ingredients are mixed to a slurry with an electric or air-driven mixer. The mixing tank should be twice as high as its diameter, should be equipped with flow-through baffles spaced at approximately 120°, and should have an impeller shaft with two blades. The slurry must be mixed until creamy and lump free, with ingredients in suspension/solution. The Baumé must be kept 25 to 30° higher than application requires and further diluted prior to use. The carrier should be added in steps to avoid overdilution, which will adversely affect suspension. Coatings should be mixed a specified time before use (usually 12 to 24 h) to permit tempering of the suspension and bonding agents, and over-mixing should be avoided.

The methods of application will depend on a number of factors, such as the size and shape of the core, plant layout (if a continuous process is used), and production requirements. For example, small cores would not lend themselves to spraying but to dipping in groups using fixtures and/or baskets. Conversely, large cores in a production line could move continuously on a conveyor through a dip tank to a drain station and then to a drying station. Regardless of the method of application, obtaining a smooth, even coat is of paramount importance.

Water- or solvent-based washes can be used for furan, furan/phenolic, urethane cold box and no-bakes, phenolic esters, and baked core-oil cores. However, water-based washes should not be used on silicate or phosphate-bonded cores, because such washes will degrade the binder.

The best practice for drying coatings is to apply coatings on cured cores and then dry them by appropriate means, such as ovens, burn-off, or warm air circulation. If cores are cold, they should be heated before or immediately after application. If cores are coated green (incomplete cure), heat should be applied immediately. Evaporation of the solvent is important for avoiding deterioration of the core binder.

## Core Venting

Venting is necessary, and the general rule is to provide the maximum allowable venting. To understand the fact that gases must be dispersed, one need only consider the volume change that occurs in the transition of a liquid or solid to a gas.

The principal gases resulting from the breakdown of the chemical binder systems have been found to be hydrogen, carbon monoxide, carbon dioxide, methane, and nitrogen (Ref 1). In venting, however, the volume of gas is more important than its composition.

Care must be taken to lead all vents to core prints and to provide exits from the mold with minimum pressure buildup. In addition, vents must be kept far enough away from the surface to prevent metal breakthrough. As coarse a sand mix as good practice permits should be used. The permeability of sand is related to its coarseness, assuming a normal distribution. The coarser material will have the highest permeability and the most natural venting.

Cut, punched, filed, or scratched vent passages can be made by removing sand during coremaking, after curing, and before assembly. Mandrels can be used to hollow out cores, thus saving sand, or small holes can be drilled into cured cores.

Strands of wax and/or plastic tubing can also be used. These materials are available in a variety of sizes. In the heat-activated processes, some of these materials melt and are absorbed into the sand, leaving a passage. Permeable plastic tubes can be used in cold box processes. In very large cores, the center can be filled with dry unbonded sand, coke, slag, or gravel, thus avoiding gas generation. A secondary advantage of using these materials is that they replace the same volume of mixed sand and thus reduce cost.

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## Plaster Molding

Revised by Charles D. Nelson, Morris Bean and Company

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## Introduction

PLASTER MOLD CASTING is a specialized casting process used to produce nonferrous castings that have greater dimensional accuracy, smoother surfaces, and more finely reproduced detail than can be obtained in sand molds or coated permanent molds. The four generally recognized plaster mold processes are:

- Conventional plaster mold casting
- Match plate pattern plaster mold casting
- The Antioch process
- The foamed plaster process

## Applications

Near-net shape castings such as compressor wheels, impellers, components of electronics gear, tire molds, aerospace fuel pump systems, and heat exchanger systems are examples of castings produced by plaster mold casting. Machining costs would be exceedingly high if these parts were cast in most other types of molds.

For many parts, only a small portion of the total area requires the capabilities of plaster molding. Composite molds are more suitable for such parts.

Although about 90% of the plaster mold castings weigh less than 9 kg (20 lb) each, castings weighing as much as 34 kg (75 lb) are being produced in substantial quantities. To illustrate the capabilities of the technique, an aluminum alloy casting weighing 1815 kg (4000 lb) has been successfully cast in a plaster mold.

Advantages. Most of the advantages to be gained from the use of plaster molds have to do with casting quality:

- As-cast surface finishes of 50 to 125 RMS are readily obtained. By using flexible rubber patterns and incorporating the advantages of lost wax techniques, slurry molding successfully produces intricate designs
- The dimensional accuracy of the castings is good (about equal to the accuracy of castings made in investment molds)
- Thin sections can be cast because the castings normally cool quite slowly due to the insulating qualities of the plaster; wall thickness limits are a function of casting design, but selected areas 0.64 to 1.02 mm (0.025 to 0.040 in.) thick are typical
- Slow cooling minimizes warpage and promotes uniformity of structure and mechanical properties in the castings
- Plaster molds are especially well suited to the use of chills, which permit close control of thermal gradients in the molds; this optimizes mechanical properties desired in isolated areas of a complex casting

Disadvantages in using plaster molds are largely related to molding and casting procedures:

- Cost is high, partly because of the lengthy processing procedures and partly because the mold materials are not reusable
- Mold processing requires more equipment than is required for most other molding processes
- Because of the lengthy processing procedures needed to make plaster molds, duplicate (or multiple) pattern equipment, as well as duplicates of other processing equipment, may be required in order to meet production schedules
- With the exception of the foamed plaster process, the permeability of plaster molds is inherently low when compared to the sand casting process; therefore, it is usually necessary to apply pressure or vacuum during pouring or to provide greater permeability by a special procedure

## Plaster Mold Compositions

In all of the processes for making plaster molds and cores, the principal mold ingredient is calcium sulfate. Other materials used to enhance such mold properties as green and dry strength, permeability, and castability include cement, ceramic talc, fiberglass, sand, clay, Wollastonite, pearlite, and fly ash.

Cores are typically made of the same material and by the same process as molds, but cores are sometimes made of other materials, such as shell molding sand. Cores for the match plate plaster mold process are made of sand. Specific mold and core formulations, as well as techniques for making the slurries, are discussed under each process in this article.

Characteristics of Calcium Sulfate. Calcium sulfate exists as two different hydrates and in an anhydrous form. In its dihydrate form ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), it is known as gypsum. (Commercially, all three forms of calcium sulfate are sometimes referred to as gypsum.) When heated above an equilibrium temperature of  $128^\circ\text{C}$  ( $262^\circ\text{F}$ ), gypsum loses three-fourths of its water to form the hemihydrate ( $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ ), which is plaster of paris. Similarly, when the plaster of paris is heated above an equilibrium temperature of  $163^\circ\text{C}$  ( $325^\circ\text{F}$ ), all of the water of crystallization is removed, and anhydrous calcium sulfate ( $\text{CaSO}_4$ ) is formed. The above temperatures are based on laboratory studies of pure calcium sulfate under equilibrium conditions. Temperatures at which the hydrates are formed depend greatly on vapor pressure. For practical purposes, temperatures well above equilibrium temperatures are generally used.

If it is exposed to moisture at a temperature lower than  $100^\circ\text{C}$  ( $212^\circ\text{F}$ ), the anhydride formed near  $163^\circ\text{C}$  ( $325^\circ\text{F}$ ) will absorb water and will revert to the hemihydrate; the anhydride produced by heating to about  $540^\circ\text{C}$  ( $1000^\circ\text{F}$ ) will absorb water less rapidly. Similarly, when plaster of paris (the hemihydrate) is mixed with water, gypsum (the dihydrate) is reestablished, yielding a coherent solid in a few minutes. This reaction is termed setting. Prolonged exposure of the hemihydrate to moist air at temperatures below  $100^\circ\text{C}$  ( $212^\circ\text{F}$ ) results in a slow conversion to the dihydrate.

In the production of a plaster mold, plaster of paris is mixed with water to form a slurry. This slurry is immediately poured over a pattern or into a core box, where it sets, forming a solid mold or core composed of gypsum with free water distributed throughout the plaster mold.

The next stage is to dry the plaster in an oven to remove the excess water. Various drying temperatures are used, depending on the plaster molding process. If partings and waxes are used, the temperatures must be high enough to remove any waxes.

Plaster molds have low heat capacity. Therefore, the cooling rates for castings made in such molds are low. Figure 1 shows that the freezing time for a test casting made in a conventional plaster mold is more than four times as long as that for one made in a hard-rammed green sand mold.

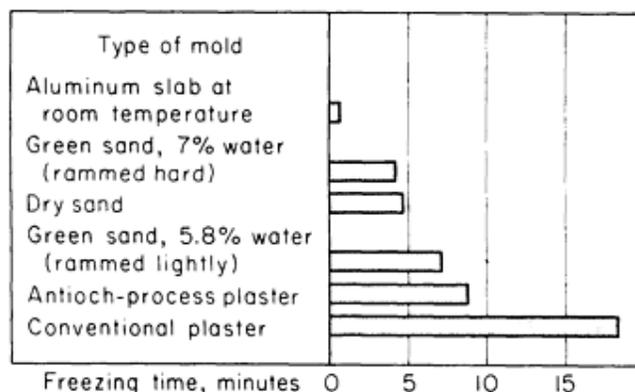


Fig. 1 Comparison of freezing times for identical test castings poured in various types of molds

Slow cooling has advantages and disadvantages. It permits better feeding, particularly in thin sections, as well as the replication of intricate detail that would be difficult to obtain with fast cooling. However, it slows production by lengthening the time between pouring and shake out, and for most alloys it results in castings of lower strength. This latter disadvantage can usually be eliminated by the use of chills in specific areas.

Metal and Rubber Patterns. Patterns and core boxes for plaster mold casting are commonly made of metal (aluminum alloy, brass, or zinc alloy). Flexible rubber patterns are widely used for producing intricate molds, such as the molds used for casting wheels having angular vanes. Flexible rubber patterns having as much as 30° negative draft can be withdrawn without damaging molds that have high green strength.

Cast epoxy resin patterns are useful for some purposes. For example, when several patterns are required, they can be made quickly by molding them from epoxy resin in metal master dies. Cast epoxy patterns also have greater dimensional stability and longer production life.

Wood Patterns. Because patterns for production casting by plaster mold processes must withstand repeated exposure to liquid slurries, wood patterns usually are not adequate. Wood patterns, although not extensively used in the production of castings, are specified as patterns for match plate pattern molds. Wood patterns must be sealed, or they will swell and distort.

## Mold Drying Equipment

Plaster molds made by any process must be dried. The most common drying temperatures range from 120 to 260 °C (250 to 500 °F), but temperatures to 870 °C (1600 °F) have been used under carefully controlled conditions. Once the optimum temperature for a specific application has been determined, it must be closely maintained--usually within  $\pm 6$  °C ( $\pm 10$  °F).

After this initial requirement has been met, the choice of equipment depends largely on the temperature to be used and the number of molds to be processed. For drying at 120 to 260 °C (250 to 500 °F), either batch-type or conveyor core ovens are satisfactory.

Higher-temperature drying requires furnaces similar to those used for the heat treating of steel. Either batch-type or conveyor furnaces can be used, but conveyor furnaces are generally preferred, especially for drying large quantities of molds. The molds must be cooled to at least 205 °C (400 °F) before they are removed from the furnace.

## Flasks

Flasks are usually made of low-carbon steel and aluminum. They vary in size in accordance with the size of the pattern, the number of identical molds to be produced, and the number of patterns in a flask.

When the flask is to hold only one pattern half, especially when only a few molds are required, a simple, bottomless flask is placed on a mold board, and the pattern half is positioned within it on the board, ready to receive the slurry. When many identical molds are required, especially when two or more patterns are placed in a single flask, a flask with a flat bottom that serves as a mold board is used; the pattern halves are arranged on the flask bottom. In the Antioch process, for small single-pattern molds, pattern and flask are often an integral unit (see the section "The Antioch Process" in this article). The flask for a given application should be large enough to allow space for the same thickness of plaster surrounding the pattern as would be needed if the mold material were dry sand.

Standardization of flask sizes is important in production operations because this simplifies tooling, especially when vacuum pouring is used. Standardization of flask size is also desirable for pouring the slurry and drying the molds. In some foundries, it is common practice to select as standard a flask size that is suitable for the largest casting that will normally be poured. When smaller castings are to be made, a family mold practice is often used. In this practice, two or more patterns (sometimes as many as 16) are positioned in the flask.

## Metals Cast in Plaster Molds

Only nonferrous metals are cast in plaster molds. Ferrous alloys are not suitable, because most of them are poured at temperatures that would melt the calcium sulfate the molds are made of. Calcium sulfate undergoes a phase transformation at 1195 °C (2180 °F) and melts at 1450 °C (2640 °F).

Aluminum. All of the aluminum alloys that can be successfully cast in sand molds are suitable for casting in plaster molds. The more readily castable alloys--43, A344, 355, 356, and 357--are preferred.

Copper. Most of the coppers and copper alloys that can be successfully cast in sand molds can be cast in plaster molds; again, the more castable alloys are preferred (see the article "Copper and Copper Alloys" in this Volume). Copper alloys containing more than approximately 5.0% Pb are generally not recommended for casting in plaster molds, because the higher-lead alloys react with some mold compositions, resulting in poor surfaces on the castings and defeating one of the objectives of plaster mold casting.

Magnesium alloys are not recommended for plaster mold casting. A reaction is likely between the magnesium alloys and the mold material. In particular, magnesium alloys will react with any free water that remains in the mold and will cause an explosion.

Zinc alloys are frequently cast in plaster molds, most often for prototype castings. The die casting alloys AG40A and AC41A are often used, but a proprietary alloy whose coefficient of thermal expansion is very close to that of aluminum alloys is frequently cast. Master patterns appropriate for this zinc alloy or for aluminum can be made according to a single shrinkage rule.

Nominal compositions of the three zinc alloys mentioned are:

Alloy	Composition, %			
	Al	Cu	Mg	Zn
AG40A	4.10	0.10 max	0.035	<b>rem</b>
AC41A	4.10	1.00	0.055	<b>rem</b>

Except for allowances for shrinkage, the technique for making the molds is the same as that for aluminum and zinc alloys.

## Conventional Plaster Mold Casting

Melting practice equipment and methods for metal to be poured into plaster molds are the same as those used for preparing the metal for pouring into other types of molds. A brief outline of conventional plaster molding is given in the following sequence of operations for producing conventional plaster molds.

- Mix dry ingredients
- Add dry ingredients to water
- Soak (2 to 4 min)
- Mix (2 to 5 min)
- Coat patterns (or core boxes)
- Pour slurry
- Set at room temperature (15 min)
- Remove pattern
- Dry molds (or cores)
- Assemble cores and mold halves

Composition and Preparation of Dry Ingredients. Dry ingredients ready to mix with water are available as proprietary compositions. For small operations, it is usually cost effective to purchase these ready-to-mix dry ingredients. Compositions vary considerably, but the gypsum content (typically, a blend of gray and white gypsum) is commonly 50 to 60%, by weight, of the dry mixture. The rest of the mixture consists of two or more filler materials, such as wollastonite, ceramic talc, fly ash, perlite, and sand. Portland cement, hydrocals, fiberglass, and terra alba are also sometimes used to enhance the strength of the mold and to improve setting behavior.

Mixing the Slurry. Equipment requirements for mixing the slurry are very precise. The principal components of a batch-type mixer are a bucket and a propeller (Fig. 2). The bucket height should be equal to or slightly greater than the top diameter, and the bottom diameter should be approximately two-thirds of the top diameter.

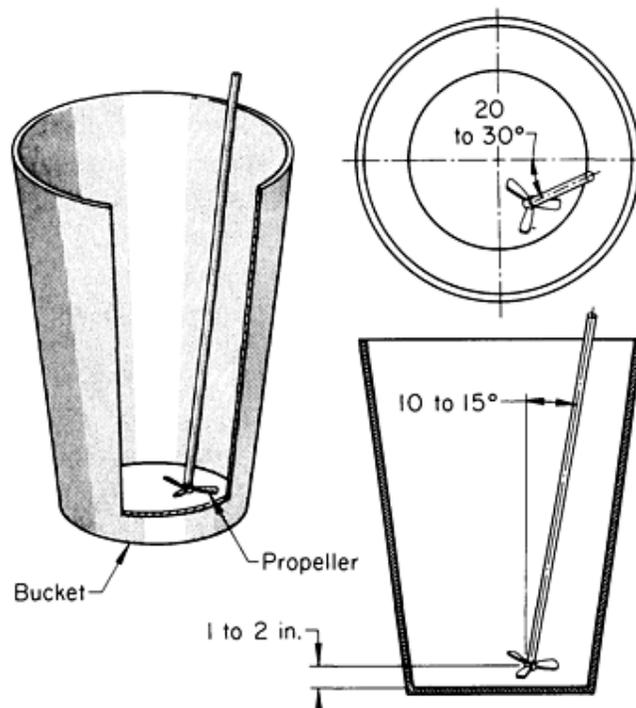


Fig. 2 Preferred shape of bucket and position of propeller used in the batch mixing of plaster slurries for conventional plaster molds

Preparing the Pattern. Because the slurry begins to set as soon as it is mixed, it must be poured over the pattern (or into the core box) almost immediately, and the pattern must be ready to receive the slurry.

Pouring the Slurry. When the slurry is poured into the flask, the lip of the bucket should be kept close to the pattern. The slurry should be poured at a constant rate and made to flow over the pattern rather than splash on it.

Set time varies somewhat, depending on the slurry composition, but 30 min is usually the maximum set time. After the slurry has set, the pattern and flask are removed, and the drying cycle is started as soon as is practical.

Drying the Molds. All conventional plaster molds must be dried enough to expel the free water and most of the water of crystallization to a depth of at least 13 mm ( $\frac{1}{2}$  in.) below the surface. Some foundries prefer to have the molds completely calcined.

Oven drying should begin as soon as is practical after the mold has been removed from the flask. Molds that have partially dried by standing at room temperature are more susceptible to cracking than those that are oven dried

immediately after setting. If the molds must stand at room temperature for some time (such as over a weekend or even overnight), they should be covered with a damp cloth or stored in a humid atmosphere.

During drying, the mold should be uniformly supported on its edge or face. Common practice is to place the mold on a perforated flat metal plate, a rigid metal grid, or some other type of level support. If smooth plates are used for support, they should be covered with a thin layer of talc or similar material to allow movement of the mold during drying without the danger of its cracking or warping.

Time and temperature cycles used for drying conventional plaster molds vary widely among foundries. Temperature may vary from about 175 to 870 °C (350 to 1600 °F), and time from 45 min to 72 h. The fact that furnaces are operated at high temperatures (760 to 870 °C, or 1400 to 1600 °F) does not mean that all areas of the mold must reach this temperature range, but the interior of the mold must be at a temperature of at least 105 °C (220 °F), to ensure removal of the free water. (Mold temperatures are measured by thermocouples in the center of mold sections.) The specific time and furnace temperature required for drying a specific mold usually must be determined by experimentation. Once established, the time-temperature cycle must be rigidly controlled for best reproducibility.

Mold Assembly. After the mold has been removed from the oven, cores are placed in the drag half. Depending on mold complexity, this can be done while the molds are still hot or after they have cooled to room temperature. Ceramic or plaster pins are placed in the holes provided in the drag half. The cope half is then lowered so that the pins protruding from the drag enter the matching pin holes in the cope, as shown in Fig. 3.

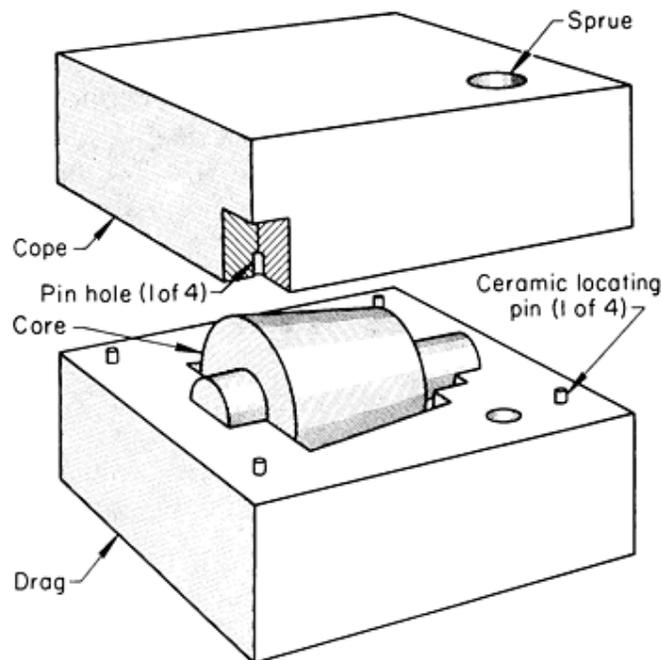


Fig. 3 Plaster mold and core showing location pins for matching the cope and drag sections

Preheating. Following assembly, the mold is ready for preheating. Some foundries preheat all conventional plaster molds to a preestablished temperature (commonly 120 °C, or 250 °F) before pouring the metal. Other foundries preheat the molds only in specific applications for which preheating has proved advantageous. Preheating of the mold can help to minimize defects or to obtain better replication of fine detail in the casting.

Pouring Practice. A dried plaster mold made by the conventional process has extremely low permeability--about 1 to 2 AFS, compared with 80 and upward for sand molds. Because of this low permeability, either vacuum assist or pressure is usually required for the pouring of molds. Simple gravity pouring is rarely done.

Most foundries use vacuum assist for pouring conventional plaster molds. A typical setup for vacuum-assist pouring is shown schematically in Fig. 4(a). In this setup, the mold is supported by a fixed bottom plate (plate B, Fig. 4a).

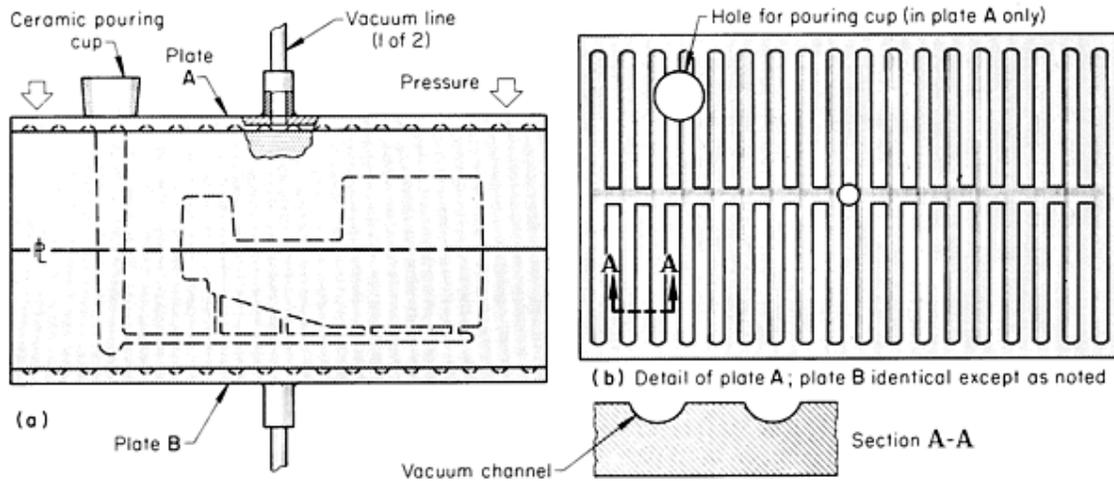


Fig. 4 Typical setup for vacuum-assist pouring of a conventional plaster mold casting. (a) Side view of conventional plaster mold positioned between upper and lower plates for pouring with vacuum assist. (b) Details of a top plate showing vacuum channels

### Casting of Match Plate Patterns

Match plate patterns are cast by a particular adaptation of the conventional method of plaster molding. Changes in details of the conventional method ensure high accuracy and smooth surface finish, which are required in metal match plate patterns.

Common dimensional requirements for match plate patterns are:

- Match between the cope and drag, within 0.25 mm (0.010 in.)
- Parallelism between the two halves, within 0.51 mm (0.020 in.)

A surface finish of 2.5  $\mu\text{m}$  (100  $\mu\text{in.}$ ) or better is obtained.

Sizes and Weights of Match Plate Patterns. A match plate pattern consists of a cope section and a drag section separated by a plate. These three components are cast as an integral unit. A typical match plate pattern is shown in Fig. 5.

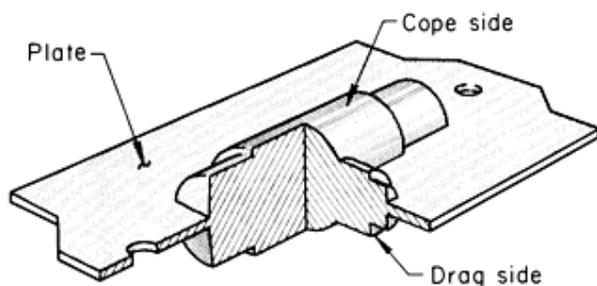


Fig. 5 A typical metal match plate pattern

Metal match plate patterns vary considerably in size and weight. Patterns weighing as much as 180 kg (400 lb) each have been cast, although these are unusually large. Match plate patterns seldom weigh more than 45 kg (100 lb) each, and most weigh from 8.2 to 16 kg (18 to 35 lb).

A single plate may hold one pattern or many patterns. The thickness of the plate for small patterns having one pattern per plate is usually 9.5 mm ( $\frac{3}{8}$  in.). The plate thickness increases as the size and weight of the pattern increase; a thickness of 19 mm ( $\frac{3}{4}$  in.) would be used for a plate measuring 1.1  $\times$  1.1 m (44  $\times$  44

in.). Plate thickness is also increased to provide adequate stiffness and bend resistance in designs involving a stepped parting line separating cope and drag mold sections.

Mold Composition. Materials for molds for match plate patterns are available as proprietary dry mixtures ready for mixing with water. However, some foundries prefer to make their own mixtures.

Master patterns for match plate patterns are usually made of wood (for economy), but they can be made of metal. Wood patterns must be lacquered or otherwise coated to prevent the absorption of water from the slurry.

Separate master patterns are made for the cope and the drag. The plate portion is developed by the technique described in the section "Mold Assembly" in this article, rather than by means of a pattern. Before the slurry is poured, the patterns are coated with a release agent.

Flasks for the casting of match plate pattern molds are bottomless boxes. They differ from flasks for conventional plaster mold casting in two respects. First, standardization of flask size is seldom feasible in match plate pattern mold work because pattern sizes vary widely. However, standardization is less important because molds are not required in production quantities. Second, because the mold remains in the flask through the drying and metal-pouring operations, provision for matching the cope and drag sections must be incorporated into the flask rather than the pattern as in conventional operations. The use of guide pins for the matching of mold sections is illustrated in Fig. 6.

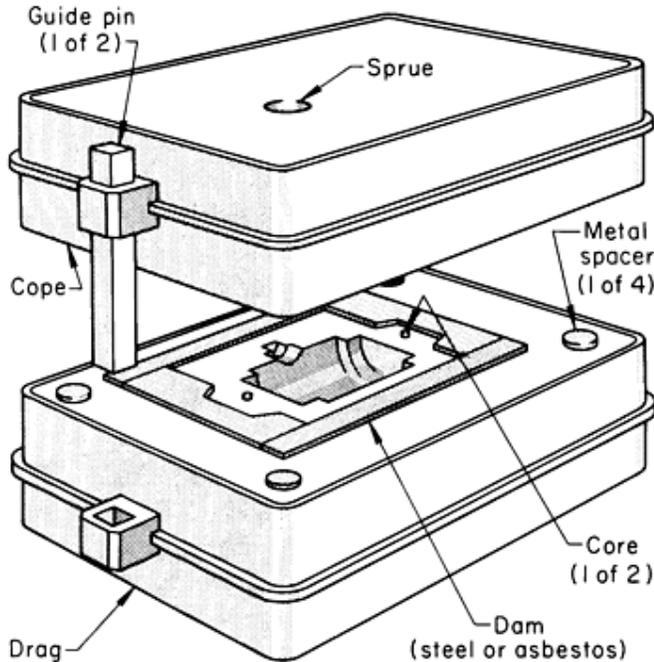


Fig. 6 Assembly details of a match plate mold

match plate mold at this stage is approximately the same as that of a conventional mold (1 to 2 AFS).

Mold Assembly. After the mold halves have reached room temperature, the cope and drag sections are matched as shown in Fig. 6. The assembly of a match plate mold is significantly different from that of a conventional plaster mold. Cores, if used, are positioned in the drag mold section. Cores are used if holes are required in the plate. Internal cores are used only in large match plate molds, so that the patterns will be lighter and can be handled more easily. Cores are made of sand.

In heavy sections, it is common practice to insert aluminum chills with nail-like protrusions into the plaster to make an internally cast chill. It is common to have 50 to 100 chills in a large mold with varying sections. The cope section, aligned by guide pins, is lowered onto the drag (Fig. 6). It is then raised for a distance equal to the desired thickness of the plate.

Mixing and Pouring the Slurry. Equipment and procedures for mixing the slurry and pouring it over the patterns are essentially the same as those for the conventional process (see Fig. 2 and accompanying text). Common practice is to make several vents in the mold with a nail or wire immediately after the slurry has been poured. The vents serve two purposes. Vent holes traversing the entire mold sections of dry molds provide openings for the escape of steam and other gases when the metal is poured. Through-vents in wet molds facilitate the separation of mold halves and the removal of patterns by acting as channels for the injection of compressed air.

Set Time. A slurry will set in 20 to 35 min. After the slurry sets, the patterns are removed, and the molds are dried.

Drying. Molds for match plate patterns, like molds for conventional plaster castings, should be dried as soon as possible after the plaster has set. High-temperature drying cannot be used for match plate molds, because it results in unacceptable distortion and size change. Match plate molds are usually dried at 120 to 205 °C (250 to 400 °F) for 12 to 72 h. Size and section thickness of the molds determine the length of time in the drying ovens. The center of the thickest section of the mold should reach at least 105 °C (220 °F) before drying is stopped. The permeability of a

Metal spacers of this thickness are inserted at each corner, and dams of steel or Fiberfrax are placed so as to form the desired outer contour of the plate (Fig. 6). When the metal is poured, it flows outward in the space between the cope and drag sections and forms the plate portion of the match plate pattern.

**Metals Used.** Match plate patterns are cast from aluminum alloys, most frequently Alloys 355 and 356. One foundry using a blend of equal quantities of 356 and 319 reported greater ductility and better machinability than could be obtained if either alloy were used alone. Ductility is important in making match plate patterns because the patterns often require straightening.

**Pouring Practice.** Because of the low permeability of a match plate mold, some assistance is required to fill the mold quickly and completely. Pressure assist is used rather than vacuum, partially because pressure equipment is more adaptable to a wider variety of flask sizes than vacuum equipment is. However, some foundries use a combination of pressure and vacuum assist.

The equipment for pressure casting is illustrated in Fig. 7. The first step in its use is to place a diaphragm of sheet Fiberfrax (about 3.2 mm, or  $\frac{1}{8}$  in., thick) over the sprue in the mold. A ceramic-lined cylinder is then placed on the diaphragm, as shown in Fig. 7. A predetermined amount of metal is poured into the cylinder, and a cap is placed on the cylinder and clamped tight. The cap is attached to a source of compressed air. After the cap has been secured in position, the air valve is opened. Air pressure against the molten metal ruptures the Fiberfrax diaphragm and forces the metal into the mold cavity. A pressure of 10 to 17 kPa ( $1\frac{1}{2}$  to  $2\frac{1}{2}$  psi) is kept on the sprue for about 30 min.

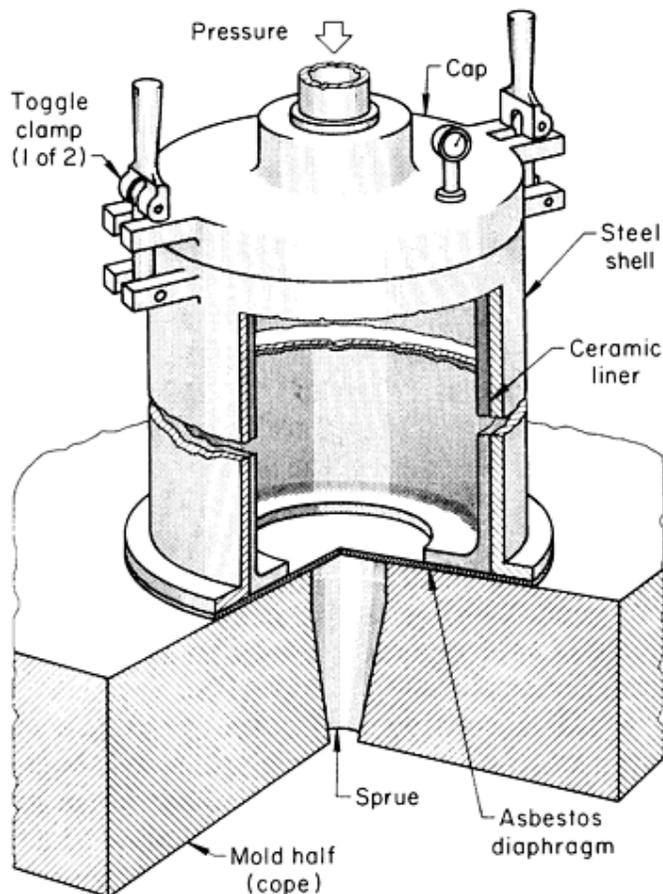


Fig. 7 Cylinder used for pouring a casting with pressure assist during processing.

## The Antioch Process

The Antioch process (U.S. Patent 2,220,703) was developed to overcome the principal limitations of conventional plaster molds and cores without sacrificing the advantages of the plaster mold process. If undried molds are partially dehydrated and then allowed to rehydrate without being disturbed, gypsum crystals slowly recrystallize into granules about the size of sand grains, and the mold acquires a porous structure of relatively high permeability. Permeability is held within a range of 15 to 30 AFS; the permeability of conventional plaster molds is 1 to 2 AFS. Recrystallization does not take place at the surface of the mold, because not enough water is present. Therefore, the surface remains smooth.

In addition to the greater permeability developed by the dehydration-rehydration process, the molds produced have greater heat capacity than conventional plaster molds because they are composed of approximately 50% sand. Figure 1 shows that the freezing time for a casting in an Antioch process mold is only about 20% longer than the freezing time for an identical casting in a lightly rammed green sand mold and is less than half the time required for a casting in a conventional plaster mold.

Unlike conventional molds, Antioch process molds do not shrink. In fact, they expand slightly--from 0.001 to 0.0025 mm/mm (0.001 to 0.0025 in./in.)--

Because of their porous structure, the molds have low dry strength. This characteristic, in promoting early collapse of cores as the casting cools, minimizes hot tears in the castings. For very large molds, the low dry strength sometimes necessitates the use of internal reinforcement, which is achieved with hardware cloth or core rods such as those used in making sand cores. When possible, reinforcement is avoided because of the difference in expansion between the reinforcing metal and the molding material.

After setting, but before the dehydration-rehydration treatment, Antioch process molds have relatively high green strength. When flexible rubber patterns are used, this high green strength permits the withdrawal of patterns having a severe back draft without damage to the mold. This makes the Antioch process particularly well suited to the production of molds for parts having angular, bladelike sections--rotor sand nozzles, for example.

In addition to the cost, which is high for all plaster molds, the major disadvantage of Antioch process molds is the long processing time required to make the mold. This occupies expensive equipment for long periods.

Mold and Core Materials. The dry mixture for Antioch process molds and cores consists of silica sand, white molding plaster, talc No. 2, and a small amount of material (such as portland cement) for expansion control. The typical mixture given in Table 1 varies somewhat among different foundries. However, once a formulation has been established in a specific foundry, it is retained for all castings, regardless of their size and shape. Optimum results are obtained by weighing all ingredients accurately. Only by consistent use of a specific formulation is it possible to obtain maximum reproducibility.

**Table 1 Typical composition of dry material for Antioch process molds**

Ingredient	Weight	
	kg	lb
Washed silica sand (AFS 50 is typical)	20.4	<b>45</b>
White molding plaster	18.6	<b>41</b>
Talc No. 2	3.6	<b>8.0</b>
Portland cement	0.2	<b>0.4</b>
Sodium silicate	0.4	<b>0.8</b>
Western bentonite	1.1	<b>2.5</b>
<b>Terra alba</b>	<b>1.5</b>	<b>3.4</b>

Processing. The sequence of operations for producing Antioch process molds is given below:

- Mix dry ingredients
- Add dry ingredients to water
- Soak (1 to 3 min)
- Mix (2 to 4 min)
- Coat patterns (or core boxes)

- Pour slurry
- Set at room temperature (15 to 20 min)
- Remove pattern
- Dehydrate in autoclave (6 to 12 h)
- Rehydrate in air (14 h)
- Dry molds (or cores)
- Assemble cores and mold halves

The set time for a slurry formulated from a composition such as that shown in Table 1 will be approximately 15 to 20 min. Set time can be decreased by adding up to 3% terra alba and heating the water. For example, the minimum set time of 6 to 7 min is achieved by adding 3% terra alba and using water at 32 °C (90 °F). The temperature and humidity of the surrounding atmosphere have very little influence on set time, although an atmospheric temperature of 21 to 27 °C (70 to 80 °F) is preferred.

Dehydration. The time between setting of the slurry and the beginning of the dehydration cycle is not extremely critical if steps are taken to prevent the mold from drying out. If the set molds are covered with damp cloths, they can be held overnight, or sometimes even over a weekend, without a significant impact on subsequent dehydration. If the molds are placed in humidity cabinets, they can be stored for longer periods before dehydrating. However, the dehydration cycle should begin soon after the pattern is removed if the mold cannot be kept moist.

For dehydration, the molds are placed on suitable racks in a standard autoclave. The autoclave is sealed, and steam is admitted. The autoclave is operated with a steam pressure of 105 kPa (15 psi) for 6 to 8 h. For extremely large molds, it is operated for 12 h. The autoclave is then opened, and the molds are removed.

Rehydration. The mold is permitted to remain at room temperature for 14 h. After rehydration, the mold is ready for drying.

Drying temperature ranges from 175 to 230 °C (350 to 450 °F), and drying time from 1 to 70 h. Drying time depends mainly on the size of the mold and the temperature used. The center of the mold must reach a temperature of at least 120 °C (250 °F). This can be accomplished considerably more quickly at an oven temperature of 230 °C (450 °F) than at 175 °C (350 °F).

Regardless of the cycle used, it is important that the same cycle be used for all molds of the same size. Maximum reproducibility (of dimensions, in particular) can be achieved only through close control of the cycle.

Mold assembly is essentially the same as that described for conventional plaster molds. After the molds have cooled to room temperature, cores (if used) are placed in the drag, and the cope is placed over the drag and core assembly. Matching is done by means of locating pins. The pins used for matching Antioch process molds are usually 13 to 19 mm ( $\frac{1}{2}$  to  $\frac{3}{4}$  in.) in diameter. Even when molds are permitted to remain in their flasks, guide pins on the sides of the flasks are seldom used for matching.

Metals Cast. All of the aluminum alloys that can be cast in other types of plaster molds can be cast in Antioch process molds. Most copper-base alloys can be cast in Antioch process molds. Yellow brass is the copper alloy most often cast. The Antioch process is seldom used for alloys that must be poured at temperatures above about 1040 °C (1900 °F).

Pouring Practice. It is generally possible to pour castings in Antioch process molds by gravity, using gating systems that are similar to those used for sand molding. Molds are usually at room temperature when pouring begins. Vacuum assist can be applied when difficulty is encountered in replicating fine detail or when thin sections have not filled properly. The technique is generally the same as that for pouring conventional molds with vacuum assist.

## Foamed Plaster Molding Process

The foamed plaster process offers a means of achieving greater mold permeability than can be obtained in conventional plaster molds and at much improved dry strength over Antioch plaster molds. This gain is achieved by adding a foaming

agent, such as alkyl aryl sulfonate, either to the dry ingredients before mixing or to the liquid slurry, as a separately generated foam mix. A special method of mixing foams the slurry with many fine air bubbles, thus decreasing the density and increasing the volume of the slurry. In general, with regard to the composition of the metal poured, casting size, and casting shape, the applicability of foamed plaster molds is the same as that of plaster molds made by other procedures.

**Characteristics.** Foamed plaster molds have smooth surfaces with air cells just below the surface. During setting and subsequent drying of the molds, these air cells become interconnected, thus permitting the escape of gases as the metal is poured. The permeability of a foamed plaster mold depends mainly on the volume increase from the addition of air when the slurry is mixed. For most molds, a volume increase of 50 to 100% is recommended. This increase usually results in a mold permeability of approximately 15 to 30 AFS for dried molds.

Equipment for mixing will vary somewhat with the slurry used. The type described below has proved suitable for mixing a proprietary dry mixture with water.

The mixer must be capable of beating air into the slurry and producing air cells no larger than about 0.25 mm (0.01 in.) in diameter. Large air cells are not permitted, because they break under pressure from molten metal, resulting in casting defects. Proper mixing can be accomplished with several types of mixers. Regardless of the type of mixer used, the greater the power input, the finer the mold structure (the smaller the air cells) and the smoother the surface of the mold.

The bucket should be similar to that shown in Fig. 2, but the mixing device is a round, two-ply, 3 mm thick ( $\frac{1}{8}$  in. thick) rubber disk (which can be made from 3 mm, or  $\frac{1}{8}$  in., two-ply rubber belting) attached to a shaft, as shown in Fig. 8. The diameter of the shaft is not critical. Other mixer designs that are successfully used for mixing air into foamed plaster incorporate a 127 to 152 mm (5 to 6 in.) diam perforated disk mounted on a shaft that is tilted slightly from normal.

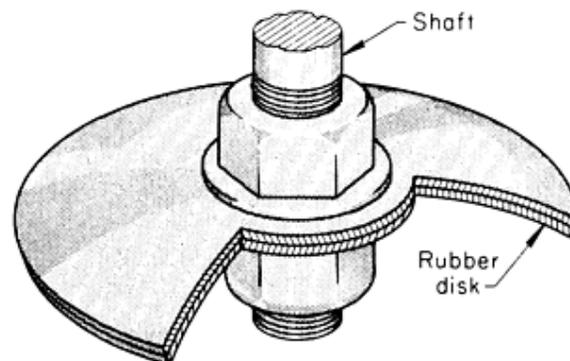


Fig. 8 Two-ply rubber disk attached to shaft for the high-speed mixing of foamed plaster slurries

**Processing.** The following sequence of operations is typical of the routing required to produce a component by the foamed plaster molding process:

- Mix foamed plaster dry mix with 32 to 43 °C (90 to 110 °F) soft water to a consistency of 80 to 100 AFS. The mixer used should have two speeds: a high speed (~1750 rpm) to mix the dry material and water thoroughly and a slower speed (~800 to 1000 rpm) to beat air into the slurry and to obtain a smooth, creamy slurry. Mixing time is varied to obtain 100% volume increase
- Pour slurry
- Set time varies from 20 to 40 min. Set time is a function of water temperature, mixing time (high speed), dry material setting characteristics, and consistency. Changes in variables to decrease set time also serve to decrease working time
- Strip patterns
- Dry in standard type dryers at temperatures from 175 to 260 °C (350 to 500 °F) for 8 to 16 h depending

on mold size. Foam plaster is very insulating, and thermal gradients can set up dimensional change, thus causing mold cracking. Avoid conditions that will cause thermal shock at mold temperatures above 120 °C (250 °F)

- Assemble and cast; molds can be poured from room temperature up to the dryer temperature

Metals Cast. For the most part, all aluminum alloys can be cast, but the aluminum-magnesium alloys are the most compatible.

Pouring Practice. All conventional foundry pouring techniques are applicable to foamed plaster molds. The insulating qualities of foamed plaster make it very suitable as a riser insulation material.

Ceramic Molding

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## Introduction

CERAMIC MOLDING techniques are based on proprietary processes (two of which are discussed in this article) that employ permanent patterns and fine-grain zircon and calcined, high-alumina mullite slurries for molding. Except for distribution of grain size, the zircon slurries are comparable in composition to those used in ceramic shell investment molding (see the article "Investment Casting" in this Volume). Like investment molds, ceramic molds are expendable. However, unlike the monolithic molds obtained in investment molding, ceramic molds consist of a cope and a drag or, if the casting shape permits, a drag only.

Both investment molding and ceramic molding can produce castings with fine detail, smooth surfaces, and a high degree of dimensional accuracy. The ceramic mold surface has refractory properties that enable it to withstand high metal pouring temperatures (such as those necessary for steel and heat-resistant alloys), give it excellent thermal stability, and do not permit burn-in.

## Applications

Ceramic molding has two principal applications. The first is the production of precision castings that require patterns too large and unwieldy for molding with expendable wax or plastic patterns. The second principal application is the production of castings in limited quantities for which permanent wood patterns may be more economical and require less lead time to make than the metal pattern dies required for molding wax or plastic patterns.

Ceramic molding is intended for the production of castings of high quality, not only in terms of their dimensional accuracy and surface finish but also in terms of soundness and freedom from nonmetallic inclusions. In general, the capabilities of ceramic shell investment molding and ceramic molding are similar, and the selection of one process over the other is largely dependent on the size of the casting, the quantities required, and the molding costs involved. In some applications, depending on casting shape, permanent patterns used in ceramic molding may provide greater dimensional accuracy than wax patterns, primarily because wax expands during melt-out. Permanent patterns are also less susceptible to damage and distortion in handling than wax or plastic patterns.

The principal disadvantage of ceramic molding in its early stages of development was the high cost of the molding materials. These materials were used in large quantities for making the slurry for all-ceramic molds and could not be reclaimed. This disadvantage was greatly diminished by the development of less expensive, composite ceramic molds, in which chamotte (an aluminous fireclay) serves as a backup for a ceramic facing, thus greatly decreasing the amount of binder and zircon or mullite required. Furthermore, as much as 80 to 90% of the backup molding material can be reclaimed.

Suitable Work Metals. Both ferrous and nonferrous alloys are cast in ceramic molds, but ferrous applications are more numerous and account for the major tonnage of castings produced. Alloys of aluminum, copper (especially beryllium copper), nickel, and titanium are nonferrous alloys that are suitable for ceramic mold casting; suitable ferrous alloys include ductile iron, carbon and low-alloy steels, stainless steels, and tool steels.

Types of Parts Cast. The range of products cast in ceramic molds is closely related to the alloy used. For example, among the products cast from tool steels (especially H12, H13, and A2) are forging dies and punches; trimming dies; die inserts; dies for hot upsetting; extrusion bridges, spiders, and cups; and inserts for die casting dies. Products cast from stainless steel include food-machinery components; valves for the chemical, pharmaceutical, and petroleum industries; glass molds; aircraft structural components; and hardware for atomic reactors and aerospace vehicles. Typical copper alloy castings include food-machinery parts, marine hardware, and decorative trim items used in architectural applications.

Complex castings with thin sections ( $\leq 1.6$  mm, or  $\frac{1}{16}$  in.) can be cast in ceramic molds, using special techniques. Casting surfaces have excellent smoothness--usually  $3.2 \mu\text{m}$  ( $125 \mu\text{in.}$ ) or better.

Dimensional accuracy depends primarily on the accuracy of the pattern. Metal contraction can normally be predicted closely enough to provide castings within the following tolerances:

- $\pm 0.08$  mm ( $\pm 0.003$  in.) on dimensions up to 25 mm (1 in.)
- $\pm 0.13$  mm ( $\pm 0.005$  in.) on dimensions over 25 to 75 mm (1 to 3 in.)
- $\pm 0.38$  mm ( $\pm 0.015$  in.) on dimensions over 75 to 203 mm (3 to 8 in.)
- $\pm 0.76$  mm ( $\pm 0.030$  in.) on dimensions over 203 to 381 mm (8 to 15 in.)
- $\pm 1.14$  mm ( $\pm 0.045$  in.) on dimensions over 381 mm (15 in.)

For dimensions across the parting line, an additional tolerance of  $\pm 0.25$  to  $\pm 0.51$  ( $\pm 0.010$  to  $\pm 0.020$  in.) must be provided.

Closer tolerances are readily obtainable by reworking the pattern after a test casting has been compared dimensionally with the pattern. Reproducibility is excellent; once the pattern has been established, subsequent castings will be extremely consistent throughout the life of the pattern.

## Shaw Process

The Shaw process relates to two distinctly different types of ceramic molds: a one-piece all-ceramic mold and a composite ceramic mold consisting of an inexpensive fireclay backup material with a relatively thin facing of ceramic slurry. Selection of mold type depends almost exclusively on the size of the casting and the cost of the mold material. Many small castings can be produced economically in one-piece all-ceramic molds, because the amount of expensive ceramic slurry needed for the mold is moderate and the additional pattern and labor costs for composite molding cannot be justified.

Patterns. Two sets of patterns are commonly required for the production of composite molds: a set of oversize preform patterns for molding the coarse backup material and a second set of patterns, representative of the dimensional accuracy desired in the casting, for molding the ceramic facing. Thus, for cope and drag molding, a total of four patterns may be required.

The preform patterns are made 2.4 to 9.5 mm ( $\frac{3}{32}$  to  $\frac{3}{8}$  in.) oversize to allow for the thickness of the ceramic facing. In

some applications, the preform pattern can be eliminated by using the final pattern, backed with a sheet of plastic, cardboard, or felt of suitable thickness, to mold the preform impression in the coarse fireclay backup. Because solid ceramic molds are made without backup material, only the final patterns are required for molding.

The pattern materials used for ceramic molding are conventional: wood, epoxy, aluminum, brass, tool steel, and cast iron. Wood, epoxy, and aluminum are most widely used. Prior to use, wood patterns are coated with a sealant that will not dissolve in alcohol.

To ensure a high degree of accuracy in the alignment of cope and drag, by mechanically meshing certain surfaces, it is common practice in ceramic molding to incorporate parting blocks and locators in the cope and drag halves of patterns. These are molded into both the backup and the ceramic facing, together with the casting contours.

Preparing the Backup. The backup refractory commonly consists of a coarse-grain chamotte (an aluminous fireclay that has been calcined at a high temperature) and a sodium silicate binder. A typical screen analysis for the chamotte is as follows:

Mesh	Cumulative percentage
6	Trace
8	5-9
12	27-41
16	60-68
30	94
70	99

The refractory and binder are mixed in a muller or an auger to the desired consistency and are rammed or vibrated over a pattern assembly. The pattern assembly consists of a preform pattern (or a final pattern covered with a suitable spacer material) mounted on a molding board and carefully located in a conventional flask, together with the required sprues. Before use, the preform pattern and other elements of the pattern assembly are coated or sprayed with a wax-silicone mixture to facilitate parting.

Carbon dioxide gas is diffused into the mold material for hardening. One method of doing this consists of piercing the mold material in several locations with small-diameter rods, thus creating channels into which the gas can be introduced. More uniform gassing can be accomplished in a vacuum chamber. After the gassing and hardening operation, the preform pattern is removed from the mold.

Preparing the Ceramic Facing. The principal ingredient of the ceramic facing is usually finely pulverized zircon, calcined mullite, or a mixture of both, although fused silica, magnesium oxide, and other refractory flours have also been used. Typical screen analyses for two calcined mullite flours are:

Mullite flour	Cumulative % on mesh size of:		
	100	200	325
A	3	35-65 <sup>(a)</sup>	...

A typical slurry contains a mixture of 75% zircon and 25% calcined mullite combined with a hydrolyzed ethyl silicate binder in proportions of approximately 0.91 kg (2 lb) of refractory blend to 100 mL (3.4 oz) of binder. To this mixture is added a small amount of gelling agent, which causes the slurry to set in a predetermined period of time, usually 3 to 4 min. Immediately after this addition, the slurry is ready for pouring.

Pouring the slurry over the pattern is always a gravity operation. However, when pattern detail is critical, the pattern and slurry are placed in a vacuum chamber, where the ungelled slurry is vacuumed to remove entrapped air bubbles.

Immediately prior to use, the final pattern is coated with a wax-silicone mixture to facilitate parting, and the backup mold is placed over it. The slurry is poured through pouring gates until the level rises to invest the final pattern. In a few minutes, the chemical gelling action is complete, leaving the green ceramic with a consistency like that of vulcanized rubber, and the pattern is stripped from the mold. The rubberlike consistency is critical because it facilitates the separation of molds from patterns that have no

(a) Remainder passes through this mesh size.

draft, straight sides, extremely fine detail, protruding pins, or holes. Stripping is sometimes done mechanically to ensure that withdrawal of the pattern will not damage the mold. Removal of the pattern does not cause the mold to expand or contract. After stripping, the mold is ready for burn-off.

All-Ceramic Mold Casting. An unbacked, all-ceramic mold is made entirely from slurry of the type used for facing a composite ceramic mold. The procedure for pouring an all-ceramic mold is shown in Fig. 1. The pattern, affixed to a flat plate, is surrounded by a flask, into which the ceramic slurry is poured. After the chemical gelling action is complete, the green mold is stripped from the pattern, and the flask, which is built with a small amount of draft, is removed from the mold. The mold is then ready for burn-off.

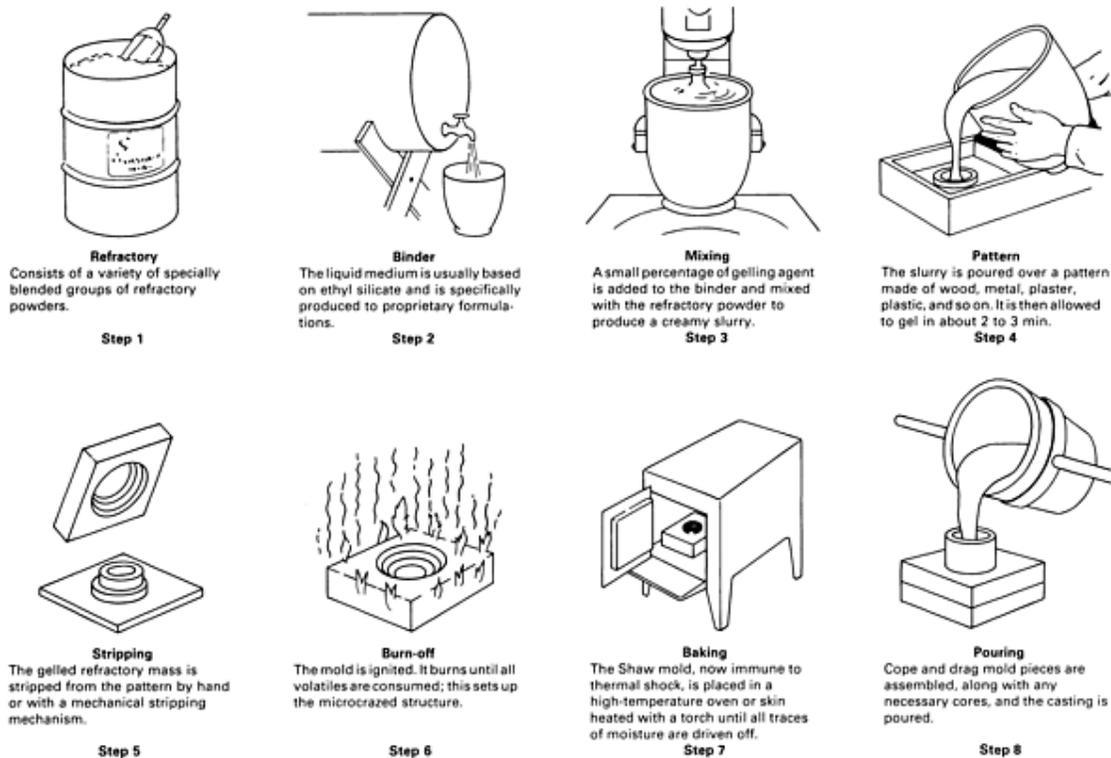


Fig. 1 Sequence of operations used in the Shaw all-ceramic mold process.

*Burn-off (Mold Stabilization)*. After gelling, the ceramic mold or mold facing is ignited with a torch and burns until most volatiles are consumed. During burn-off, the ceramic develops a microcrazed pattern, which is a three-dimensional network of microscopic cracks induced by the rapid evaporation of the alcohol in the slurry and by solid-phase reactions. Microcrazing is characterized by jagged ceramic particles separated by minute fissures or air gaps. These fissures are small enough to prevent molten metal from penetrating the mold surface, but they are large enough to permit the venting of air and other gases and to accommodate the expansion of the ceramic particles when they are in contact with the molten metal. Thus, microcrazing is advantageous in promoting dimensional stability without detracting from surface finish (see the section "Mold Stabilization" in this article).

*Baking* is the final stage of processing. All remaining volatiles are removed, and the colloidal silica left by the hydrolyzed ethyl silicate binder forms a high-temperature bond of  $\text{SiO}_2$  that is stable nearly to its melting point (1710 °C, or 3110 °F), thus providing enough mold strength to resist washout, or erosion, by molten metal. To perform these functions satisfactorily, baking must be done at not less than 480 °C (900 °F). Baking composite molds at more than 650 °C (1200 °F) may cause a differential expansion between the facing and backup layers due to the contraction of the soda-rich silica bond in the backing material. This can produce distortion in the mold cavity. Nevertheless, some foundries bake composite molds at temperatures as high as 815 to 980 °C (1500 to 1800 °F) without harmful effects.

Two methods of baking are currently in use. In one method, termed skin heating, the mold is directly heated from above with electric or gas-torch heaters. This method has the advantage of fully curing the ceramic facing without overheating the backup material. It is a rapid technique, and it permits molds to be cured in conventional steel flasks.

Heating the molds in an electric or gas-fired furnace is the other method of baking. Furnace baking has the advantage of removing all moisture and volatiles from the backup material as well as from the facing, thus minimizing the risk of bleeding moisture from the backup to the facing after mold assembly. Such bleedback can produce surface defects in the casting.

The normal baking period for molds is 4 to 6 h at the prescribed baking temperature. After baking, molds are allowed to cool to an appropriate temperature for pouring.

*Pouring.* Before pouring, molds are usually checked for cleanliness and temperature. Mold temperature at the start of pouring ranges from 40 to 540 °C (100 to 1000 °F), depending on casting shape and the alloy being poured. Cope and drag halves are assembled, and a layer of cement is usually troweled on to seal the mold around the parting line. For safety, heavier molds are reinforced by fastening a steel band around the outside of the mold. This assists in handling of the mold and prevents seepage of hot metal in the event that the mold wall cracks during pouring. Finally, ceramic pouring tubes and exothermic or insulating riser sleeves are set up in the cope.

The mold is clamped firmly, and metal is poured either directly from the melting furnace or from a ladle. Pouring must proceed as rapidly as possible to avoid cold shuts and gas voids. After the metal has been poured, additional exothermic material is sprinkled on the risers to keep them fluid and to prevent shrinkage tears.

Composite Ceramic Mold. This type of mold is a sodium silicate/carbon dioxide cured and fired chamotte backing that significantly decreases the cost of refractory materials. A preform pattern and a finish pattern are needed to make composite molds (Fig. 2). Cope and drag preforms are made 2.4 mm ( $\frac{3}{32}$  in.) oversize on all mold cavity surfaces to allow for the thickness of the ceramic facing material.

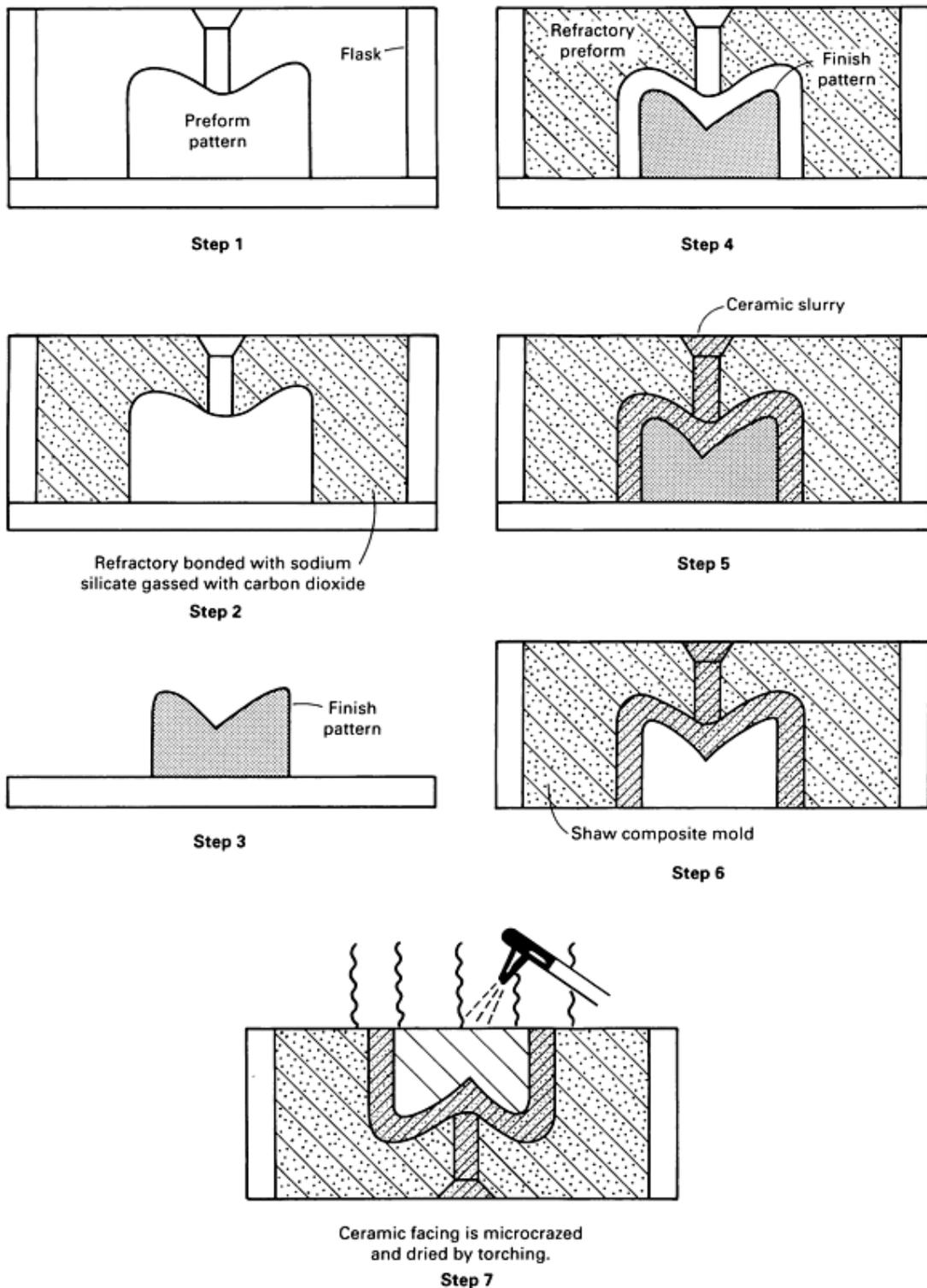


Fig. 2 Diagram of Shaw composite mold process. See text for details.

The cope and drag flasks must be accurately aligned, and at each stage of mold production, alignment holes are drilled and reamed to a jig. As a further safeguard, a sand strip is cast into the insides of the flasks to keep the hardened preforms from shifting during handling. Preform patterns are then mounted on a pin lift molding table. The flasks are aligned by dowel pins and the alignment holes on the table before they are fastened to the patterns by quick-acting clamps.

The sodium silicate refractory mixture contains a percentage of invert sugar, which aids shakeout of the mold after pouring. The refractory mixture is rammed around a preformed pattern (step 1, Fig. 2), and the rammed half mold is placed in a bell jar for 10 to 20 s, during which it is gassed with a commercial grade carbon dioxide (step 2). While the first preform is being gassed, the operator rams the second flask with the composite mixture. By this time, the first preform is hardened and is removed from the bell jar. The operator repeats the gassing procedure for the second preform. The gassed preform mold halves are then stripped from the preform patterns, and each hardened preform mold is aligned with the final pattern bolted to the molding table. The flasks are fastened to the patterns by the quick-acting clamps.

The Shaw ceramic slurry needed for the facing of the composite mold is virtually the same as that used for the solid body mold—a specially blended formula of refractory aggregates, ethyl silicate-base binder, and a gelling agent. The thick, creamy slurry is then poured into the gap between the final pattern and the hardened preform material (steps 3 to 6). The slurry not only fills all of the details of the mold cavity but also penetrates the aggregate voids of the surface of the porous backing, creating a strong mechanical bond.

Gelling of the slurry requires 2 to 3 min, and the fine ceramic facing of the composite mold is formed. The composite cope and drag are unclamped and lifted from the patterns by a foot-operated stripping plate. The molds are then placed on a conveyor for movement through a torching zone, where the volatiles are ignited and consumed (step 7). The microcrazed structure of the Shaw mold occurs during this burn-off period. The cope and drag molds are moved directly into a high-pressure torching zone for 5 to 10 min; in this zone, the molds are brought to incandescence. The copes and drags are assembled using the alignment pins to ensure accuracy. The molds can be assembled either hot or cold.

## Unicast Process

The Unicast process differs from the Shaw process principally in the method of mold stabilization employed. Mold stabilization refers to the treatment given the fine ceramic facing of a composite mold, or the total mass of an all-ceramic mold, shortly after it has set and while it is still green.

Advantages. The Unicast process provides accurate dimensional control, and warpage or distortion is almost entirely eliminated. As a result of the stabilized molecular growth, the mold develops a cellular or spongelike structure caused by the interstitial separation of particles. This structure provides for gas venting and particle expansion during casting. The advantages of this structure are metal soundness, ease of casting long, thin sections, and reductions in traditional mold venting. Molds can be poured hot or at room temperature without any change in thermal characteristics. Directional solidification of the cast alloy is fully controlled, resulting in high physical properties and outstanding metal soundness.

The major advantages of solid ceramic mold casting include the following:

- Only a short lead time is necessary due to simple tools and a fast mold build cycle
- A modest installation cost can be maintained using simple equipment
- The manufacturing cost is considerably lower than that of machining or other alternate methods
- Patterns are usually inexpensive and quickly prepared
- The die life of cast tooling is longer than that of dies made from wrought materials
- Cast tooling can frequently be used as-cast without further machining
- The process is suitable for impossible-to-machine grain and texture details for large injection mold bodies
- The process is feasible for casting sizes ranging from small to very large

Composite Mold. Another difference between the Shaw and Unicast processes relates to the sequence followed in preparing composite molds. In the Shaw process, preparation of the coarse mold backup precedes pouring of the fine ceramic facing. In the Unicast process, this sequence is reversed (see the section "Typical Process Sequence" in this article). The castings produced by the two processes are comparable in quality and surface finish, and several foundries are licensed to use both processes.

Although the Unicast process commonly uses a solid ceramic mold for smaller and short-run castings, it generally employs a composite-ceramic mold for large parts and for those produced in high volume. In this case, the Unicast

ceramic is used as a 6.4 to 13 mm ( $\frac{1}{4}$  to  $\frac{1}{2}$  in.) facing backed by a specially blended, coarse-sand aggregate for support.

This technique sharply reduces mold cost by conserving the ceramic material, and it permits the mechanized production of molds.

**Patterns and Flasks.** The Unicast process employs conventional pattern equipment throughout. The patterns must be of good quality because the slightest flaw or defect in the pattern will be reproduced on the final casting. The reproduction of detail is such that even fingermarks on a pattern coating are likely to be transferred to the casting. Most of the common pattern materials are used, including the denser hardwoods, plaster, aluminum, plastics, and hard rubber.

**Alloys Cast.** Alloys normally poured in Unicast molds are about evenly divided between ferrous and nonferrous. Of the ferrous alloys, about 60% are irons, and the rest are principally stainless steels and tool steels. Of the nonferrous alloys, about 30% are alloys of cobalt, titanium, or uranium, and about 20 to 30% are alloys of aluminum, magnesium, or zinc. The rest are principally copper alloys, with beryllium copper predominating.

**Slurries.** The fine ceramic slurries used in the Unicast process are comparable to those used in the Shaw process and consist of mixtures of a finely pulverized ceramic, such as zircon, and an organic gelling binder, such as hydrolyzed ethyl silicate. Accordingly, the chemical reactions that take place during gelation are the same as those in the Shaw process. Backup slurries, used in composite mold preparation, are coarse and less expensive ceramic grains mixed with a refractory binder that will harden in the presence of carbon dioxide.

Mold stabilization refers to the treatment given the fine ceramic slurry after it has gelled but while it is still green. The methods used for mold stabilization in the Shaw and Unicast processes are distinctly different, although the chemical reactions involving the binder are the same.

When the binder becomes a hard, rubbery gel, it consists of a liquid and a solid phase. The liquid phase is largely free alcohol, and the solid phase is a form of polysilicic acid. By itself, polysilicic acid is unstable and rapidly forms new chemical chains that are of larger mass than the original molecule. Molecular growth in the green state causes the suspended ceramic particles to move or separate, thus producing a pattern of microscopic cracks. Unless molecular growth is arrested in a short period of time, the cracks can become excessive and form macrocracks.

In the Shaw process, rapid evaporation of the alcohol resulting from hydrolysis or gelling reaction is accomplished immediately after (or very soon after) gelling by ignition or firing of the mold. This operation, referred to as burn-off, is usually performed by igniting the mold facing with a torch, as shown in Fig. 1. Burn-off follows removal of the pattern from the mold. It arrests excessive molecular growth, which may be catalyzed by moisture in the air or by other contaminants. This reaction must be avoided to ensure optimum binding properties and to avoid excessive cracking of the mold.

In the Unicast process, the gelled mold is immersed in a liquid hardening bath or vapor atmosphere that permits aging and internal stabilization of the mold. Various hardening media can be used, depending on the composition of the mold binder and the final curing step. Thus, commercial ethyl alcohol can be used with an ethyl silicate binder because the binder evolves ethyl alcohol as a result of the hydrolysis action.

Alternatively, the bath can be a liquid such as acetone, kerosene, benzene, or other hydrocarbon with which the evolved alcohol is readily miscible. The hardening bath is more reactive when hot; the heat provides good results even when the bath liquid is not chemically identical to the evolved alcohol. Even boiling water can be used; the temperature of the water drives the volatiles out of the mold to be dissolved in the water.

A typical aging period for the mold in the bath is 10 to 15 min. The aging reaction is enhanced when the pH of the hardening bath or atmosphere is maintained at a level somewhat higher than that of the mold and, preferably, on the alkaline side of neutral pH. Decreasing acidity serves to accelerate setting and gelation. Organic amines or other generally alkaline ammonium compounds can be added to the bath for this purpose.

The precise function of the hardening medium is not completely understood. Aging is enhanced when the gelled mold material is entirely immersed in a liquid or vapor that is substantially identical to the evolved alcohol, as compared to burn-off or to isolation of the mold surface from air by application of a wax or other suitable impermeable coating.

Final curing, which follows the hardening bath, is usually done in an oven maintained at about 980 °C (1800 °F), but direct flame heating can be used. The cured molds are then transferred to the melting station for pouring.

Typical Process Sequence. In a typical molding and casting sequence (Fig. 3), a pattern, mounted on a baseplate, is enclosed within a flask. A thin (4.8 to 9.5 mm, or  $\frac{3}{16}$  to  $\frac{3}{8}$  in.) coating of fine-grain ceramic slurry is applied to exposed pattern surfaces by spraying or similar means. The coating becomes tacky almost upon contact and is ready to receive backing material. An inexpensive, coarse backup slurry is poured rapidly over the facing coat until the flask is filled. The slurry is chemically controlled to set to a semirigid state within 2 to 3 min, at which time the upper surface of the mold is leveled with the flask edges with a striking tool. The flask is removed, and a vacuum clamping plate is placed in position on top of the mold. The entire assembly is inverted on a stripping machine, the pattern is stripped from the mold, and the clamping vacuum is released.

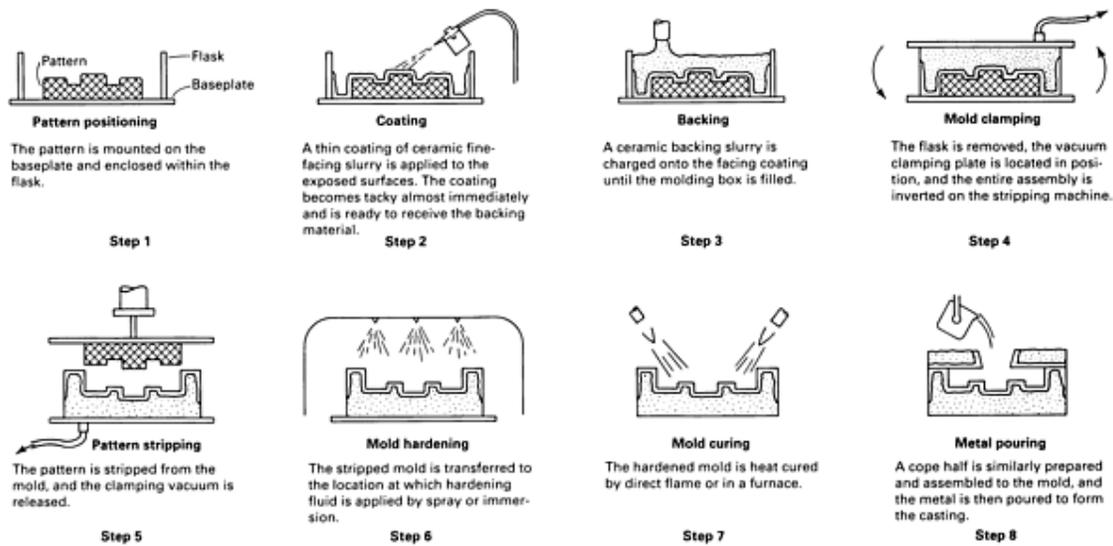


Fig. 3 Steps involved in producing a Unicast process casting

The stripped mold is transferred to the chemical hardening tank or chamber, where it is immersed in, or sprayed with, hardening fluid. It is then cured by heating with direct flame impingement or in a furnace.

## Introduction

IN INVESTMENT CASTING, a ceramic slurry is applied around a disposable pattern, usually wax, and allowed to harden to form a disposable casting mold. The term disposable means that the pattern is destroyed during its removal from the mold and that the mold is destroyed to recover the casting. Related processes, in which ceramic slurries are poured against permanent patterns to make cope and drag molds, are covered in the articles "Plaster Molding" and "Ceramic Molding" in this Volume.

There are two distinct processes for making investment casting molds: the solid investment (solid mold) process and the ceramic shell process. The ceramic shell process has become the predominant technique for engineering applications, displacing the solid investment process. By 1985, fewer than 20% of non-airfoil investment castings and practically no airfoil castings (the largest single application of investment casting) were being made by the solid investment process (Ref 1). Today the solid investment process is primarily used to produce dental and jewelry castings and has only a small role in engineering applications, mostly for nonferrous alloys. Because of its declining role and because it was discussed in the article "Molten Salt Bath Cleaning" in *Surface Engineering*, Volume 5 of the *ASM Handbook*, the solid investment process will not be covered in this article. Only the ceramic shell process will be described. The basic steps in this process are illustrated in Fig. 1.

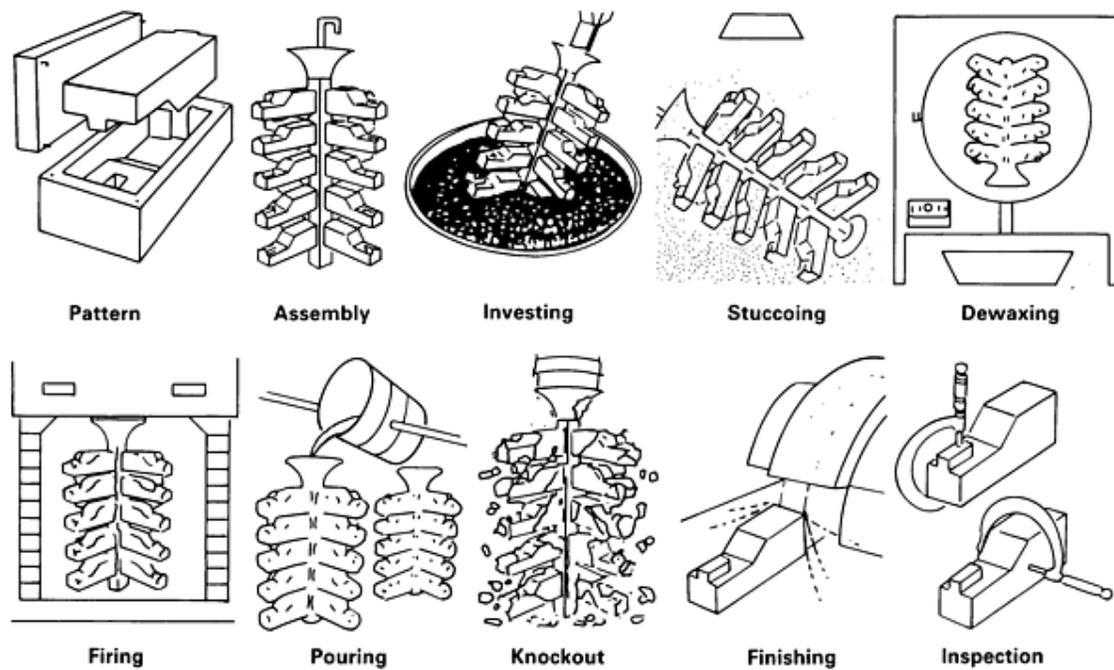


Fig. 1 Steps in the investment casting process.

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## Pattern Materials

Pattern materials for investment casting can be loosely grouped into waxes and plastics. Waxes are more commonly used. Plastic patterns (usually polystyrene) are frequently used in conjunction with relatively thin ceramic shell molds in a process known as Replicast CS (see the article "Replicast Process" in this Volume).

### Waxes

Wax is the preferred base material for most investment casting patterns, but blends containing only waxes are seldom used. Waxes are usually modified to improve their properties through the addition of such materials as resins, plastics, fillers, plasticizers, antioxidants, and dyes (Ref 2).

The most widely used waxes for patterns are paraffins and microcrystalline waxes. These two are often used in combination because their properties tend to be complementary. Paraffin waxes are available in closely controlled grades with melting points varying by 2.8 °C (5 °F) increments; melting points ranging from 52 to 68 °C (126 to 156 °F) are the most common. The low cost of these waxes, combined with their ready availability, convenient choice of grades, high lubricity, and low melt viscosity, accounts for their wide usage. However, applications are limited somewhat by their brittleness and high shrinkage. Grades designated fully refined should be selected for pattern waxes. Microcrystalline waxes tend to be highly plastic and lend toughness to wax blends. Hard, nontacky grades and soft, adhesive grades are available. Microcrystalline waxes are available with higher melting points than the paraffins and are often used in combination with paraffin.

Ozocerite is an imported mineral wax that can serve a similar function. Fisher-Tropsch waxes are synthetic hydrocarbon waxes resembling paraffins, but are available in grades that are much harder and higher melting. They improve hardness and rigidity and promote faster setup in pattern-making operations. Polyethylene waxes (of much lower molecular weight

than the usual polyethylene plastics) function in much the same manner as the Fisher-Tropsch waxes, but are available in even higher melting grades (to over 132 °C, or 270 °F).

Candelilla is an imported vegetable wax that is moderately hard and slightly tacky. It has relatively low thermal expansion and somewhat less solidification shrinkage than the hydrocarbon waxes. Candelilla is useful for hardening paraffin and raising its softening point. Unfortunately, it has been subject to shortages and wide price fluctuations.

Carnauba is another imported vegetable wax. It has a fairly high melting point (83 °C, or 181 °F) and a low coefficient of thermal expansion. Carnauba is very hard, nontacky, and brittle. It is rather costly, which tends to limit its use.

Beeswax is a natural insect wax that melts at approximately 64 °C (147 °F). It is widely used for modeling and is also useful in pattern blends, contributing some of the same characteristics as comparable microcrystalline waxes. It is believed to be the original wax used for lost wax casting, but today its use is limited by its cost relative to other waxes.

Palmitic and stearic acids are fatty acids that have good wax properties. They have low viscosity when melted, relatively low thermal expansion in the solid state, relatively low solidification shrinkage, and good compatibility with a wide range of materials. Still other waxes that have been used are montan wax (both acid and ester types), fatty acid amides, ceresin, stearone, and hydrogenated castor oil.

The waxes listed represent those most commonly used for pattern blends. Of these, the paraffins and microcrystalline waxes are the most popular. Many other waxes are available and are at least potentially useful. In many cases, a particular wax is not used simply because a less expensive wax offers similar properties.

Waxes are reasonably priced, yet they provide a good balance of properties not readily obtainable in other materials. They are easily blended to suit different requirements and are compatible with other materials that can improve their properties still further. Their low melting points and low melt viscosities make them easy to compound, inject, assemble into clusters, and melt out without cracking the thin ceramic shell molds. These properties allow waxes to be injected at low temperatures and pressures, and this, combined with their lack of abrasiveness, leads to lower tooling costs.

Additives. Plain waxes possess many useful properties, but there are two important areas in which they are deficient:

- Strength and rigidity, especially where very fragile patterns need to be made
- Dimensional control, especially with regard to surface cavitation resulting from solidification shrinkage during and after pattern injection

Improvements can be made in these areas with nonwaxy additives.

The strength and toughness of waxes are improved by the addition of well-known high molecular weight plastics such as polyethylene, ethyl cellulose, nylon, ethylene vinyl acetate, and ethylene vinyl acrylate. These materials are highly viscous at wax-working temperatures, which tends to limit the amounts that can be used.

Nevertheless, these amounts are sufficient to make significant improvements in the handling characteristics of patterns and clusters. Polyethylene is widely used because it is economical and compatible with a wide spectrum of waxes. Ethyl cellulose has had some use, but it is much more limited in terms of compatibility and is more expensive. Polystyrene is rarely used because of its incompatibility with the commonly used waxes. Ethylene vinyl acetate and ethylene vinyl acrylate are newer materials that are finding increased application. Nylon has had only small usage.

Solidification shrinkage, which causes surface cavitation, is reduced somewhat by the plastics mentioned above. The effect, however, is limited by the low amounts that can be used before viscosity becomes excessive. Greater effects can be obtained by adding resins and fillers. Resins are used in most present-day pattern waxes. Fillers are used more selectively, and this leads to the description of pattern waxes as being either filled or unfilled.

The resins used for shrinkage reduction are of lower molecular weight than the plastics used for toughening\*. The most useful resins soften gradually and continuously with increasing temperature, and they do not exhibit the large solid-to-liquid expansions during heating, or the reverse contractions during cooling, that characterize the solid-to-liquid

transformation in waxes. Thus, resins reduce this effect in direct proportion to the amount used. The amount used can be quite large because resins yield relatively low viscosity melts at wax-processing temperatures.

Suitable resins include the numerous rosin derivatives (esterified, polymerized, hydrogenated, and dehydrogenated) as well as such tree-derived resins as Burgundy Pitch, dammar, and the terpene resins. Additional resins include coumarone-indene, various hydrocarbon resins from petroleum, and a number of coal tar resins. The resins listed encompass a wide range of softening points and viscosity-versus-temperature relationships. They vary at room temperature from soft and tacky to hard and brittle, and they may have widely different compatibilities with particular waxes and plastics. All these factors must be considered and properly balanced in using resins in pattern waxes.

**Fillers.** The solidification shrinkage of waxes can also be reduced by mixing in powdered solid materials called fillers. These are insoluble in, and higher melting than, the base wax, and they produce an injectable suspension when the mixture is molten.

Because they do not melt, fillers do not contribute to the solidification shrinkage of the mixture, which is reduced in proportion to the amount used. Figure 2 shows the manner in which fillers reduce expansion during heating (as well as corresponding shrinkage upon cooling). Fillers that have been used in pattern waxes include polystyrene, various dicarboxamides and related compounds, isophthalic acid, pentaerythritol, and hexamethylenetetramine. The filler should preferably be in the form of small, equally sized spheres (Ref 5). Several such fillers have been developed, including spherical polystyrene, hollow carbon microspheres, and spherical particles of thermosetting plastic. In a variation of the filler concept, water has been emulsified into molten wax to serve the same function as the solid fillers (Ref 6). This type of wax is commercially available.

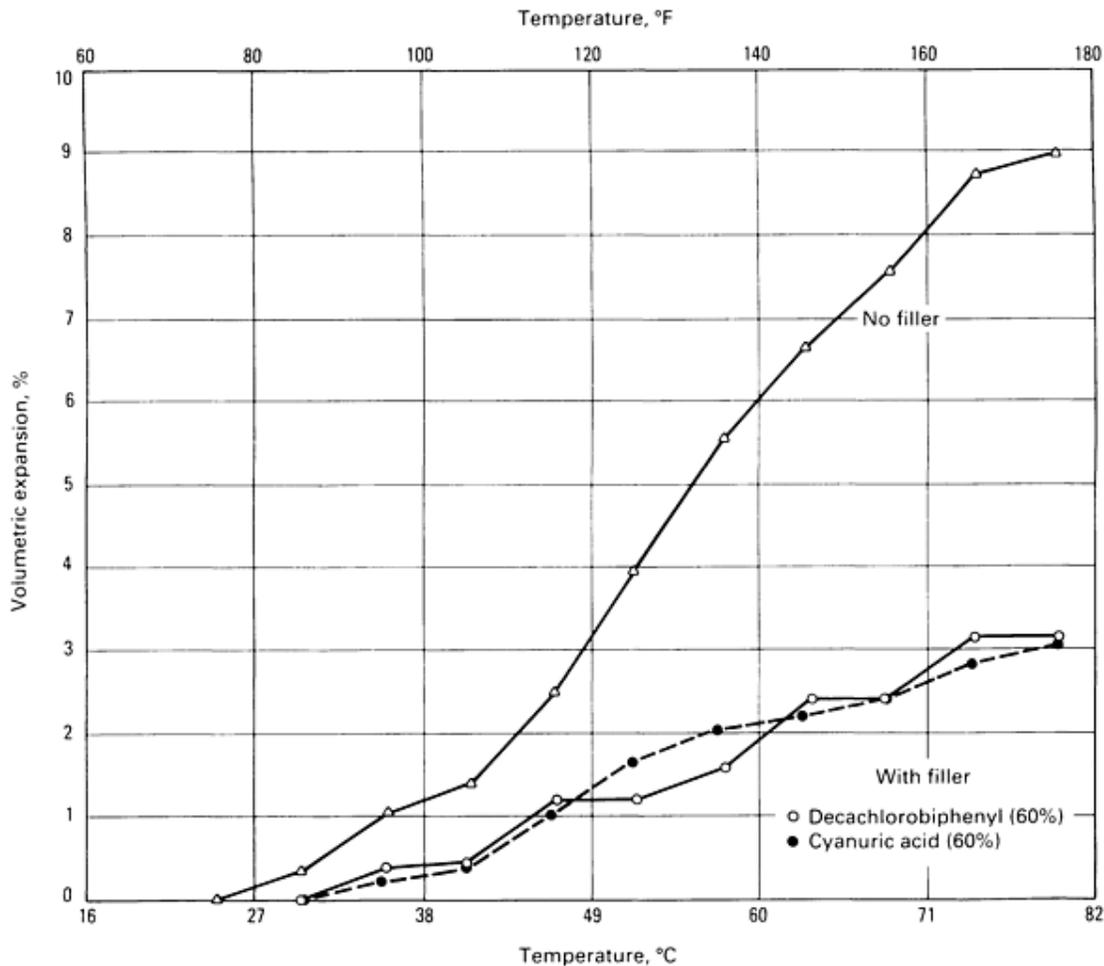


Fig. 2 Effects of filler materials on the volumetric thermal expansion of a pattern wax. Source: Ref 3, 4.

Several other additives can be used in pattern waxes. Colors in the form of oil-soluble dyes are used to enhance appearance, to provide identification, and to facilitate inspection of molded patterns. Antioxidants can be used to protect waxes and resins subject to thermal deterioration. Oils and plasticizers have been used to alter injection properties and, in certain cases, to reduce shrinkage.

As a result of the above considerations, the compositions of present-day pattern waxes (unfilled) typically fall into the ranges given below:

<b>Ingredients</b>	<b>Composition, %</b>
Waxes (usually more than one)	<b>30-70</b>
Resins (one or two)	<b>20-60</b>
Plastic (one)	<b>0-20</b>
<b>Other</b>	<b>0-5</b>

Filled waxes usually have similar base materials, with 15 to 45% filler added.

**Wax Selection.** In formulating wax pattern materials, a number of processing areas and other concerns must be addressed. These are listed below, along with the properties or considerations appropriate to each:

- *Injection:* Softening point, freezing range, rheological properties, ability to duplicate detail, surface, and setup time
- *Removal, handling, and assembly:* Lubricity, strength, hardness, rigidity, impact resistance, stability, and weldability
- *Dimensional control:* Thermal expansion/shrinkage, solidification shrinkage, cavitation tendency, distortion, and stability
- *Mold making:* Strength, wettability, and resistance to binders and solvents
- *Mold dewaxing and burnout:* Softening point, viscosity, thermal expansion, thermal diffusivity, and ash content
- *Miscellaneous:* Cost, availability, ease of recycling, toxicity, and environmental factors

Assistance in formulating pattern waxes can be found in Ref 2, 7, and 8. Reference 8 provides an extensive listing of pattern ingredients and their properties. A number of standard tests are available to facilitate the effort (Ref 9, 10, 11). The application of thermal analysis methods to wax testing is being investigated (Ref 7, 12), and this approach warrants extension for both control and development work. The Investment Casting Institute has provided a test die for evaluating waxes and wax injection presses (Ref 13, 14). No simple laboratory tests are available that can evaluate the suitability of a pattern wax. The best approach usually consists of laboratory tests for screening purposes combined with practical evaluation under such productionlike conditions as injection behavior, handling characteristics, dimensional consistency, and dewaxability.

## Plastics

Next to wax, plastic is the most widely used pattern material. A general-purpose grade of polystyrene is usually used.

The principal advantages of polystyrene and other plastics are their ability to be molded at high production rates on automatic equipment and their resistance to handling damage even in extremely thin sections. In addition, because polystyrene is very economical and very stable, patterns can be stored indefinitely without deterioration. Most wax patterns deteriorate with age and eventually must be discarded.

A disadvantage that limits the use of polystyrene is its tendency to cause mold cracking during pattern removal, a condition that is worse with ceramic shell molds than with solid investment molds. Other common plastics, such as polyethylene, nylon, ethyl cellulose, and cellulose acetate, are similar in this regard. In addition, tooling and injection equipment for polystyrene is more expensive than for wax. As a result, polystyrene finds only limited use. A recent survey of 72 investment casting plants in the United States revealed that fewer than 20% had machines for injecting polystyrene and that wax machines outnumbered plastics machines by almost 13 to 1 (Ref 15).

Perhaps the most important application for polystyrene is for small, delicate airfoils. Patterns for such castings are incorporated into composite wax/plastic assemblies for integral rotor and nozzle patterns. These airfoils are extremely thin and delicate; they would be too fragile if molded in wax because even a single chip or crack will cause an expensive casting to be rejected. Polystyrene solves this problem, and the use of wax for the rest of the assembly makes it feasible to process such large patterns without excessive mold cracking. The other important use for polystyrene is for small patterns running in large quantities. However, this application has declined as ceramic shell molds have replaced solid investment molds.

## Other Pattern Materials

Urea-base patterns were developed in Europe and have found some application there (Ref 16). They resemble plastics in that they are very hard and strong and require high-pressure injection machines. An advantage of urea patterns is that they can be easily removed without stressing ceramic shell molds; the pattern is simply dissolved out in water or an aqueous solution. Another water-soluble pattern material is based on mixtures of low-melting salts (Ref 17). Patterns based on paradichlorobenzene and naphthalene have found some application in Japan (Ref 18). Foamed polystyrene has long been used for gating system components, and it is also being used for patterns in the Replicast Process (see the article "Replicast Process" in this Volume).

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\* The terms resins and plastics are used in accordance with the definitions proposed for pattern wax technology in Ref 2.

## Patternmaking

Patterns for investment casting are made by injecting the pattern material into metal molds of the desired shape. Small quantities of patterns can also be produced by machining (see the section "Machining of Patterns" in this article).

### *Injection of Wax Patterns*

Wax patterns are generally injected at relatively low temperatures and pressures in split dies using equipment specifically designed for this purpose. Patterns can be injected in the liquid, slushy, pastelike, or solid condition. Injection in the solid condition is often referred to as wax extrusion. Temperatures usually range from about 43 to 77 °C (110 to 170 °F), and pressures from about 275 kPa to 10.3 MPa (40 to 1500 psi). Liquid waxes are injected at higher temperatures and lower pressures; solid waxes, at lower temperatures and higher pressures. In some cases, the same wax can be injected under some, or all, of these conditions, but it is often beneficial to tailor a wax for one particular condition.

Equipment for wax injection ranges from simple and inexpensive to sophisticated and costly. It can be as simple as a pneumatic unit with a closed, heated reservoir tank that is equipped with a thermostat, pressure regulator, heated valve, and nozzle and is connected to the shop air line for pressurization. A small die is held against the nozzle with one hand while the valve is operated with the other. Such machines are limited by available air pressure (usually <690 kPa, or 100 psi) and are therefore generally used to inject liquid wax. Such equipment is satisfactory for a large variety of small hardware parts that are commonly made as investment castings.

Parts that are more demanding in terms of size, complexity, or dimensional requirements are made on hydraulic machines. These machines provide higher pressures for improved injections as well as high clamping pressures to accommodate large dies and high injection pressures. They can also be operated with very low pressures, as is often necessary when injecting around thin ceramic cores. Hydraulic wax injection machines are sized according to their clamping force capability, with models ranging in capacity from 9.1 to 363 Mg (10 to 400 tonf) or more.

Machines for manual or semiautomatic operation generally have horizontal platens that clamp the die closed (one stationary, one movable). Injection is horizontal along the parting line; a second vertical nozzle is sometimes available. Models are available with C-frame construction and with two-, three-, and four-post H-frame construction.

Machines for automatic injection have the platens mounted vertically, with injection through the stationary platen and one-half of the die or at the parting line. A reservoir tank is usually provided for liquid and slushy wax, having either slow agitation or recirculation to keep the wax uniform and to retain solid material (wax or filler) in suspension. Reservoir tanks are sometimes omitted, and the machines are connected directly to a central wax supply.

Machines for paste wax injection require preconditioned wax in a metal cylinder. The cylinder is inserted into the machine, and the wax is pushed out by a piston. Solid injection (extrusion) machines require pretempered wax billets.

Paste and solid injection both require a separate unit (oven or tempering bath) for tempering the cylinders or billets. Liquid injection usually requires separate units for melting and tempering the wax before it is introduced into the reservoir tank.

The parameters customarily controlled include wax and nozzle temperature, pressure, flow rate, and dwell time. Other available features, which may or may not be considered standard, include control of flow rate acceleration and deceleration, purging of the nozzle with fresh wax before each shot, nozzle drool control, unlimited shot capacity, die handling means, nozzle position adjustment, water-cooled platens, and multistation operation.

Reference publications that are available include a guide for troubleshooting wax injection operations (Ref 19) and an atlas of pattern defects (Ref 20). Other recommended publications are given in Ref 21, 22, 23, 24, 25, 26.

### *Injection of Plastic Patterns*

Polystyrene patterns are generally injected at temperatures of 177 to 260 °C (350 to 500 °F) and pressures of 27.6 to 138 MPa (4 to 20 ksi) on standard plastic injection machines. These are hydraulic machines with vertical water-cooled platens that carry the die halves, and horizontal injection takes place through the stationary platen. Polystyrene granules are loaded into a hopper, from which they are fed into a plasticizing chamber (barrel). Modern machines have a rotating screw that reciprocates within the heated barrel to prepare a shot of material to the proper consistency and then inject it into the die. Some older machines having plungers instead of screws are still in use.

The use of multicavity dies, as well as the running of a number of dies at once, is commonplace. Coupled with automatic or semiautomatic operation, this results in extremely high productivity.

The same parameters are controlled as for wax injection. The development of wax-base compositions that perform well in plastic injection machines has permitted the advantages of wax patterns to be combined with the advantages of plastic injection for certain applications (Ref 27).

### *Machining of Patterns*

When only one or a few patterns are required, as for prototype and experimental work, it is expedient to machine them directly from wax or polystyrene. This avoids the time and expense involved in making pattern tooling. Special waxes have been specifically developed for this application (Ref 28).

### *Pattern Tooling For Investment Casting*

Investment casting permits various potential tooling options that are made possible by the low melting point, good fluidity, and lack of abrasiveness of waxes. This often represents an important competitive advantage. For a given part configuration, anticipated production requirements, choice of pattern material, and available patternmaking equipment, the selection is based on a consideration of cost, tool life, delivery time, pattern quality, and production efficacy. The methods in use can be grouped into three basic categories: machining, forming against a positive model (using a variety of methods), and casting into a suitable foundry mold.

Many materials can be used, including soft metals (lead-bismuth-tin alloys), zinc alloys, brass, bronze, beryllium copper, nickel-plate, steel, rubber, plastic, metal-filled plastic, plaster, and combinations of these. All of these are suitable for wax patterns, but plastic patterns usually require steel or beryllium copper tooling. Soft metals and nonmetallics are often used for temporary tooling.

**Machined Tooling.** Most production tooling is made by machining. The early investment casting industry favored tooling made from master models, but as parts became larger and more complex and production methods more demanding, machined tooling became dominant. Computer-aided design, electric discharge machining, and computer numerical controlled machine tools are commonly used.

Aluminum is preferred for most wax tooling, steel, for plastic tooling. Aluminum is economical to machine, has good thermal conductivity, and is conveniently light. Brass or steel inserts can be used in areas subject to wear. The higher strength of steel is not usually needed for wax injection; instead, steel is primarily used for plastic injection for small parts that run in sufficiently large quantities to justify its higher cost. For polystyrene, this quantity is usually around 10,000 pieces or more; for very small parts, perhaps as low as 5000.

Tool steels are most frequently used for plastic dies. AISI type P20 is extensively used because it can be purchased prehardened, then machined, and finally put into use without heat treatment. AISI A2 and O1 are also used. Both are machined in the annealed state, then hardened and tempered. Carbon steels such as 1020 are sometimes used for intermediate quantities. Holder blocks, shoes, and mold bases used to hold the plastic injection molds can be made of prehardened alloy steel (for example, 4140).

Tooling made against a positive model includes a variety of methods for forming metal or metal-faced tooling, such as spraying (Ref 29), pressure casting (Ref 30), cold and warm hobbing (Ref 31, 32), electroforming (Ref 33, 34), and (potentially) gas plating (Ref 35). It also includes the casting of such nonmetallic materials as plaster (usually used to back up a spray metal facing), plastics (Ref 36), and rubber (Ref 37), as well as the vulcanizing of solid rubber under pressure (Ref 38).

All these methods begin with a positive model in the shape of the final investment casting; the model is machined oversize to include the appropriate shrink factors. The methods are economical because it is generally (although not always) less expensive to machine a positive model than to machine a negative cavity of identical shape. Furthermore, with the exception of hobbing, the model can be made of a material that is easier to machine. The various methods of making dies from the master model are relatively inexpensive, so that the combined cost of machining the model and making the die is usually less than that for full machining. When multiple cavities are needed or where molds must be replaced, the same master can be used, resulting in further economies.

Cast Tooling. Steel and beryllium copper are frequently used for cast tooling. Aluminum and zinc alloys have also been used. Wax can be cast against a master model to produce a pattern, which is then used to make an investment cast cavity. Better as-cast accuracy can be achieved if the model is coated with only a thin layer of wax. This is used to investment cast a steel shell, which is then backed up with cast aluminum (Ref 39). The ceramic mold process can also be used to cast injection cavities (Ref 40).

Both casting and hobbing can produce excellent tooling that is suitable for the wax or plastic injection of relatively simple parts, such as many small hardware castings. Machined tooling is also used for many of the same applications, as well as for complex parts, such as airfoils, and for large structural parts. Soft metal tooling and nonmetallic tooling are primarily used for short runs and experimental work or for temporary tooling. However, under favorable conditions, runs of up to 40,000 parts have been reported for cast bismuth-tin tooling (Ref 41). Cast, hobbled, and machined dies used for wax injection often last indefinitely. Rubber molds are regularly used for making patterns for jewelry casting.

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## Pattern and Cluster Assembly

Large patterns for investment casting are set up and processed individually, but small-to-medium ones are assembled into multipattern clusters for economy in processing. Clusters of aircraft turbine blades, for example, may range from 6 to 30 parts. For small hardware parts, the number may run into the dozens or even the hundreds. Most patterns are injected complete, including their casting gates. However, very large or complex parts can be injected in segments, which are assembled into final form. The capacity of injection machines and the cost of tooling are important considerations. Gating components, including pour cups, are produced separately, and patterns and gating are assembled to produce the pattern cluster. Standard extruded wax shapes are often used for gating, especially for mock-up work. Preformed ceramic pour cups are often used in place of wax ones. Most assembly is done manually.

### *Pattern Assembly*

Wax components are readily assembled by wax welding using a hot iron or spatula or a small gas flame. The wax at the interface between two components is quickly melted, and the components are pressed together until the wax resolidifies. The joint is then smoothed over. A hot melt adhesive can be used instead of, or in addition to, wax welding. A laser welding system was recently described for this purpose (Ref 42).

Manual wax welding requires a fair degree of skill and considerable attention to detail. Fixtures are essential to ensure accurate alignment in assembling patterns, and they are often useful for cluster assembly. Patterns must be properly spaced and aligned. Joints must be strong and completely sealed with no undercuts. Care must be taken to avoid damaging patterns or splattering drops of molten wax on them.

Polystyrene pattern segments can be assembled by solvent welding. The plastic at the interface is softened with the solvent, and the parts are pressed together until bonded. The polystyrene becomes very tacky when wet with solvent (such as methyl ethyl ketone) and readily adheres to itself. Frequently, only one of the two halves needs to be wet. The assembly of polystyrene to wax is done by welding, with only the wax being melted.

Automation. Most assembly and setup operations are still performed manually, but some automation is being introduced. In one application, a robot is used to apply sealing compound in the assembly of patterns for integrally cast nozzles having 52 to 120 airfoils apiece. In the area of cluster setup, a few units for automatic assembly are being offered commercially, one of which has been described in great detail (Ref 43). Clusters are assembled automatically by welding pairs of wax patterns on opposite sides along the length of a wax runner bar, using heated copper blades and spring pressure. Standard gate designs in a range of size increments eliminate the need for special fixturing. The unit is suitable for most small-to-medium size castings.

### *Cluster Design*

The design of the cluster is a critical factor because it affects almost every aspect of the process. Factors to be considered include ease of assembly, number of pieces processed at a time, ratio of metal poured to castings shipped, handling strength, ease of mold forming and drying, wax removal, liquid metal flow, filling of thin sections, feeding of shrinkage,

control of grain size and shape (when specified), shell removal, ease of cutoff and finishing, and available equipment and processes.

Three requirements are essential:

- Providing a cluster that is properly sized and strong enough to be handled throughout the process
- Meeting metallurgical requirements
- Providing separate specimens for chemical or mechanical testing (when required)

Once these essentials are satisfied, other factors are adjusted to maximize profitability. The process is very flexible, and foundries approach this goal in various ways. Some tailor the cluster design to each individual part to maximize parts per cluster and metal usage. Others prefer standardized clusters to facilitate handling and processing. Where close control of grain is required, whether for equiaxed, columnar (directionally solidified), or single-crystal casting, circular clusters are often used to provide thermal uniformity. The specific casting process used, such as counter-gravity casting, directional solidification (see the articles "Counter-Gravity Low-Pressure Casting" and "Directional and Monocrystal Solidification" in this Volume), or centrifugal casting (see the article "Centrifugal Casting"), may dictate the basic features of cluster design.

The critical aspects of cluster design are gating and risering, which are discussed in the articles "Riser Design" and "Gating Design" in this Volume. Basic concepts of risering borrowed from sand casting, such as progressive solidification toward the riser, Chvorinov's rule and its extensions, solidification mode, and feeding distance as a function of alloy and section size, also apply to investment casting.

However, feeding distances tend to be longer in hot investment molds than in sand molds (Ref 44, 45). Separate risers are sometimes used, but more often the gating system also serves the risering function, especially for the myriad of small parts that are commonly investment cast. The use of wax clusters permits great flexibility in the design of feeding systems. Process development clusters are readily mocked up for trial. Extruded wax shapes are easily bent into feeders that can be attached to any isolated sections of the part that are prone to shrinkage. Once proved, they can be incorporated into tooling if this is cost effective. If not, they can be applied manually during cluster assembly. This capability makes it practical to cast very complex parts with high quality and makes it feasible to convert fabrications assembled from large numbers of individual components into single-piece investment castings at great cost savings.

Considerable effort is being directed toward applying heat transfer models based on finite-element and finite-difference methods to the analysis of solidification and the design of feeding systems for castings, including investment castings (Ref 46). Although this has not yet had a significant impact on production engineering activities, eventual implementation and widespread use is anticipated. A specific application to a complex investment casting has recently been described (Ref 47).

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## Manufacture of Ceramic Shell Molds

Investment shell molds are made by applying a series of ceramic coatings to the pattern clusters. Each coating consists of a fine ceramic layer with coarse ceramic particles embedded in its outer surface. A cluster is first dipped into a ceramic slurry bath. The cluster is then withdrawn from the slurry and manipulated to drain off excess slurry and to produce a uniform layer. The wet layer is immediately stuccoed with relatively coarse ceramic particles either by immersing it into a fluidized bed of the particles or by sprinkling the particles on it from above.

The fine ceramic layer forms the inner face of the mold and reproduces every detail of the pattern, including its smooth surface. It also contains the bonding agent, which provides strength to the structure. The coarse stucco particles serve to arrest further runoff of the slurry, help to prevent it from cracking or pulling away, provide keying (bonding) between individual coating layers, and build up thickness faster.

Each coating is allowed to harden or set before the next one is applied. This is accomplished by drying, chemical gelling, or a combination of these. The operations of coating, stuccoing, and hardening are repeated a number of times until the required mold thickness is achieved. The final coat is usually left unstuccoed in order to avoid the occurrence of loose particles on the mold surface. This final, unstuccoed layer is sometimes referred to as a seal coat.

### *Mold Refractories*

The most common refractories for ceramic shell molds are siliceous, for example, silica itself, zircon, and various aluminum silicates composed of mullite and (usually) free silica. These three types in various combinations are used for most applications. Alumina has had some use for super-alloy casting, and this application has increased with the growth of directional solidification processes. Alumina is generally considered too expensive and unnecessary for commercial hardware casting. Silica, zircon, aluminum silicates, and alumina find use for both slurry refractories and stuccos. Table 1 lists the typical properties of these materials, and Fig. 3 shows thermal expansion curves.

**Table 1 Nominal compositions and typical properties of common refractories for investment casting**

Data are for comparison only, are not specifications, and may not describe specific commercial products.

Material	Nominal composition, %	Crystalline form	Approximate theoretical density		Relative leachability <sup>(a)</sup>	Approximate melting point		PCE temperature <sup>(b)</sup>		pH	Color
			g/cm <sup>3</sup>	lb/in. <sup>3</sup>		°C	°F	°C	°F		
Aluminosilicates											
42%	Al <sub>2</sub> O <sub>3</sub> -53SiO <sub>2</sub>	Mixture	2.4-2.5	0.086-0.090	Poor	...	...	1750	3180	6.5-7.8	Gray to tan
47%	Al <sub>2</sub> O <sub>3</sub> -49SiO <sub>2</sub>	Mixture	2.5-2.6	0.090-0.094	Poor	...	...	1760	3200	6.5-7.8	Gray to tan
60%	Al <sub>2</sub> O <sub>3</sub> -36SiO <sub>2</sub>	Mixture	2.7-2.8	0.097-0.10	Poor	...	...	1820	3310	6.5-7.8	Gray to tan
70%	Al <sub>2</sub> O <sub>3</sub> -25SiO <sub>2</sub>	Mixture	2.8-2.9	0.10-0.104	Poor	...	...	1865	3390	6.5-7.8	Gray to tan
73%	Al <sub>2</sub> O <sub>3</sub> -22SiO <sub>2</sub>	Mixture	2.8-2.9	0.10-0.104	Poor	...	...	1820	3310	6.5-7.8	Gray to tan

Alumina	99% + Al <sub>2</sub> O <sub>3</sub>	Trigonal	4.0	0.144	Poor	2040	3700	...	...	8.5-8.9	<b>White</b>
Fused silica	99.5% SiO <sub>2</sub>	Typically 97% + amorphous	2.2	0.079	Good	1710	3110	...	...	6.0-7.5	<b>White</b>
Silica-quartz	99.5% SiO <sub>2</sub>	Hexagonal	2.6	0.094	Good	1710	3110	...	...	6.4-7.5	<b>White to tan</b>
<b>Zircon</b>	<b>97% + ZrSiO<sub>4</sub></b>	<b>Tetragonal</b>	<b>4.5</b>	<b>0.162</b>	<b>Moderate</b>	<b>2550</b>	<b>4620</b>	...	...	<b>4.7-7.0</b>	<b>White to tan</b>

Source: Ref 48

(a) Poor: slight reaction in hot concentrated alkali; Good: soluble to very soluble in hot concentrated alkali or hydrofluoric acid; Moderate: reacts with hot concentrated alkali solutions.

(b) PCE, pyrometric cone equivalent.

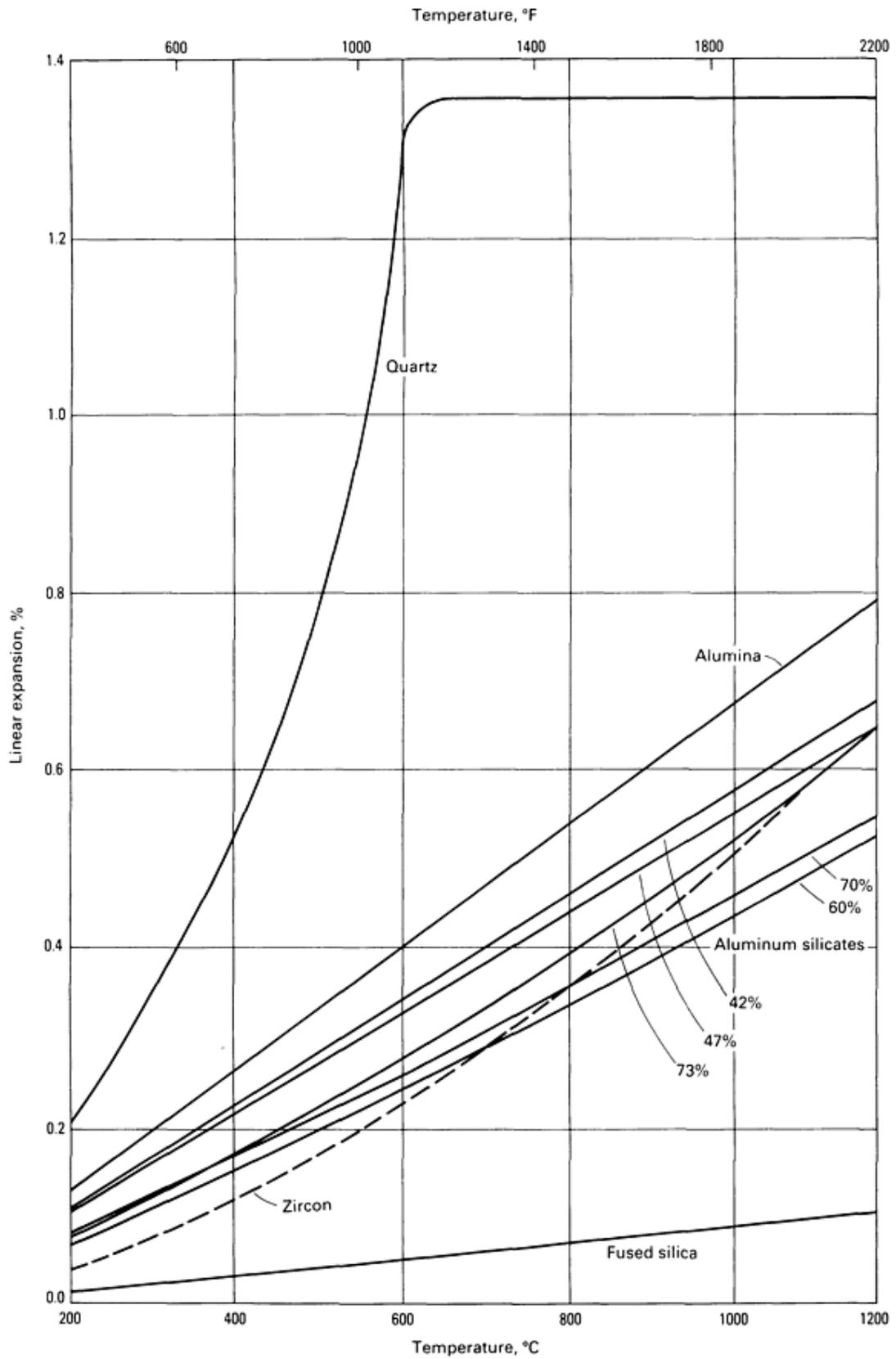


Fig. 3 Linear thermal expansion of some refractories common to investment casting. Source: Ref 48.

Other refractories, such as graphite, zirconia ( $ZrO_2$ ), and yttria ( $Y_2O_3$ ), have been suggested for use with reactive alloys. Still other materials have been proposed for specific purposes. These specialized applications are summarized in Ref 49.

Silica is generally used in the form of silica glass (fused silica), which is made by melting natural quartz sand and then solidifying it to form a glass. It is crushed and screened to produce stucco particles, and it is ground to a powder for use in slurries. Its extremely low coefficient of thermal expansion imparts thermal shock resistance to molds, and its ready solubility in molten caustic and caustic solutions provides a means of removing shell material chemically from areas of castings that are difficult to clean by other methods.

Silica is also used as naturally occurring quartz. This is the least expensive material used to any extent. However, its utility is limited by its high coefficient of thermal expansion and by the high, abrupt expansion at  $573\text{ }^\circ\text{C}$  ( $1063\text{ }^\circ\text{F}$ ) accompanying its  $\alpha$ -to- $\beta$ -phase transition. As a result, shells containing quartz must be fired slowly, a practice most foundries find inconvenient.

Zircon occurs naturally as a sand, and it is used in this form as a stucco. It is generally limited to use with prime coats because it does not occur in sizes coarse enough for stuccoing backup coats. It is also ground to powder (and sometimes calcined) for use in slurries, often in conjunction with fused silica and/or aluminum silicates. Its principal advantages are high refractoriness, resistance to wetting by molten metals, round particle shape, and availability.

Aluminum silicates for investment casting are made by calcining fireclays or other suitable materials to produce a series of products ranging in alumina content from about 42 to 72%, with the remainder being silica plus impurities. Refractoriness and cost increase with alumina content. The only stable compound between alumina and silica at elevated temperatures is mullite ( $3Al_2O_3 \cdot 2SiO_2$ ), which contains 72% alumina. Mixtures containing less than 72% alumina produce mullite plus free silica. The latter is usually in the form of silica glass, although some crystalline silica in the cristobalite form may be present. As the alumina content increases, the amount of mullite increases and free silica decreases until, at about 72% alumina, the material contains only mullite. Fired pellets of these materials are crushed or ground and carefully sized to produce a range of powder sizes for use in slurries, and granular materials for use as stuccos.

Alumina is produced from bauxite ore by the Bayer process. It is more refractory than silica or mullite and is less reactive toward many alloys than the siliceous refractories. Its use is primarily confined to superalloy casting, in which these properties can be used to advantage. The usual grades are tabular, which has been calcined just below the melting point, and fused, which has been electrically melted. The latter is slightly denser and slightly purer.

### *Binders*

The commonly used binders are also siliceous and include colloidal silica, hydrolyzed ethyl silicate, and sodium silicate. Hybrid binders have also been developed, and alumina or zirconia binders are used for some processes.

Colloidal silica is the most widely used. It is manufactured by removing sodium ions from sodium silicate by ion exchange. The product consists of a colloidal dispersion of virtually spherical silica particles in water. The dispersion is stabilized by an ionic charge, which causes the particles to repel one another, thus preventing agglomeration. The stabilizing ion is usually sodium (up to 0.6%), although ammonia can also be used. In either case, the product is alkaline.

Colloidal silica can also be stabilized at an acid pH, but such products are not widely used. The most popular grades are sodium-stabilized with a silica content of 30% and an average particle size of either 7 or 12 nm. They are either used at this 30% level or diluted with water to reduce the silica content to 18 to 30%. Coherent gels having excellent bonding properties are formed by adding ionic salts that neutralize the ionic charge or by concentrating the sol (as by drying a coating).

Colloidal silica is an excellent general-purpose binder. Its main disadvantage is that its water base makes it slow drying, especially in inaccessible pockets or cores.

Ethyl silicate is produced by the reaction of silicon tetrachloride with ethyl alcohol. The basic compound formed is tetraethylor-thosilicate ( $Si(OC_2H_5)_4$ ). This corresponds to a theoretical silica content of 28.8%. The grade used for investment applications is designated ethyl silicate 40, and it consists of a mixture of ethyl polysilicates averaging five silicon atoms per molecule and having a silica content of around 40%.

By itself, ethyl silicate has no bonding properties. It is converted to ethyl silicate binder by reaction with water (hydrolysis). The reaction is usually carried out in ethyl alcohol, which serves as a mutual solvent, using an acid catalyst such as hydrochloric acid. The reaction is fairly rapid and highly exothermic. Its progress can be monitored with temperature measurements. The reaction forms complex silicic acids that are capable of condensing to form coherent gels having good bonding properties. This process is promoted by drying (concentrating) or by adding an alkali such as ammonia. The result is similar in many ways to that obtained using colloidal silica. Prehydrolyzed grades of ethyl silicate having reasonable shelf life are also available, making it unnecessary for foundries to perform this chemical operation themselves.

Ethyl silicate, with its alcohol base, dries much faster than colloidal silica. It is, however, more expensive and poses fire and environmental hazards. It is best used in applications involving rapid dipping cycles. Ethyl silicate slurries are readily gelled by exposure to an ammonia atmosphere; this permits dips to be applied very quickly, yet still provides proper drying because of the high volatility of the alcohol.

Hybrid binders have been developed in an effort to combine the advantages of colloidal silica and ethyl silicate. The water required for hydrolysis of the ethyl silicate is supplied by using colloidal silica, providing an additional source of silica for improved strength. Less flammable solvents can be substituted for alcohol. The resulting product presents a desirable combination of properties (Ref 50).

Liquid sodium silicate solutions are used where a very inexpensive binder is desired. Upon evaporation, these binders form a strong, glassy bond. Sodium silicate binders have poor refractoriness, which greatly limits their sphere of application. In addition, they are not resistant to the steam atmosphere of dewaxing autoclaves. Nevertheless, they have found some use, sometimes in conjunction with colloidal silica or ethyl silicate.

**Other Binder Materials.** The operation of directional solidification processes, which subject the mold to high temperatures for relatively long times, along with the introduction of even more reactive superalloys, has led to interest in more refractory binders. Colloidal alumina and colloidal zirconia binders have been made available for this purpose (Ref 51, 52). Both, however, are inferior to colloidal silica in room-temperature bonding properties.

### *Other Ingredients*

**Wetting Agents.** In addition to the binder and refractory, slurries generally contain anionic or nonionic wetting agents, such as sodium alkyl aryl sulfonates, sodium alkyl sulfates, or octylphenoxy polyethoxyethanol, to promote wetting of the pattern or prior slurry coats. These are generally used in amounts of 0.03 to 0.3% by weight of the liquid. Wetting agents are sometimes omitted from ethyl silicate/alcohol slurries and from water-base backup slurries.

**Antifoam Compounds.** Where wetting agents are used, especially in prime coats, an antifoam compound may be included to suppress foam formation and to permit air bubbles to escape. Commonly used defoamers are aqueous silicone emulsions and liquid fatty alcohols such as *n*-octyl alcohol and 2-ethyl hexyl alcohol. Depending on type, these formulations are effective in very low concentrations of 0.002 to 0.10%, based on the liquid weight.

**Miscellaneous Constituents.** Organic film formers are sometimes used to improve the green strength and resilience of the dried coating or to enhance the coating ability of the slurry. Aqueous polyvinyl acetate emulsions, polyvinyl alcohol, and ammonium alginate have been used for this purpose. Small additions of clay have also been used to improve coating characteristics. Where close control of grain size is required, as for equiaxed superalloy casting, a nucleating agent (grain refiner) is added to the prime slurry in amounts ranging from about 0.5 to 10% by weight of the slurry refractory (Ref 53, 54, 55). Preferred nucleating agents are refractory cobalt compounds such as aluminates, silicates, titanates, and oxides.

### *Slurry Formulation*

The actual percentage composition of ceramic shell slurries depends on the particular refractory powder, type and concentration of binder, liquid vehicle, and desired slurry viscosity. Composition generally falls in the following broad range by weight:

Ingredient	Composition, %
Binder solids	<b>5-10</b>
Liquid (from binder or added)	<b>15-30</b>
Refractory powder	<b>60-80</b>

Other optional ingredients, when present, are used in the amounts already given. Slurry compositions are usually proprietary, but three published formulas for zircon slurries are given in Table 2.

**Table 2 Formulations and properties of three types of zircon slurries**

Slurry	Constituents										Properties		
	Colloidal silica (30%)		Water		Zircon powder		Wetting agent		Silica		Density		Viscosity, s <sup>(a)</sup>
	L	gal.	L	gal.	kg	lb	cm <sup>3</sup>	Fl oz	kg	lb	g/cm <sup>3</sup>	lb/in. <sup>3</sup>	
1 <sup>(b)</sup>	9.5	2.5	3.8	1.0	45	100	10	0.34	...	...	2.7-2.75	0.097-0.099	<b>8-10</b>
2 <sup>(c)</sup>	11.4	3	...	...	45	100	10	0.34	...	...	2.9-2.95	0.104-0.106	<b>9-11</b>

(a) No. 4 Zahn cup.

(b) A general-purpose slurry.

(c) A high-strength slurry used for ceramic shell molds for castings with heavy sections and for applications in which high wax pressure during meltout and high metal pressure are used.

(d) Modified with silica; used with castings with small cored holes from which cores are removed by leaching with molten alkali salts

Two extremely important properties of ceramic shell molds are green strength and fired strength. A fundamental study of the effects of composition and processing parameters on these properties is described in Ref 56 and 57, which also provide additional examples of slurry compositions. This work was further amplified by another researcher (Ref 58). The effects of the usual refractory powders and stuccos on hot strength were investigated, and it was found that strength after firing is not a good indication of hot strength (Ref 59). However, it is still an important property because it affects the shell removal operation.

### *Slurry Preparation and Control*

Preparation. Slurries are prepared by adding the refractory powder to the binder liquid, using sufficient agitation to break up agglomerates and thoroughly wet and disperse the powder. Viscosity initially tests excessively high because of air entrainment and lack of particle wetting; therefore, mixing is continued until the viscosity falls to its final level before the slurry is put into use. Continued stirring is required in production to keep the powder from settling out of suspension. Either rotating tanks with baffles or propeller mixers are used for this purpose--but generally at a lower agitation level than that used for the initial dispersion.

Control procedures for slurries vary considerably among foundries, reflecting in part the wide range of specifications that different shops work to, depending on their product line. The most prevalent controls are the measurement of the initial ingredients and the viscosity of the slurry. The latter is measured by a flow cup, such as a No. 4 or 5 Zahn cup, or a rotating viscometer of the Brookfield type.

Other parameters that are often controlled include slurry temperature, density, and pH, all of which are easily determined. More involved and time consuming is the determination of the actual composition of the slurry in terms of water content, silica binder, and refractory powder. This type of analysis, therefore, is performed less often and is sometimes reserved for troubleshooting rather than control. In the ceramic retention test, which is used by relatively few foundries, the actual weight of slurry adhering to a standard test plate under controlled conditions is determined.

Some properties of the finished ceramic shells that can be monitored include weight, modulus of rupture (green and/or fired), and permeability. Equipment for determining the hot strength of shells is relatively rare in the industry and is largely used for research. Test procedures for raw materials, slurries, molds, and cores are described in Ref 48, and the problems involved in slurry control are discussed in Ref 60, 61, 62.

### *Cluster Preparation*

Before dipping, pattern clusters are usually cleaned to remove injection lubricant, loose pieces of wax, or dirt. Cleaning is accomplished by rinsing the pattern clusters in an appropriate solution, such as a water solution of a wetting agent, a solvent that does not attack the wax, or a solvent mixture capable of attacking the wax in a controlled manner to produce a fine uniform etching action that promotes slurry adhesion without affecting the cast surface. An additional rinse can be used to remove the cleaning agent. Another procedure involves dipping the cluster into a liquid that deposits an ultrathin refractory oxide coating that renders the surface hydrophilic; thus, the cluster is readily wetted by the ceramic slurry (Ref 63). These different solutions can sometimes be used in combination.

The clusters are usually allowed to dry before dipping. Drying produces a chilling effect, which causes unwanted contraction in pattern dimensions; therefore, the clusters are generally allowed to stand until they return to room temperature.

### *Coating and Drying*

Dipping, draining, and stuccoing of clusters are carried out manually, robotically, or mechanically. Companies are increasingly using robots in order to heighten productivity, to process larger parts and clusters, and to produce more uniform coatings. When robots are introduced, they are often programmed to reproduce the actions of skilled operators. Dedicated mechanical equipment can sometimes operate faster, especially with standardized clusters, and finds some application. Most dipping is done in air. Dipping under vacuum is very effective for coating narrow passageways and for eliminating air bubbles, but it is not widely practiced.

The cleaned and conditioned cluster is dipped into the prime slurry and rotated; it is then withdrawn and drained over the slurry tank with suitable manipulation to produce a uniform coating. Next the stucco particles are applied by placing the cluster in a stream of particles falling from an overhead screen in a rainfall sander or by plunging the cluster into a fluidized bed of the particles. In the fluidized bed, the particles behave as a boiling liquid because of the action of pressurized air passing through a porous plate in the bottom of the bed.

Generally, prime slurries contain finer refractory powder, are used at a higher viscosity, and are stuccoed with finer particles than backup coats. These characteristics provide a smooth-surfaced mold capable of resisting metal penetration.

Backup coats are formulated to coat readily over the prime coats (which may be somewhat porous and absorbent), to provide high strength, and to build up the required thickness with a minimum number of coats. One or two additional prime coats are sometimes used before starting the backup coats. The number of coats required is related to the size of the

clusters and the metal weight to be poured and may range from as few as 5 for small clusters to as many as 15 or more for large ones. For most applications, the number ranges from 6 to 9.

Between coats, the slurries are hardened by drying or gelling. Air drying at room temperature with circulating air of controlled temperature and humidity is the most common method. Drying is usually carried out on open racks or conveyors, but cabinets or tunnels are sometimes used.

Drying is complicated by the high thermal expansion/contraction characteristics of waxes. If drying is too rapid, the chilling effect causes the pattern to contract while the coating is wet and unbonded. Then, as the coating is developing strength and even shrinking somewhat, the wax begins to expand as the drying rate declines and it regains temperature. This can actually crack the coating. Therefore, relative humidity is generally kept above 40%. For normal conditions, a relative humidity of 50% has been recommended as ideal (Ref 64). The essential point is that the maximum temperature differential between the wax and the drying air should not be excessive. Shop experience indicates that 4 to 6 °C (7.2 to 10.8 °F) is a practical maximum (Ref 65).

The slurry does not have to be thoroughly dried between coats, but it must be dry enough so that the next coat can be applied without washing off the previous one. An alternative technique is to harden the slurry by chemical gelation, which can be accomplished without drying. This is most successful with ethyl silicate binders, which can be surface gelled by exposure to an ammonia atmosphere. Hardening by chemical gelation permits the minimum time between coats. Gelling can also be accomplished by adding gelling agents to the stucco or by alternating alkaline and acidic slurries or negatively charged and positively charged slurries in the dipping sequence. Shells that are gelled without drying are generally weaker even when subsequently dried. In addition, the weight of the unevaporated solvent can be excessive and can cause the wax cluster to yield or even break in some cases.

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## Manufacture of Ceramic Cores

Ceramic coring is widely used in investment casting to produce internal passage-ways in castings. Investment casting cores are either self-formed (produced in place during the mold building operation) or preformed (made separately by an appropriate ceramic forming process).

### *Self-Formed Cores*

Self-forming requires that the wax patterns already have the openings corresponding to the passageways desired in the castings. For simple shapes, this is accomplished by the use of metal pull cores in the pattern tooling. For shapes in which a simple pull core cannot be extracted, soluble wax cores are made, placed in the pattern tooling, and the pattern injected around them. The soluble core is then dissolved out in a solution that does not affect the wax pattern, such as an aqueous acid. Soluble cores are generally made from a solid polyethylene glycol, with a powdered filler such as sodium bicarbonate or calcium carbonate. The fillers dissolve in the acid with vigorous gas evolution, which provides agitation to speed the dissolution process.

Where openings are large enough, self-formed cores are made in the normal course of shelling, but where openings are deep or narrow, the shelling process must be modified to accommodate the special requirements of the cores. This may require special attention to slurry viscosity, stucco particle size, and drying. Vacuum dipping is an excellent tool in this case. Ethyl silicate/alcohol slurries reduce drying problems. The self-forming of cores is extensively practiced for small hardware castings, for which the cost of a preformed core would be prohibitive.

### *Preformed Cores*

Self-formed cores have severe limitations, which are overcome by using preformed cores. Preformed cores require separate tooling and can be produced by a number of ceramic forming processes. Simple tubes and rods are commonly extruded from silica glass. Many cores, especially larger ones, are produced from ethyl silicate slurries that are cast by gravity or injected under pressure into aluminum dies and then gelled. The technology is similar to ceramic molding processes (see the article "Ceramic Molding" in this Volume).

Many cores are made by injection molding; a smaller number, by transfer molding. Ceramic injection molding is similar to the plastics injection molding described earlier, except that a mixture of fine ceramic powder in an organic vehicle is injected, usually into hardened tool steel dies. The organic vehicle, which also functions as a green binder, employs such thermoplastic materials as polyethylene, ethyl cellulose, shellac, resins, waxes, and subliming organic compounds such as naphthalene and paradichlorobenzene. After forming, the cores are subjected to a two-stage heat treatment. In the first stage, the organics are removed without disrupting the core (which is sometimes a lengthy process), and in the second stage, the core is sintered to its final strength and dimensions.

Transfer molding is similar to injection molding. The primary difference is that a preform of thermosetting plastic and ceramic powder is softened and injected into a die, where it is cured (thermally set) under heat and pressure.

Although a considerable number of materials have been proposed for ceramic cores, they are usually made of fused silica, sometimes with additions of zircon. Fused silica cores provide satisfactory refractoriness and are readily leached from the castings in molten caustic baths, aqueous solutions of caustic in open pots or autoclaves, and hydrofluoric acid solutions.

Preformed cores are usually used by placing them in the pattern die and injecting wax around them. For some simple shapes, the cores are inserted into the patterns immediately after the patterns are injected. Cores expand differently from the shell molds in which they are used because of differences in composition and heating rates; therefore, cores of any size must be provided with slip joints in the mold (Ref 66). The factors to be considered in using ceramic cores are discussed in Ref 66.

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## Pattern Removal

Pattern removal is often the operation that subjects the shell mold to the most stresses, and it is a frequent source of problems. These arise from the fact that the thermal expansions of pattern waxes are many times those of the refractories used for molds (compare Fig. 2 and 3). When the mold is heated to liquify the pattern, this expansion differential leads to enormous pressure that is capable of cracking and even destroying the mold. In practice, this problem can be effectively circumvented by heating the mold extremely rapidly from the outside in. This causes the surface layer of wax to melt very quickly before the rest of the pattern can heat up appreciably. This molten layer either runs out of the mold or soaks into it, thus providing space to accommodate expansion as the remainder of the wax is heated. Melt-out tips open to the outside are sometimes provided or holes are drilled in the shell to relieve wax pressure.

Even with these techniques, the shell is still subjected to high stress; therefore, it should be as strong as possible. It should also be thoroughly dried before dewaxing. To achieve thorough drying, shells are subjected to 16 to 48 h of extended drying after the last coat; this drying is sometimes enhanced by the application of vacuum or extremely low humidity.

A number of methods have been developed to implement the surface melting concept (Ref 67), but only two have achieved widespread use: autoclave dewaxing and high temperature flash dewaxing. In addition, hot liquid dewaxing has found some use among smaller companies seeking to minimize capital investment.

Autoclave dewaxing is the most widely used method. Saturated steam is used in a jacketed vessel, which is generally equipped with a steam accumulator to ensure rapid pressurization, because rapid heating is the key to success. Autoclaves are equipped with a sliding tray to accommodate a number of molds, a fast-acting door with a safety lock, and an automatic wax drain valve. Operating pressures of approximately 550 to 620 kPa (80 to 90 psig) are reached in 4 to 7 s. Molds are dewaxed in about 15 min or less. Wax recovery is good. Polystyrene patterns cannot be melted out in the autoclave.

Flash dewaxing is carried out by inserting the shell into a hot furnace at 870 to 1095 °C (1600 to 2000 °F). The furnace is usually equipped with an open bottom so that wax can fall out of the furnace as soon as it melts. Some of the wax begins to burn as it falls, and even though it is quickly extinguished, there is greater potential for deterioration than with an autoclave. Nevertheless; wax from this operation can be reclaimed satisfactorily. Flash dewaxing furnaces must be equipped with an after-burner in the flue or some other means to prevent atmospheric pollution. Polystyrene patterns are readily burned out in flash dewaxing, but polystyrene often can cause extensive mold cracking unless it is embedded in wax in the pattern (as in integral nozzle patterns) or unless the polystyrene patterns are very small.

Liquid dewaxing requires the minimum investment in equipment. Hot wax at 177 °C (350 °F) is often used as the medium. Other liquids can also be used. Cycles are somewhat longer than for autoclave and flash dewaxing, and there is a potential fire hazard.

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## Mold Firing and Burnout

Ceramic shell molds are fired to remove moisture (free and chemically combined), to burn off residual pattern material and any organics used in the shell slurry, to sinter the ceramic, and to preheat the mold to the temperature required for casting. In some cases, these are accomplished in a single firing. Other times, preheating is performed in a second firing. This permits the mold to be cooled down, inspected, and repaired if necessary. Cracked molds can be repaired with

ceramic slurry or special cements. This will not heal cracks, but will seal them and reinforce the shell so that it can be successfully cast. Many molds are wrapped with ceramic-fiber blanket at this time to minimize the temperature drop that occurs between the preheat furnace and the casting operation or to provide better feeding by insulating selected areas of the mold.

Gas-fired furnaces are used for mold firing and preheating, except for molds for directional solidification processes, which are preheated in the casting furnace with induction or resistance heating. Batch and continuous pusher-type furnaces are most common, but some rotary furnaces are also in use. Most furnaces have conventional firebrick insulation, but furnaces with ceramic-fiber insulation and luminous wall furnaces (Ref 68) are also in use. The latter two provide very fast heat up and cool down as well as good fuel economy. Conventional and ceramic-fiber furnaces can be equipped with ceramic recuperators for greater fuel economy and reduced smoke emissions (Ref 69). Good circulation is essential, especially in preheat furnaces, to provide uniform temperatures. Approximately 10% excess air is provided in burnout furnaces to ensure the complete combustion of organic materials.

Burnout is commonly conducted between 870 and 1095 °C (1600 and 2000 °F). Many molds can be placed directly into the hot furnace, but others may have to be loaded at a low temperature and heated gradually. This includes molds made with crystalline silica and molds in which some parts are shielded from radiation. Preheat temperatures vary over a large range above and below burnout temperatures, depending on part configuration and the alloy to be cast. Common ranges are 150 to 540 °C (300 to 1000 °F) for aluminum alloys, 425 to 650 °C (800 to 1200 °F) for many copper-base alloys, and 870 to 1095 °C (1600 to 2000 °F) for steels and superalloys. Molds for the directional solidification process are preheated above the liquidus temperature of the alloy being cast.

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## Melting and Casting

Melting Equipment. In the past, the small carbon arc rolover furnace was the workhorse of the early investment casting industry (Ref 70), but this furnace has been gradually displaced by the induction furnace, which is more flexible and economical to operate. Induction furnaces are used in conjunction with various casting methods developed for the specific requirements of investment casting. Today most investment casting uses induction melting.

The furnaces used are of the coreless type and generally employ preformed crucibles for melting (or monolithic linings for large sizes). They consist of a water-cooled copper coil that surrounds the melting crucible, a power supply to energize the coil with alternating current, and the appropriate electrical controls. The alternating current flowing through the coil sets up an alternating magnetic field that induces eddy currents in the metal charge. The heating effect is self-generated within the charge as a result of its resistance to the current flow. Earlier models used spark gap converters or motor-generator sets as power supplies, but today solid-state power supplies are standard.

Most induction furnaces for investment casting have capacities ranging from 7.7 to 340 kg (17 to 750 lb). They are usually tilting models, although some small rolover models are used where very rapid mold filling is required. Melting rates of 1.36 kg/min (3 lb/min) are common, but this depends on the relative size of the power supply and the melt. Induction furnaces can be employed for melting in air, inert atmosphere, or vacuum. They are extensively used for melting steel, iron, cobalt and nickel alloys, and sometimes copper and aluminum alloys. The crucibles typically used are magnesia, alumina, and zirconia, which are made by slip casting, thixotropic casting, dry pressing, or isostatic pressing. For vacuum casting, there is some use of disposable liners, which are made by conventional ceramic shell techniques or by the slip casting of fused silica.

Gas-fired crucible furnaces and, more recently, electrical resistance furnaces are used for aluminum casting. Gas-fired furnaces using glazed clay-bonded graphite crucibles are satisfactory for aluminum and copper alloy castings, and these furnaces are inexpensive. Silicon carbide crucibles are sometimes used for copper-base alloys. Resistance furnaces eliminate combustion products and help reduce hydrogen porosity. Magnesium can be melted in gas-fired furnaces using low-carbon steel crucibles.

Consumable-electrode vacuum arc skull furnaces are used for melting and casting titanium in a process originally developed at the U.S. Bureau of Mines (Ref 71). A billet of the alloy to be cast serves as the consumable electrode and is melted under vacuum into a water-cooled copper crucible. The crucible has a permanent, thin skull of solidified alloy on its inner face, and this skull prevents the crucible from contaminating the melt. Molten alloy accumulates in the crucible until there is a sufficient quantity to fill the mold, at which time it is poured. Furnaces of various sizes are available and are capable of melting up to 522 kg (1150 lb). The number of such installations is small because only a few companies make titanium investment castings, but this reflects the technical difficulties involved rather than any lack of a market.

Electron beam melting has been used in Europe as an alternative to vacuum arc melting for the casting of titanium (Ref 72). It is being used by an aircraft engine manufacturer in the United States for melting superalloys for directionally solidified and single-crystal casting (Ref 73). The arrangement is basically similar to that used for vacuum arc skull melting except that the electron beam is used in place of the vacuum arc.

**Casting Methods.** Both air and vacuum casting are important in investment casting. Most vacuum casting is investment casting, although there is some use of rammed graphite molds in vacuum arc furnaces for casting titanium. Most castings are gravity poured.

Air casting is used for such commonly investment cast alloys as aluminum, magnesium, copper, gold, silver, platinum, all types of steel, ductile iron, most cobalt alloys, and nickel-base alloys that do not contain reactive elements. Zinc alloys, gray iron, and malleable iron are usually not investment cast for economic reasons, but if they were, they would be air cast.

Vacuum casting provides cleaner metal and often superior properties, and sometimes this is an incentive to cast some of the normally air-melted alloys in vacuum. However, its major use is for alloys that cannot be satisfactorily cast in air, such as the  $\gamma'$ -strengthened nickel-base alloys, some cobalt alloys, titanium, and the refractory metals. Batch and semicontinuous interlock furnaces are satisfactory for vacuum casting, but the latter are clearly preferred.

A major advantage of investment casting is its ability to cast very thin walls. This results from the use of a hot mold, but is further enhanced by specific casting methods, such as vacuum-assist casting, pressurized casting, centrifugal casting, and counter-gravity casting.

In vacuum-assist casting, the mold is placed inside an open chamber, which is then sealed with a plate and gaskets, leaving only the mold opening exposed to the atmosphere. A partial vacuum is drawn within the chamber and around the mold. The metal is poured into the exposed mold opening, and the vacuum serves to evacuate air through the porous mold wall and to create a pressure differential on the molten metal, both of which help to fill delicate detail and thin sections.

Rollover furnaces are pressurized for the same purpose. The hot mold is clamped to the top with its opening in register with the furnace opening, and the furnace is quickly inverted to dump the metal into the mold while pressure is applied using compressed air or inert gas.

Centrifugal casting uses the centrifugal forces generated by rotating the mold to propel the metal and to facilitate filling. Vacuum arc skull furnaces discharge titanium alloy at a temperature just above its melting point, and centrifugal casting is usually needed to ensure good filling. Dental and jewelry casting use centrifugal casting to fill thin sections and fine detail. These three applications represent the major uses for centrifugal casting in investment casting.

Counter-gravity casting is discussed in the article "Counter-Gravity Low-Pressure Casting" in this Volume. Counter-gravity casting is also an excellent method of filling thin sections, and it is not limited to use with investment molds.

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## Postcasting Operations

Postcasting operations represent a significant portion (often 40 to 55%) of the cost of producing investment castings. A standard shop routing is provided for each part, and important savings can be realized by specifying the most cost-efficient routing. For example, it is often cost effective to detect and eliminate scrap early to avoid wasting finishing time, even if this means including an extra inspection operation. Alternative methods may be available for performing the same operation, and the most efficient one should be selected. The actual sequence in which operations are performed can be important. Some specifications require verification of alloy type, and this is done before parts are removed from the cluster.

**Knockout.** Some of the shell material may spall off during cooling, but a good portion usually remains on the casting and is knocked off with a vibrating pneumatic hammer or by hand. Brittle alloys require special attention. Part of the prime coat sometimes remains adhered to the casting surface, and bulk shell material may remain lodged in pockets or between parts. This is removed in a separate operation, usually shotblasting. Clusters are hung on a spinner hanger inside a blasting cabinet or are placed on a blasting table. If cores are to be removed in a molten caustic bath, the entire cluster can be hung in the bath at this point, and the remaining refractory can be removed along with the cores. High-pressure water blasting (69 MPa, or 10 ksi) is sometimes used instead of mechanical knockout.

**Cut-Off.** Aluminum, magnesium, and some copper alloys are cut off with band saws. Other copper alloys, steel, ductile iron, and superalloys are cut off with abrasive wheels operating at approximately 3500 rpm. Torch cutting is sometimes used for gates that are inaccessible to the cutting wheel. Some brittle alloys can be readily tapped off with a mallet if the gates are properly notched. Shear dies have also been used to remove castings from standardized clusters. Following cutoff, gate stubs are ground flush and smooth using abrasive wheels or belts. These are also used for other finishing operations, along with small hand grinders equipped with mounted stones.

**Core Removal.** Where the opening size permits, cores can be removed by abrasive or water blasting. If abrasive or water blasting cannot be used, the cores can be dissolved out. This can be accomplished in a molten caustic bath (sodium hydroxide) at 480 to 540 °C (900 to 1000 °F), in a boiling solution of 20 to 30% sodium hydroxide or potassium hydroxide in an open pot, or in the same solutions in a high-pressure autoclave. Hydrofluoric acid can also be used with alloys that are inert to it, such as platinum and many cobalt superalloys.

**Heat Treatment.** Both air and vacuum heat treatments are extensively performed as needed to meet property requirements. The vacuum heat treatment of stainless steels (instead of in air) is sometimes practiced to achieve a clean, bright surface and to avoid the need for any further cleaning. Before they are heat treated, single-crystal castings must be handled very carefully to avoid recrystallization during subsequent heat treatment. They must not be dropped, allowed to hit one another, or subjected to a blasting operation until heat treated.

**Abrasive Cleaning.** Blast cleaning is also used to remove scale resulting from core removal or heat treatment. Both pneumatic and airless (centrifugal) blasting machines are employed. Metallic abrasives (steel or iron grit or shot) and ceramic abrasives (silica sand, aluminum oxide, garnet, and staurolite) are all commonly used, depending on the application.

The hardness and angular shape of alumina produce rapid cleaning, which is especially cost effective when work is being blasted by hand. Alumina blasting is very effective at opening up and exposing surface defects, thus facilitating subsequent finishing or inspection operations. However, it is rather expensive, and less costly materials such as garnet, staurolite, or silica sand are often used instead. Metal shot and glass beads provide good peening action and produce shiny surfaces, both of which are sometimes desired. Equipment used for blasting includes hand cabinets as well as automatic units with rotating tables, spinner hangers, or rotating tumblers to hold the work.

Another type of abrasive finishing process is mass finishing. In this process, castings are treated with chemical finishing compounds and synthetic abrasives of specific geometric shapes, such as cones, triangles, and stars, to produce deburring, fine finishing, and radii blending in vibratory, tumbling, or centrifugal machines.

**Miscellaneous Operations.** Hot isostatic pressing is becoming increasingly important for the densification of castings to eliminate porosity, to improve fatigue, ductility, and other properties, and to reduce property scatter (see the article

"Hot Isostatic Pressing of Castings" in this Volume). Its most important application in investment casting is for titanium. Applications for steel, superalloys, and aluminum are more selective but still very important.

Machining is often performed on investment castings, although the amount may be minimal, and there are many applications in which no machining is required. Machining is generally confined to selected areas requiring closer dimensions than can be achieved by casting, and it is occasionally used to incorporate some detail that is less expensive to machine in than to cast. The machining and welding of investment castings are discussed in Ref 74. Welding can be used to repair and join castings--primarily large, structural castings. Other methods used to improve dimensional accuracy are broaching and coining, as well as abrasive grinding. Straightening operations are performed when required, either manually or using hydraulic presses, with suitable fixtures. Castings can be heated to facilitate straightening.

Chemical finishing treatments are also used. The various treatments include acid pickling to remove scale, passivation treatments for stainless steel, chemical milling to remove the  $\alpha$  case on titanium, and chemical treatment to apply an attractive satin finish to aluminum or to polish stainless steel.

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## Inspection and Testing

**Alloy Type Test.** The first inspection operation performed is often an alloy verification test. This test is conducted on the cluster before cutoff. A spectrometer or x-ray analyzer is used to verify that the correct alloy has in fact been poured.

**Visual Inspection.** An early visual inspection is essential so that obvious scrap does not get passed on to expensive finishing or inspection operations. Some commercial parts require only visual inspection.

Liquid fluorescent penetrant inspection is extensively used for nonmagnetic alloys. It can also be used for magnetic alloys, but a magnetic penetrant is generally specified instead. The liquid fluorescent penetrant detects defects on, or open to, the surface, such as porosity, shrinkage, cold shuts, some inclusions, dross, and cracks of any origin (hot tears, knockout, grinding, heat treat, straightening).

In this technique, the surface is properly cleaned, and a liquid penetrant with low surface tension and low viscosity is applied and is drawn into the defects by capillary action. Excess liquid is wiped away, a developer is applied that functions as a blotter to draw the liquid out, and the area is examined visually in a dark enclosure under black (near ultraviolet) light, which reveals defects that cannot be detected visually.

Applicable specifications include ASTM E 165 and MIL-1-6866. Turbine blades, which represent one of the most demanding applications for investment casting, are often subjected to a thermal cycle before the final fluorescent penetrant inspection; this is done to open very small defects that might otherwise go undetected.

Because the defects detected are often only surface defects, they can sometimes be removed by various finishing operations, and such rework operations are commonly attempted. They are generally successful if the defect is not so deep that dimensional or surface finish requirements are violated in removing it.

Magnetic particle inspection is used to detect the same types of defects as fluorescent penetrant inspection, but is preferred for use on ferromagnetic alloys. The method involves surface preparation, magnetization of the casting, and application of either a liquid suspension of magnetic particles (wet method) or fine magnetic iron particles (dry method). The presence of a defect causes a leakage field that attracts the magnetic particles and causes them to cling to the defect and define its outline. Colored particles and fluorescent particles (for viewing under black light) are available. Applicable specifications include ASTM E 125 (Reference Photographs), ASTM E 109 (Dry Particle), ASTM E 138 (Wet Particle), and MIL-STD-1949.

X-ray radiography is used to detect differences in material density or thickness to reveal such internal defects as dross, shrinkage, gas holes, inclusions, broken cores, and core shift. Many parts receive 100% inspection; others are inspected according to an appropriate sampling plan. Even when x-ray inspection is not required, it can be used as a foundry control

tool to aid in establishing a satisfactory gating system, to determine the effect of process changes, to monitor process reliability, and to troubleshoot foundry problems. X-ray inspection is sometimes used to examine wax patterns containing delicate ceramic cores to ensure that the cores were not broken during the pattern injection operation. Applicable specifications for castings are ASTM E 192, MIL-C-2175, and MIL-STD-453. Real time x-ray inspection is beginning to be used in the larger investment foundries serving the aircraft industry.

Formerly, defects within the casting detected by x-ray radiography could be repaired only by grinding and welding the affected area, but this procedure was not always cost effective and could not be applied to all alloys or applications. Currently, many castings, including those that cannot be welded, are being repaired by hot isostatic pressing.

**Miscellaneous Inspection Methods.** Hardness testing is widely used to verify the response of castings to heat treatment. Chemical analysis is generally controlled through the use of certified master heats. Mechanical properties are determined on separately cast test bars or test specimens mounted on production clusters. Specimens machined from castings are used for process development and periodic audits.

Grain size is regularly checked on many equiaxed castings, following chemical or electrolytic etching. Even where grain inspection is not specified, it is often used as part of the process development effort. Electrolytic etching is also used for examining and detecting grain defects in directionally solidified and single-crystal castings. The orientation of single-crystal castings is determined by Laue back-reflection x-ray diffraction.

Pressure tightness tests are conducted for a variety of applications. Dimensional inspection ranges from manual checks with a micrometer or simple go/no-go gages to the use of coordinate-measuring machines and automatic three-dimensional inspection stations capable of checking a sculptured surface in a continuous sweep. Wall thickness on many cored turbine blade castings is determined ultrasonically. Nodularity is checked metallographically on the first and last cluster poured from heats of ductile iron. Metallography is an essential part of process development for high-performance castings.

## Design Advantages of Investment Castings

The challenge in designing for investment casting is to make full use of the enormous capability and flexibility inherent in the process to produce parts that are truly functional and cost effective. Often such parts will also be more aesthetically pleasing. The principal advantages of investment casting that permit this challenge to be met will be discussed in this section.

**Complexity.** Almost any degree of external complexity, as well as a wide range of internal complexity, can be achieved, and in certain cases, the only limitation is the state of the art in ceramic core manufacturing. As a result, parts previously manufactured by assembling many individual components are currently being made as integral castings at much lower costs and often with improved functionality. This ability to produce complexity with ease can even benefit simple parts, which can be redesigned to save weight without loss of strength by providing I- or H-sections, or thin walls with ribs. Thus, many parts from competitive processes can be converted to investment casting.

**Freedom of Alloy Selection.** Any castable alloy can be used, including ones that are impossible to forge or are too difficult to machine. Further, the cost of the alloy is less important in the final price of an investment casting than it is in many other metal-forming processes; therefore, an upgraded alloy can often be specified (especially if the part is redesigned to save weight) at little or no increase in price.

**Close Dimensional Tolerances.** The absence of parting lines and the elimination of substantial amounts of machining by producing parts very close to final size give investment casting an enormous advantage over sand casting and conventional forging.

The availability of prototype and temporary tooling is a major advantage in the design and evaluation of parts. The direct machining of wax patterns or the use of any of the quick, inexpensive tooling methods described earlier facilitates timely collaboration between the designer and the foundry to produce parts that are functional and manufacturable. This capability is simply not found in such competitive processes as die casting, powder metallurgy, or forging. Further, temporary tooling used in the design phase can often serve for production while the market is tested or permanent tooling is constructed.

Reliability. The long-standing use of investment castings in aircraft engines for the most demanding applications has fully demonstrated their ability to be manufactured to the highest standards.

Wide Range of Applications. In addition to complex parts and parts that meet the most severe requirements, investment casting also produces many very simple parts competitively. This capability is often made possible by the low tooling costs associated with investment casting. Investment castings are competitively produced in sizes ranging from a few grams to more than 300 kg (660 lb), and the upper limits continue to increase.

## Design Recommendations

The following recommendations provide a useful guide to the design of investment castings:

- Look for ways to implement the advantages mentioned above
- Focus on final component cost rather than casting cost
- Design parts to eliminate unnecessary hot spots through changes in section sizes, use of uniform sections, location of intersections, and judicious use of fillets, radii, and ribs
- Promote good communication between foundry and customer to resolve questions of functionality versus producibility
- Use prototype castings to resolve questions of functionality, producibility, and cost
- Do not overspecify; permit broader-than-usual tolerances wherever possible
- Use the data in Ref 75 as a guide to the dimensional tolerances attainable
- Indicate datum planes and tooling points on drawings; follow ANSI Y14.5M for dimensioning and tolerancing

More detailed information is available in Ref 75 and 76.

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## Applications

Applications for investment castings exist in most manufacturing industries. A partial list is given in Table 3. The largest applications are in the aircraft and aerospace industries, especially turbine blades and vanes cast in cobalt- and nickel-base superalloys as well as structural components cast in superalloys, titanium, and 17-4-PH stainless steel. Examples of current applications for investment castings are shown in Fig. 4, 5, and 6. All were cast in ceramic shell molds using wax patterns unless otherwise noted.

**Table 3 Some applications of investment casting**

Aircraft engines, air frames, fuel systems
Aerospace, missiles, ground support systems
Agricultural equipment
Automotive
Baling and strapping equipment
Bicycles and motorcycles
Cameras
Computers and data processing
Communications
Construction equipment
Dentistry and dental tools
Electrical equipment

Electronics, radar  
Guns and small armaments  
Hand tools  
Jewelry  
Machine tools  
Materials handling equipment  
Metalworking equipment  
Oil well drilling and auxiliary equipment  
Optical equipment  
Packaging equipment  
Pneumatic and hydraulic systems  
Prosthetic appliances  
Pumps  
Sports gear and recreational equipment  
Stationary turbines  
Textile equipment  
Transportation, diesel engines  
Valves  
Wire processing equipment

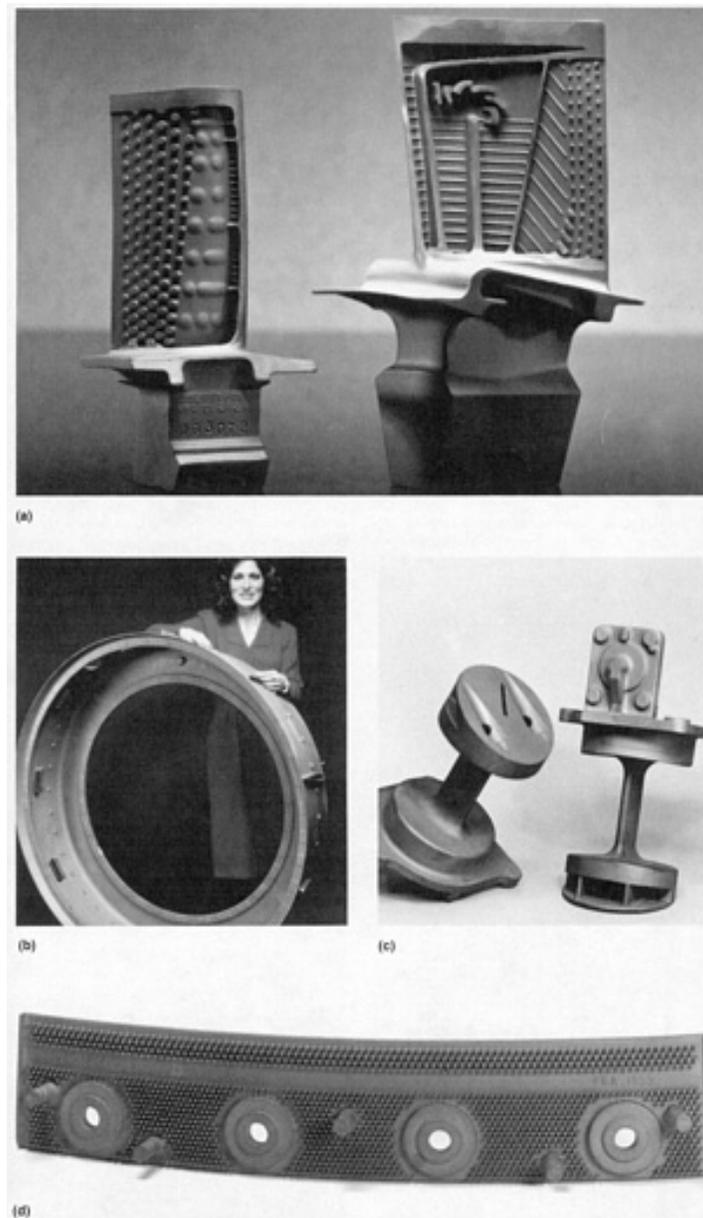


Fig. 4 Some aircraft and aerospace applications for investment castings. (a) Single-crystal turbine blades investment cast using complex ceramic cores. Courtesy of Pratt and Whitney Aircraft. (b) 17-4PH stainless steel fan exit case; weight: 96 kg (212 lb). Courtesy of Precision Castparts Corporation. (c) Aircraft fuel sensor strut cast in 17-4PH stainless steel. Both ceramic and soluble cores were used to produce the complex internal passages. Courtesy of Northern Precision Casting Company. (d) Aircraft combustion chamber floatwall. The large number of small posts required high mold and pouring temperatures. Courtesy of Pratt and Whitney Aircraft.

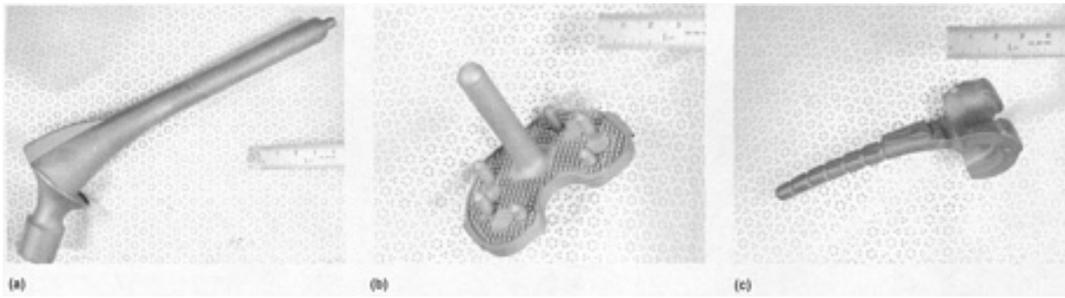


Fig. 5 Biomedical applications for investment castings. (a) Whiteside hip-femoral prosthesis. (b) Whiteside II-C knee-tibial base. (c) London elbow-humeral prosthesis. All cast in ASTM F75 cobalt-chromium-molybdenum alloy; all courtesy of Dow Corning Wright.

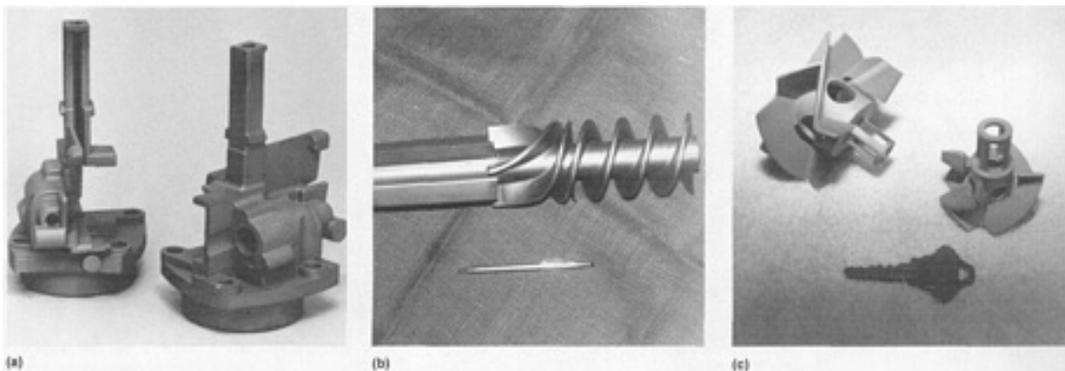


Fig. 6 Miscellaneous applications for investment castings. (a) Nosepiece for nailgun cast in 8620 alloy steel. The part is used as-cast. Courtesy of Northern Precision Casting Company. (b) Ni-Resist Type II cast iron inducer for deep well oil drilling. Courtesy of Bimac Corporation. (c) Small 17-4PH turbine vanes; the smaller weighs 71 g (2.5 oz); the larger, 185 g (6.5 oz). Courtesy of K.W. Thompson Tool Company, Inc.

## Special Investment Casting Processes

The investment casting process is highly flexible and can handle a great variety of parts with the same basic method. However, specialized versions of the process can be highly effective in reducing costs on particular types of parts. Two variations that are being increasingly applied are the Shellvest system and the Replicast CS process.

The Shellvest system provides a unique method of manufacturing small parts in high quantities at low cost. To provide large numbers of patterns at high production rates and low cost, automatic plastic injection machines are used, along with a special plastic/wax pattern material. Wax patterns are used when production requirements do not justify plastic tooling.

Pattern assemblies are made by attaching the patterns to large-diameter horizontal cardboard drums instead of conventional wax sprues. As shown in Fig. 7, the drum has a through handle for handling and for mounting in the moldmaking equipment. Each end of the drum is closed with an end plate, one of which is removable. The drum is wrapped with a thin layer of cardboard having corrugations on its inner surface and a smooth outer surface. The corrugated cardboard is attached with masking tape. Over the cardboard is a layer of thin, perforated paper called a gate master. As shown in Fig. 7, the gate master has markings printed on it that indicate the cross section of each pattern gate and exactly where it is to be mounted on the drum. This greatly facilitates the operation of mounting patterns on the drum and ensures proper spacing and orientation.



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#### Replicast Process\*

R.E. Grote, Missouri Precision Castings; Thomas S. Piwonka, University of Alabama

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## Introduction

THE REPLICAST PROCESS was developed to overcome several shortcomings of the early evaporative pattern (lost foam) casting processes--primarily the formation of lustrous carbon defects in the castings and carbon pickup in steel castings. The process has two variations:

- Replicast FM (full mold), which is nearly identical to the lost foam process

- Replicast CS (ceramic shell), which is similar to investment casting in that it employs a ceramic shell to surround the pattern

The difference between the Replicast CS process and investment casting is that in the Replicast process the pattern is made from expanded polystyrene (EPS) and is surrounded by a much thinner shell than in investment casting. Figure 1 shows a flow chart of the Replicast CS process, and Table 1 compares the essential features of the Replicast CS and investment casting processes.

**Table 1 Essential features of the Replicast CS and investment casting processes**

Feature	Replicast CS	Investment casting
Pattern manufacture	Partially expanded EPS beads are blown into aluminum tooling and completely expanded. Finished patterns are lightweight, have high density, and provide good surface finish and excellent dimensional accuracy.	Softened wax is injected at high pressure into a metal tool. The wax is subject to shrinkage and deformation, and it is expensive and heavy. It is reclaimable to some degree.
Shell manufacture	Successive coats of refractory slurry and stucco are applied. Three or four coats are required, resulting in a relatively light and easy-to-handle shell. Firing at 925-1000 °C (1700-1830 °F) for 5 min removes the EPS pattern and hardens the shell.	Successive coats of refractory slurry and stucco are applied. Five to ten coats are required; completed shells are often heavy and difficult to handle. Firing at 1000 °C (1830 °F) for 20 min removes the residual wax and hardens the shell.
Pouring	Thin ceramic shell is surrounded by loose sand vibrated to maximum bulk density, and the vacuum is applied during pouring to prevent shell breakage.	Metal is frequently poured into hot, unsupported shells; breakage is possible.

Source: Ref 2

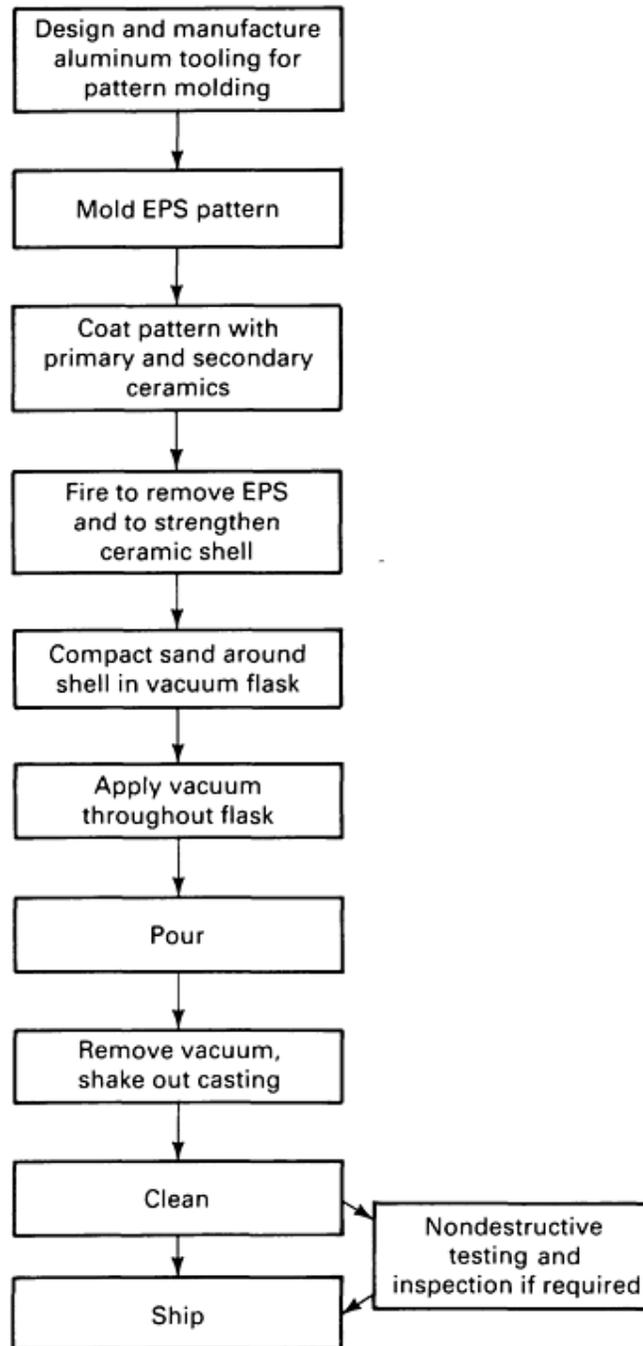


Fig. 1 Flow chart of the Replicast CS process. Source: Ref 1

The Replicast CS process is the one that is commonly referred to as Replicast. More information on lost foam casting is available in the article "Sand Molding" in this Volume (see the discussion of the evaporative foam process in the section "Unbonded Sand Molds").

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## Note

\* Replicast is a registered trademark of the Steel Castings Research and Trade Association (SCRATA), Sheffield, England.

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## Replicast Process\*

R.E. Grote, Missouri Precision Castings; Thomas S. Piwonka, University of Alabama

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## Process Details

Pattern Production. Aluminum tooling must be developed in order to produce the EPS pattern. The tooling is made from cast aluminum and incorporates risers, cored passages, and so on, wherever possible. The necessity of incorporating styrofoam fill openings, vents, steam, air, and water lines makes the tooling complex and more expensive than metal green sand equipment. However, the use of insert-type tooling can significantly reduce tooling costs.

Patterns are produced from size "T" high-density polystyrene beads. The beads are preexpanded using steam or vacuum, passed into the aluminum tooling, and expanded again to fill the tool cavity and to bond with each other. The high-density EPS used in the Replicast process yields a better casting surface finish than the low-density material used for lost foam patterns.

The following steps are required for the production of EPS patterns:

- Close and hydraulically clamp molding box halves
- Blow in preexpanded styrofoam beads
- Close off styrofoam fill guns, then inject steam to expand and bond the beads
- Stop the steam and run water through cooling lines
- Open the mold box
- Eject pattern from cavity

The finished EPS pattern has a density of 10.75 to 12.90 g/cm<sup>3</sup> (2.5 to 3.0 lb/ft<sup>3</sup>) and a smooth, hard surface. Minimal shrinkage of the EPS pattern occurs with age. Coating the EPS pattern with ceramic immediately after fabrication produces no detrimental effects.

Pattern Assembly. In some cases, the EPS pattern is complete as-molded and is sent to the ceramic coating area. More frequently, additional work is needed to produce a complete pattern assembly. Risers can be glued to the pattern, and ceramic pouring cones can be added. Gluing is done by spray, brush, or glue gun. A low ash content hot-melt glue is used for brush or gun application. A low-melting wax is used to fill and smooth the glue joints. Figure 2 shows completed pattern assemblies ready for the ceramic coating area.



Fig. 2 Completed EPS pattern assemblies ready for ceramic coating. Courtesy of R.E. Grote, Missouri Precision Castings

Ceramic Coating and Firing. The next step in the Replicast process is the formation of a thin ceramic shell over the EPS pattern assembly. This is done by using techniques similar to those found in investment casting. The pattern assembly is first dipped into a ceramic slurry and then stuccoed using a granular refractory in a fluidized bed or rain sander. The shell is allowed to air dry for a minimum of 1 h. This process is repeated until the desired shell thickness is achieved. Thickness depends on product size, shape, and section thickness; shell thicknesses of 3.2 to 4.8 mm ( $\frac{1}{8}$  to  $\frac{3}{16}$  in.) are common.

Completed shells are then fired at 925 to 1000 °C (1700 to 1830 °F) to remove the EPS pattern material completely and to harden the ceramic. The shell is then embedded in an unbonded sand mold to support the thin ceramic shell and to prevent breakage. This allows the use of shells thinner than those employed for investment casting.

unbonded loose sand, which is vibrated to achieve maximum bulk density. A vacuum is applied to the flask immediately before pouring. Pouring is then accomplished using conventional techniques. The vacuum can be switched off a few minutes after pouring.

Pouring. The completed ceramic shells are transported to the foundry, where several shells are placed into a molding flask. The flask incorporates a plenum chamber through which air can be extracted to create a vacuum. The flasks are filled with

Cleaning. After cooling, the castings are shaken out and moved to a cleaning area. The brittle ceramic shell fractures easily and tends to break off the casting surface. After initial abrasive blast cleaning, conventional cleaning techniques are implemented (see the article "Blast Cleaning of Castings" in this Volume).

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#### Replicast Process\*

R.E. Grote, Missouri Precision Castings; Thomas S. Pivonka, University of Alabama

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### Process Capabilities

Outstanding features of the Replicast process include:

- Surface finish comparable to that obtainable in conventional investment casting
- Elimination of cores through the use of core inserts in patternmaking tooling; patterns can often be produced in one piece, including risers
- Improved casting yields because of the elimination of downsprues, runners, and so on
- High as-cast quality levels with regard to casting integrity and dimensional accuracy

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#### Replicast Process\*

R.E. Grote, Missouri Precision Castings; Thomas S. Pivonka, University of Alabama

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### Dimensional Accuracy

The dimensional accuracy of Replicast parts is comparable to that of investment castings. Based on measurements of Replicast parts of various sizes, the following tolerances on linear dimensions are recommended:

Dimension, mm (in.) <sup>(a)</sup>	Tolerance, mm (in.)
2.5-102 (0.1-4)	±0.25 (±0.010) or 0.75% of dimension, whichever is greater
104-305 (4.1-12)	±0.76 (±0.030)
307-610 (12.1-24)	±1.52 (±0.060)

(a) Nonrisered surfaces

With no wear occurring on tooling, long-term dimensional reproducibility is readily obtainable.

The smooth surface finish of Replicast parts, combined with near zero draft molding capabilities, can result in the elimination of considerable machining. Cast bolt holes, virtually flat flange faces, and blind and through holes as small as 9.6 mm ( $\frac{3}{8}$  in.) in diameter can be attained. For those surfaces requiring finish machining, an allowance of 1.6 to 3.2 mm ( $\frac{1}{16}$  to  $\frac{1}{8}$  in.) is usually sufficient.

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Replicast Process\*

R.E. Grote, Missouri Precision Castings; Thomas S. Piwonka, University of Alabama

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## Applications

Because the EPS pattern material is completely removed from the ceramic shell during firing, the Replicast process is suitable for pouring any metal or alloy without fear of carbon pickup. The process is commonly used to produce carbon, low-alloy, and stainless steel castings. Figure 3 illustrates two typical applications.

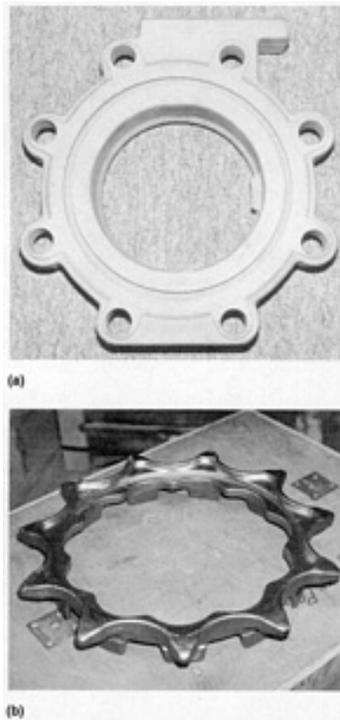


Fig. 3 Two applications of Replicast steel parts. (a) CF-8M stainless steel 150 mm (6 in.) butterfly valve body. The part is approximately 305 mm (12 in.) in outside diameter, 64 mm ( $2\frac{1}{2}$  in.) thick, and weighs 11 kg (25 lb). Note as-cast bolt holes and O-ring groove. (b) 8640 steel drive sprocket for armored personnel carrier. The part is 510 mm (20 in.) in outside diameter, 114 mm ( $4\frac{1}{2}$  in.) thick, and weighs 28 kg (62 lb). Sprocket teeth are used as-cast, resulting in a significant savings in machining costs. Courtesy of R.E. Grote, Missouri Precision Castings

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### Replicast Process\*

R.E. Grote, Missouri Precision Castings; Thomas S. Piwonka, University of Alabama

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### References

1. R.E. Grote, Replicast Ceramic Shell Molding: The Process and Its Capabilities, *Trans. AFS*, Vol 94, 1986, p 181-186
2. M.C. Ashton, S.G. Sharman, and A.J. Brookes, The Replicast FM (Full Mold) and CS (Ceramic Shell) Process, *Trans. AFS*, Vol 92, 1984, p 271-280

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### Rammed Graphite Molds

Dan Kihlstedius, Oregon Metallurgical Corporation

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### Introduction

RAMMED GRAPHITE is used to produce molds for the casting of reactive metals and alloys such as titanium and zirconium (see the articles "Titanium and Titanium Alloys" and "Zirconium and Zirconium Alloys" in this Volume). Because such metals and alloys react vigorously with silica, conventional molding sands cannot be used.

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## Rammed Graphite Molds

Dan Kihlstadius, Oregon Metallurgical Corporation

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### Production of Rammed Graphite Molds

**Mold Mixture.** Rammed graphite molds are manufactured from a mixture consisting primarily of finely divided graphite having a closely controlled particle size and size distribution. To this mixture, nominally 10% water, 10% pitch, 7% baumé syrup, and 3% starch are added. These ingredients are required for good coating of the graphite grains and for the development of optimal mold properties. The mold mixture has the appearance of green sand (Fig. 1). The mold mixture is pneumatically tamped (rammed) around a pattern, stripped from the pattern, air dried, baked, and fired.

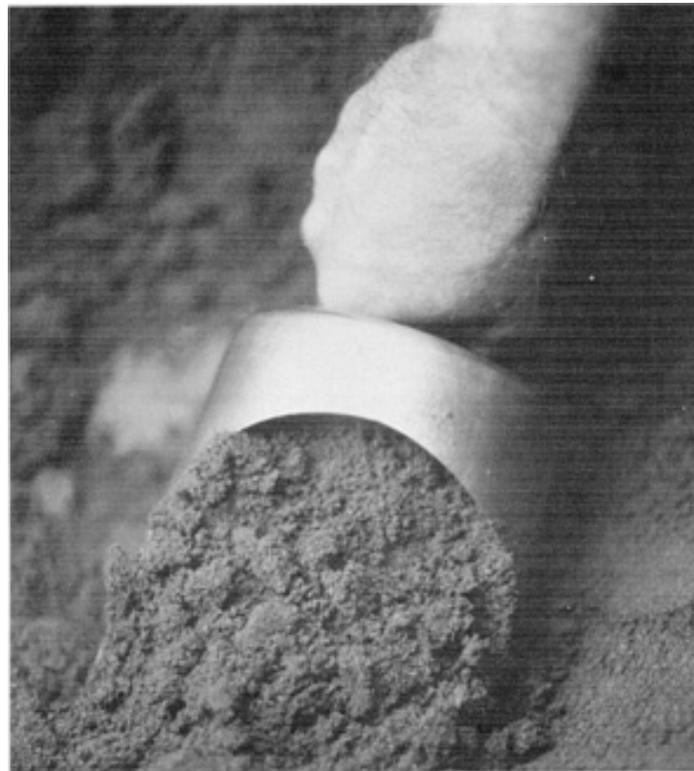
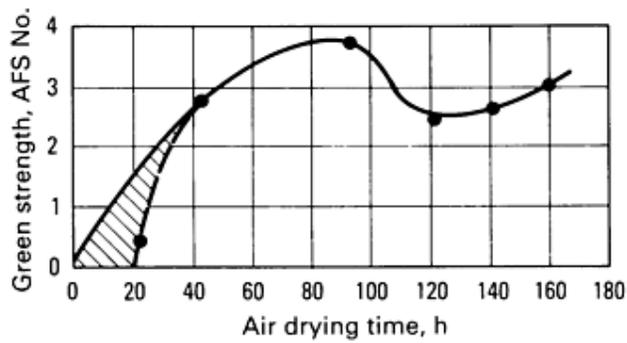
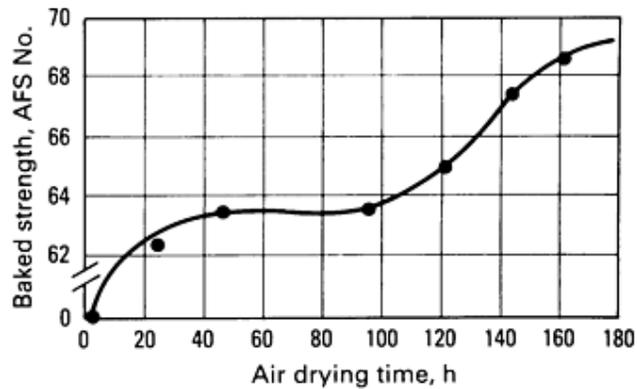


Fig. 1 Graphite mold mixture, which resembles green sand in appearance

Air drying influences both the green and baked strengths of the mold (Fig. 2). Molds are air dried on racks; after 24 h of air drying, the mold reaches about 13% of its maximum green strength. Maximum green strength is achieved after 94 h of air drying.



(a)



(b)

Fig. 2 Effect of air drying time on green strength (a) and baked strength (b) of graphite molds

Baking. After air drying, molds are baked at 175 °C (350 °F). Baking time depends on mold section thickness and geometry. All moisture must be removed during baking to prevent steam generation and potential mold cracking during firing.

Firing removes all of the remaining volatile carbonaceous materials from the mold and develops final bonds. The strength and hardness of the mold increase with firing temperature (Fig. 3); best results are obtained at minimum firing temperatures of 870 °C (1600 °F). Firing is performed in a reducing atmosphere to prevent oxidation of the graphite. The fired mold is rigid and is similar to ceramic in texture and hardness (see the article "Ceramic Molding" in this Volume).

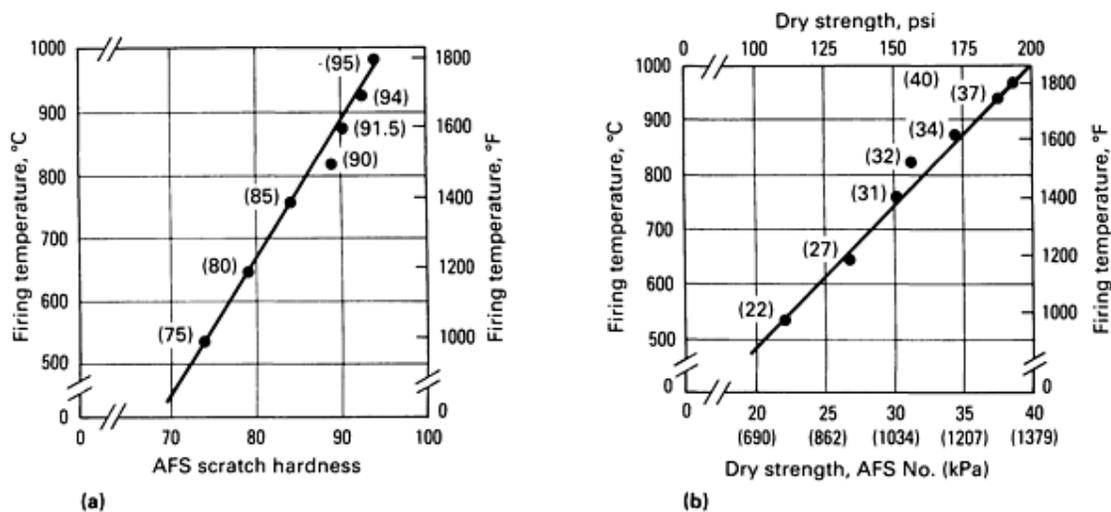


Fig. 3 Effect of firing temperature on the hardness (a) and strength (b) of graphite molds

Storage. After firing, molds should be stored in a controlled environment (minimum temperature of 25 °C, or 75 °F, and relative humidity below 40%) to prevent moisture absorption. Moisture absorption is particularly rapid at high relative humidities and low temperatures.

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#### Rammed Graphite Molds

Dan Kihlstadius, Oregon Metallurgical Corporation

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#### Molding Problems

Although a correct binder system can be developed for any graphite particle size distribution, mold permeability will vary with the type and amount of binder used. Mold shrinkage can be predicted and controlled if ramming pressure and binder composition are constant.

Graphite mixing problems may also be related to the pitch and syrup ingredients. Good mixing should result in uniform coating of the graphite grains with pitch and the water-syrup mixture. Pitch or syrup in excess of that required for coating of the graphite particles may cause balling of the mold mixture. Pitch balls are aggregates of excess graphite and graphite fines containing a greater-than-average amount of syrup. Mold mixtures become more susceptible to balling as the percentage of reclaimed graphite fines in the mixture increases. Therefore, control of graphite particle size distribution is crucial.

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#### Permanent Mold Casting

Revised by Charles E. West and Thomas E. Grubach, Aluminum Company of America

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#### Introduction

IN PERMANENT MOLD CASTING, sometimes referred to as gravity die casting, a metal mold consisting of two or more parts is repeatedly used for the production of many castings of the same form. The liquid metal enters the mold by gravity. Simple removable cores are usually made of metal, but more complex cores are made of sand or plaster. When sand or plaster cores are used, the process is called semipermanent mold casting.

Permanent mold casting is particularly suitable for the high-volume production of castings with fairly uniform wall thickness and limited undercuts or intricate internal coring. The process can also be used to produce complex castings, but production quantities should be high enough to justify the cost of the molds. Compared to sand casting, permanent mold casting permits the production of more uniform castings, with closer dimensional tolerances, superior surface finish, and improved mechanical properties. Figure 1 shows castings made by the permanent mold process.

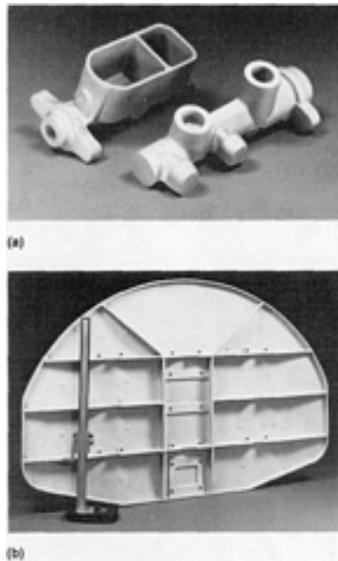


Fig. 1 Two examples of aluminum alloy castings made in permanent molds. (a) Alloy 356 brake master cylinder. (b) Alloy 356 basketball backboard. Courtesy of Stahl Specialty Company

Permanent mold casting has the following limitations:

- Not all alloys are suitable for permanent mold casting
- Because of relatively high tooling costs, the process can be prohibitively expensive for low production quantities
- Some shapes cannot be made using permanent mold casting, because of parting line location, undercuts, or difficulties in removing the casting from the mold
- Coatings are required to protect the mold from attack by the molten metal

Metals that can be cast in permanent molds include the aluminum, magnesium, zinc, and copper alloys and hypereutectic gray iron. Practical sizes of permanent mold castings differ according to materials cast, part configuration, and number of parts needed.

**Aluminum Alloys.** In high production, permanent mold castings weighing up to 70 kg (150 lb) have been made from aluminum alloys in casting devices. However, much larger castings can be produced. For example, aluminum alloy engine blocks with a trimmed weight of 354 kg (780 lb) have been produced in a four-section permanent mold having a vertical parting line.

Magnesium alloys, despite their comparatively low castability, have been cast in permanent or semipermanent molds to produce relatively large and complex castings. For example, an 8 kg (17.7 lb) housing for an emergency power unit was poured from Alloy AZ91C in a semipermanent mold. In another application, 24 kg (53 lb) spoolhead castings 760 mm (30 in.) in diameter were produced from Alloy AZ92A in a two-segment permanent mold with vertical parting.

Copper alloy permanent mold castings weighing more than 9 kg (20 lb) can rarely be justified.

Gray Iron. The production of gray iron castings in permanent molds is seldom practical when the castings weigh more than 13.6 kg (30 lb).

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## Permanent Mold Casting

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### Casting Methods

Manually operated permanent molds may consist of a simple book-type mold arrangement (Fig. 2a). For castings with high ribs or walls that require mold retraction without rotation, the manually operated device shown in Fig. 2(b) can be used. With either type of device, the mold halves are separated manually after releasing the eccentric mold clamps.

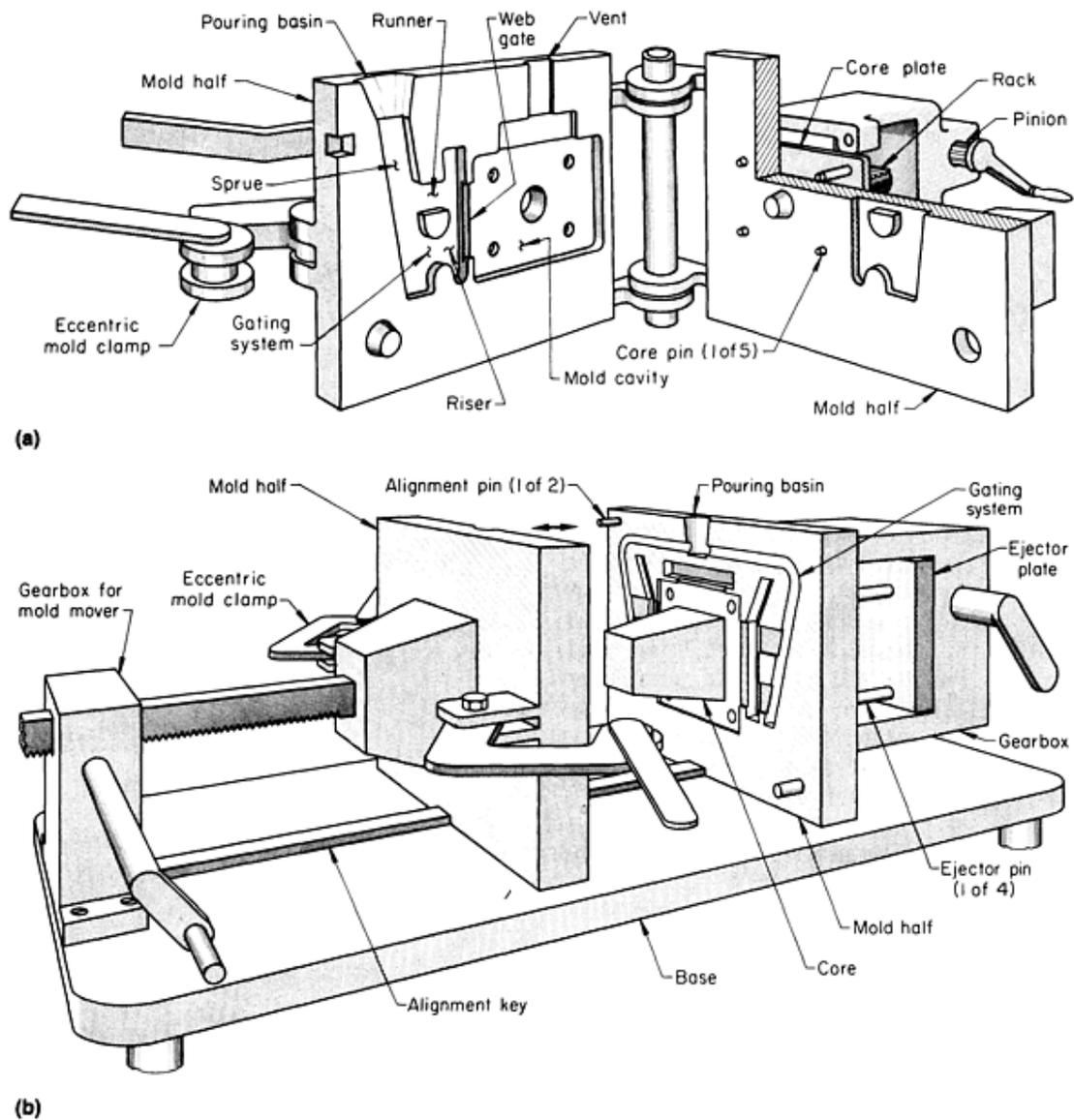


Fig. 2 Two types of manually operated permanent mold casting machines. (a) Simple book-type mold for shallow-cavity castings. (b) Device with straight-line retraction for deep-cavity molds

Semiautomatic Devices. For high-volume production, manual drives are replaced by two-way air or hydraulic mechanisms. These units can be programmed to open and close in a preset cycle. Therefore, the operation is automatic except for pouring of the metal and removal of the castings.

Figure 3 shows an automatic casting device equipped with automatic mold, core, and insert-setting components; the only manual operations are pouring of the metal and placing the inserts in the setter. For simple castings, this type of device can be fully automatic.

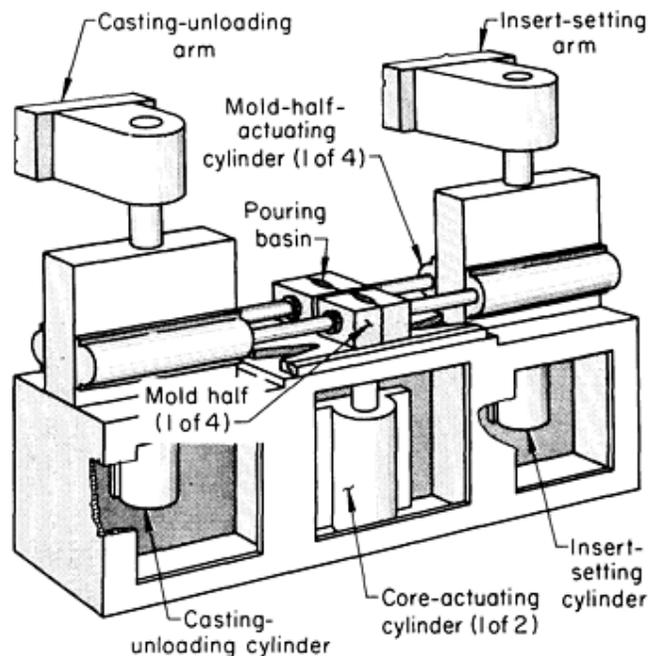


Fig. 3 Automatic permanent mold casting machine with a setter for cast-in inserts

Devices for Horizontal Parting and Tilt Casting. The mold parting for the casting devices shown in Fig. 2 and 3 is in a vertical plane, which is often the preferred position for mold opening and casting removal. Many castings, however, are best poured with the parting in a horizontal plane. Some castings with horizontal parting are poured using devices with a tilting mechanism; thus pouring is done with the parting in the horizontal plane, and the mold position is then changed to permit removal of the casting with parting in the vertical plane.

Some castings are partially poured with the parting in the horizontal plane and then slowly rotated while the pouring is completed. For example, in casting a frame for a duplicating machine, pouring with the parting in a vertical plane required a long drop of molten metal, which resulted in splashing and severe turbulence and produced unacceptable castings. To eliminate the long drop of molten metal, the mold was placed in a tilt device that allowed the metal to be introduced into the mold with the parting oriented horizontally. The main body of the casting was poured with the mold in this position. The lower offset segment of the casting was then gently filled as the mold was rotated 90° to place the parting in a vertical plane. At this position, the casting was allowed to solidify and was then removed from the mold.

Turntables. Small, lightweight castings can be poured and removed manually, but manual handling becomes increasingly difficult as pouring temperatures rise and casting weight increases. The casting process must then be automated. This is often done by using casting machines mounted on a turntable.

A commonly used turntable accommodates 12 casting devices, as shown in Fig. 4, and completes one revolution in 2 to 7 min. Steps in the casting process, which include pouring, mold coating, core setting, solidification, and ejection, are completed progressively as the casting devices pass through the various work stations. With this type of equipment, maximum production rates are achieved when all 12 devices have identical molds. However, different molds can be used in all 12 devices.

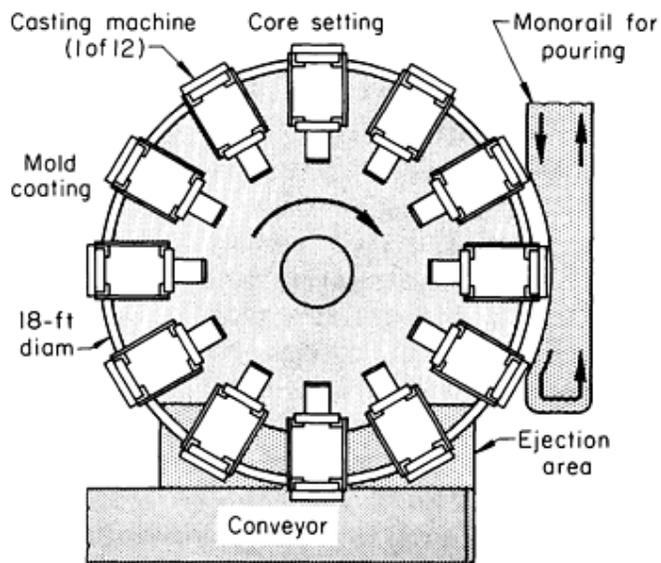


Fig. 4 Schematic of a 12-machine turntable for automatic permanent mold casting

In low-pressure die casting, the mold is placed in a casting device above a sealed airtight chamber that contains a crucible holding molten metal (Fig. 5a). A fill tube extends from the mold down into the molten metal bath. The casting is made by pressurizing the chamber and forcing the metal up into the mold. The metal in the fill tube acts as the riser; this gives low-pressure die casting very favorable casting yields. The low-pressure method lends itself to automation, and it usually runs at lower mold temperatures and with shorter cycle times than conventional gravity-poured permanent mold methods. The rapid solidification rates associated with low-pressure casting result in castings with finer grain size, smaller dendrite arm spacings, and enhanced mechanical properties.

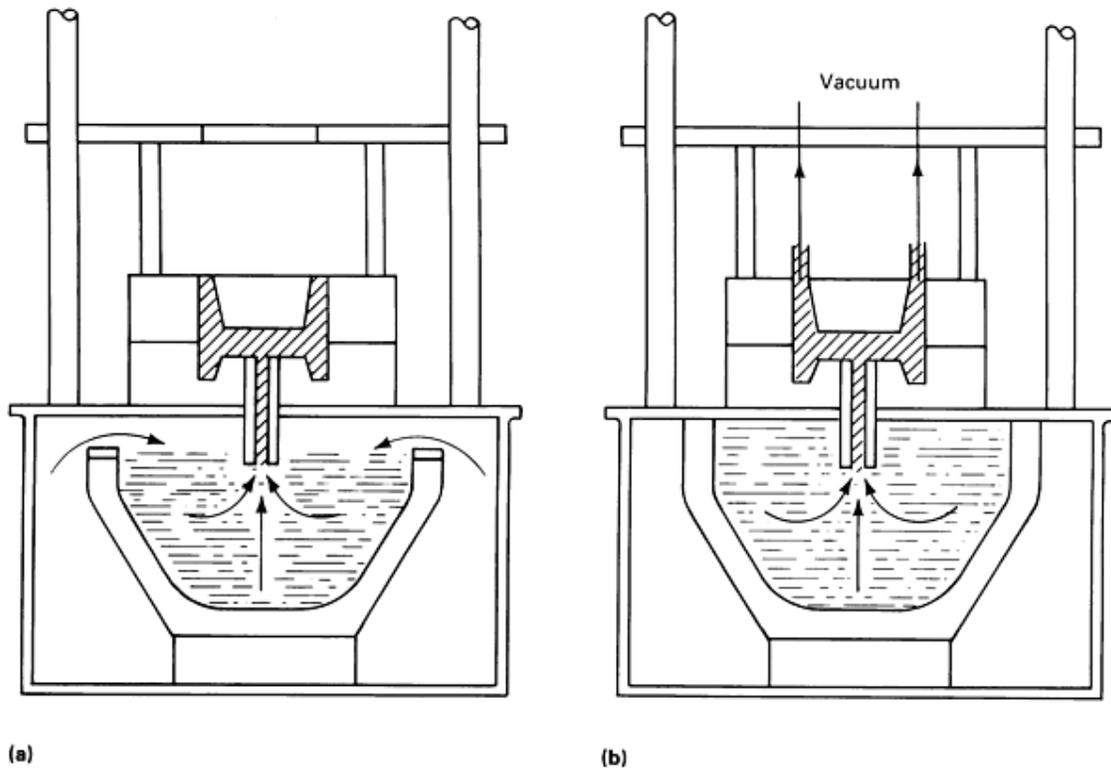


Fig. 5 Schematics of low-pressure (a) and vacuum casting (b) units used with permanent molds

Vacuum casting is similar to low-pressure casting, except a vacuum is created within the mold cavity and the metal is pulled rather than pushed into the mold (Fig. 5b). Excellent mechanical properties and high production rates are often realized in vacuum casting because of the low mold temperatures associated with the method. As with low-pressure die casting, the metal in the fill tube acts as a riser, and excellent metal yields are obtainable. The process lends itself to

automation, and the result is the ability to produce large quantities of high-quality castings at a competitive price. The process is usually associated with smaller castings and requires specialized, complex mold designs to induce the vacuum properly.

In constant-level pouring, the mold is placed in a device, and as the metal is poured into the mold, the mold is lowered at a rate consistent with the rate of fill, effectively pouring the metal at one constant level. If the metal source, rather than the mold, is in the device, the metal source is raised and the mold remains stationary. This method virtually ensures lamellar flow and greatly reduces oxide formation.

In centrifugal casting, cylindrical or symmetrically shaped castings are poured using the centrifugal force of a spinning mold to force the metal into the mold. The sprue is located at the center of rotation. The force generated by the spinning of the mold helps the metal fill thin casting sections and maintains good contact between the metal and the mold. This provides a higher rate of heat flow and a more rapid solidification rate, resulting in increased mechanical properties. Multiple molds can be used in centrifugal casting, and care should be taken to design gating systems that produce little or no turbulence. Segregation can be a problem with alloys containing immiscible or heavy elements, such as tin in the 850 aluminum alloys. These alloys require special casting practices. More information on centrifugal casting is available in the article "Centrifugal Casting" in this Volume.

Squeeze casting is another variation of the permanent mold process. It consists of pouring a specific amount of metal into the lower half of a mold, closing the mold, and then allowing the metal to solidify under pressure. One of the advantages of squeeze casting is the casting yield, because no gating system is required. More information on this process is available in the article "Squeeze Casting" in this Volume.

Continuous casting is usually considered an ingot-making process (see the article "Continuous Casting" in this Volume). However, it can also be used to make small, solid cylindrical castings. It is primarily used with the 850 series aluminum-tin alloys. Continuous casting can be done either horizontally or vertically, but vertical casting is the most common.

The process consists of a highly chilled mold with a movable base. The metal is poured into the mold as the base is lowered. As the solidified portion of the casting is lowered out of the mold, the water cooling the mold flows onto the casting, increasing the solidification rate of the casting. The molten metal flowing into the top of the mold acts as the casting riser. The lack of a gating and risering system provides for a good casting yield, and the rapid solidification rate gives continuous cast material good mechanical properties.

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## Permanent Mold Casting

Revised by Charles E. West and Thomas E. Grubach, Aluminum Company of America

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## Mold Design

A simple permanent mold is shown in the book-type casting device illustrated in Fig. 2. Here the two mold halves are hinged on a pin and aligned. The mold cavity with the mold halves closed determines the shape of the casting. The casting is poured by means of the sprue and runners to the riser, which is provided with a web gate to the mold cavity. The cavity is vented to allow air to escape. The plate-shape cavity shown in Fig. 2 required five core pins, which were moved by means of the manually driven gearbox mounted on the back of the right-hand mold half.

In operation, the mold halves are closed and locked. Metal is then poured to fill the gating system and the mold cavity. After the metal has solidified, the mold is opened, leaving the casting on the core pins. The core pins are withdrawn, and the casting is removed manually.

The mold shown in Fig. 2 is designed with the parting vertical and in a single plane. This mold could also be designed for horizontal parting or with parting in two or more planes, and instead of side gating, it could have bottom gating (Fig. 6a).

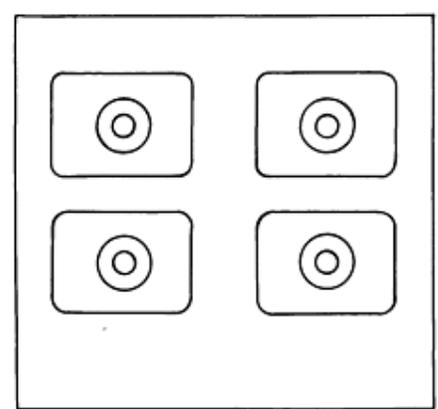
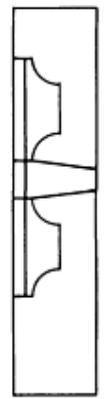
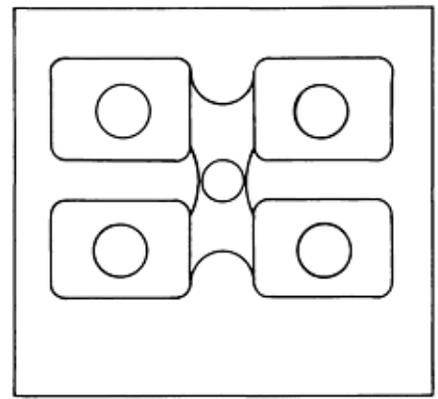
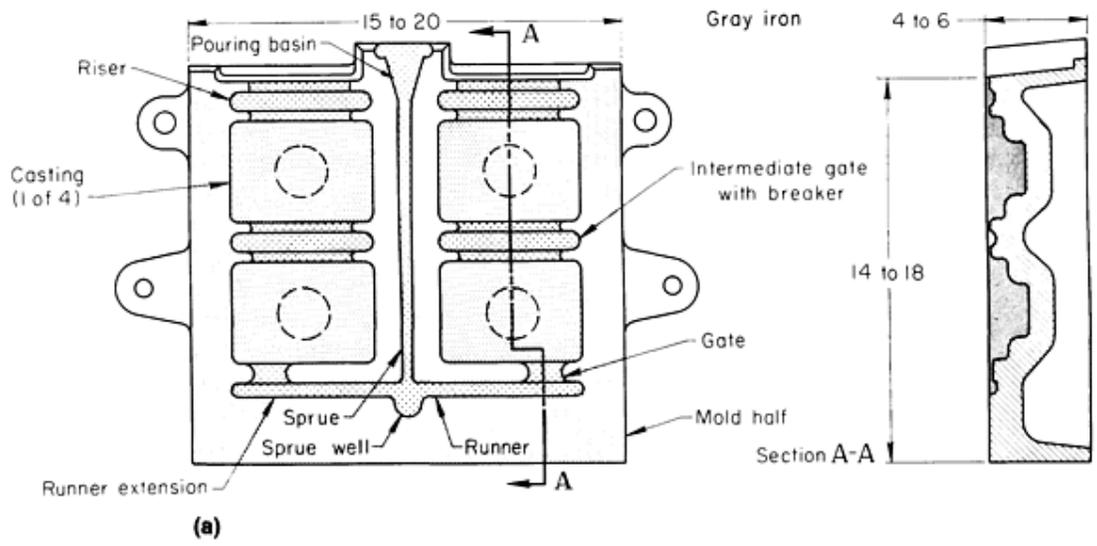


Fig. 6 Bottom-gated permanent mold (a) with stacked cavities for four castings. (b) Multicavity mold with low-pressure gating system. (c) Alternate gating system for low-pressure or vacuum casting

The mold shown in Fig. 2(b) is also designed for vertical parting and side gating. However, because of the deep cavity and correspondingly long core required, a hinged-type mold cannot be used. The mold shown is opened and closed by straight-line movement of one mold half to and away from the other mold half, which remains fixed.

Undercuts on the outside of a casting complicate mold design and increase casting cost because additional mold parts or expendable cores are needed. Complicated and undercut internal sections are usually made more easily with expendable cores than with metal cores, although collapsible steel cores or loose metal pieces can sometimes be used instead of expendable cores.

Isolated heavy sections completely surrounded by thin areas should be avoided. Thin deep ribs should also be avoided because they are likely to cause cold shuts and misruns. Adequate draft must be allowed in order to prevent ribs from sticking and breaking off in the mold.

**Casting Ejection.** Only the most simple permanent mold castings can be ejected from the mold with no mechanical help. Most castings are ejected by well-distributed ejector pins, or are confined in one mold half during opening of the mold and then ejected by the withdrawal of the retaining core or cores. It is important that the casting remain in the correct mold half until ready for ejection.

The number of castings per mold is a major consideration in designing the mold; the objective is to have the optimum number of cavities per mold that will yield acceptable castings at the lowest cost. Except for very small and thin castings, the machine cycle time increases as the weight of the metal being cast per mold increases. However, these increases are not directly proportional. A mold with the maximum number of cavities will often produce more castings per unit of time than a mold with a smaller number of cavities that was designed to operate on a shorter cycle. This is because there is a minimum solidification time for every casting, regardless of the number of cavities in the mold. The number of rejects sometimes increases as the number of cavities is increased, but this is usually offset by the greater productivity. For relatively simple castings, the cavities can be placed one above the other. This permits maximum use of the face area of the mold. However, for more complex castings, especially those for which there are significant projections in the cavities, it is usually necessary to gate each cavity individually.

For low-pressure casting, the mold parting plane will be horizontal, and the gating system shown in Fig. 6(a) will be replaced by the system shown in Fig. 6(b). In Fig. 6(b), the metal enters the mold through a centrally located fill tube and is distributed to the casting cavities by the gating system shown. The gating system also acts as a riser. An alternate system (Fig. 6c) is often used in low-pressure and vacuum casting. Here the metal enters the cavity directly, reducing the need for an additional gating system, decreasing feeding distances, and increasing casting yield.

**Progressive Solidification.** Alloys should be cast so that solidification takes place progressively toward the risers, which are generally to one side or on top of the casting. To achieve this solidification pattern, thinner sections of the casting should be away from the gating system, and heavy sections should be adjacent to it. Rib sections and thin walls vent and fill more easily when they are vertical, but filling a vertical mold cavity may promote turbulence in the molten metal, resulting in excessive dross; consequently, the mold should be tilted when being poured. To avoid oxide contamination, dross traps or filters are placed in the gating system as shown in Fig. 7. Steel or fiberglass can be used to filter the metal and reduce metal velocity. Tilt molding can be used for large, vertically gated castings.

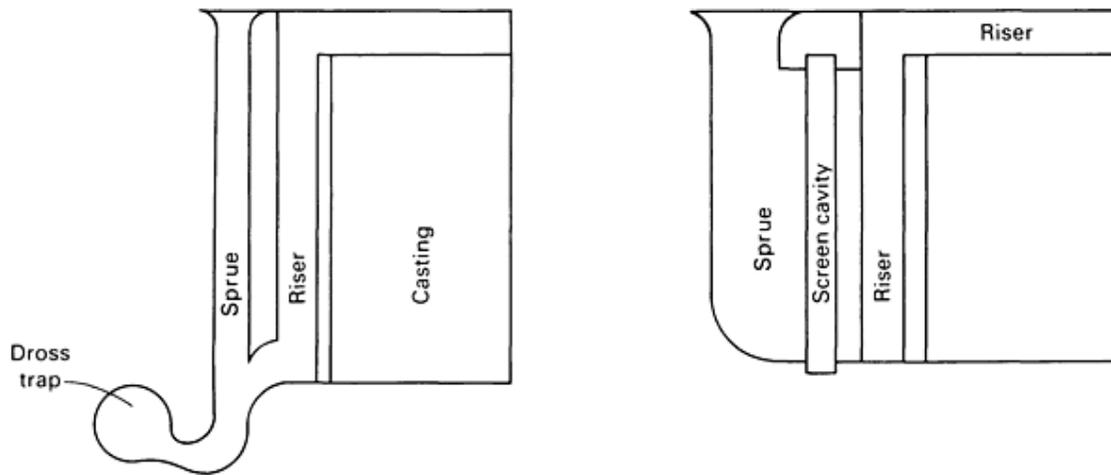


Fig. 7 Gating systems with dross traps or screens

In designing a permanent mold, the part is laid out in the desired orientation, and the mold is designed around it, allowing sufficient space for gating, for the seal needed to prevent metal leakage, and for coring and mold inserts. It is common practice to contour the back of the mold so that its exterior conforms roughly with the cavity. This permits a more even temperature distribution and heat dissipation. For castings with heavy sections, the adjacent mold sections are generally heavier. For aluminum castings, a ratio of three or four mold wall thicknesses to one casting wall thickness is often used, but a mold wall this thin cannot always be used in making thin-wall castings without jeopardizing mold stability. Ribbing is often used to stiffen the mold structure, but excessive ribbing can cause distortion by increasing the temperature differential between inner and outer mold surfaces.

Temperature stability must also be considered in the design of molds for thin-wall castings. Thin-wall castings are sensitive to temperature changes and will misrun readily. Consistent, relatively high mold temperatures are required; this necessitates the use of thicker, more massive molds.

Vents. The gap that exists between the mold halves after closing is sometimes large enough to permit air to escape and thus prevent misruns and cold shuts. Frequently, however, vents must be added to allow the air to escape as the mold is filled. Mold coatings can also be used for this purpose. Some form of venting also must be provided in die casting (see the article "Die Casting" in this Volume).

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## Permanent Mold Casting

Revised by Charles E. West and Thomas E. Grubach, Aluminum Company of America

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## Gating Systems

Permanent mold castings can be gated from the top, side, or bottom. Single or multiple gates can be used.

**Top Gating.** In this arrangement, the sprue and the riser are usually the same. Thin sections are placed farthest from the gate so that directional solidification is toward the gate. After pouring, the gate functions as a riser. The metal in the riser solidifies last, thus ensuring sound metal throughout the casting.

**Side gating** is frequently used, particularly for aluminum castings. In this gating system, the riser is at the top of the casting. The gate extends up the side of the casting to nearly 90% of its height, which ensures that the metal at the top of the casting and in the riser is hotter than the first metal to enter the mold. Thin sections should be placed remote from the gate and riser. The direction of solidification is from the mold cavity toward the gate and riser so that shrinkage porosity is minimized.

Gating systems for permanent molds are less flexible than those for sand molds and are nearly always located in parting planes. Gating must supply metal fast enough to fill all sections of the casting with minimal turbulence. Gating systems that permit minimal turbulence are especially important in the casting of aluminum and magnesium alloys because turbulence creates excessive amounts of oxide, which may cause defective castings. Molds for aluminum and magnesium alloys are poured in the vertical position or tilted from vertical. With this method, air is readily displaced and vented off at the mold parting.

Bottom Gating. If bottom-gating systems are not properly designed, the last metal into the casting (the hottest metal) will be at the bottom of the casting. This will interfere with gravity feeding and progressive solidification and will produce castings with shrinkage porosity. The same is true, even with proper gating, if the casting is too thick. Bottom gating in conventional permanent molds is usually used on castings with thinner sections.

With low-pressure or vacuum casting, bottom gating is the most widely used system. The difference is that in these methods the metal is moved into the mold by a pressure differential. This pressure differential allows the metal to feed into the casting during solidification.

In addition to supplying liquid metal to compensate for casting shrinkage, risers reduce the velocity of the metal before it enters the cavity and help sustain the mold temperature. The number of points at which metal is admitted to the mold cavity depends on the section thickness and the distance the metal must flow. Excessive flow through too few inlets may result in hot spots and consequent shrinkage. Sprues are usually restricted in area to choke off and prevent dross and air from entering the cavity. Because gating systems are often easier to enlarge than to reduce and because oversize gating can slow the cycle, it is common practice to start with small gates and then to enlarge them if necessary.

Misruns have several possible causes, including entrapped air, low mold temperature, or low pouring temperature. Misruns are often caused by a combination of two or more such conditions. Adequate venting is the simplest way to eliminate entrapped air. Increasing the mold temperature or the pouring temperature, or both, may eliminate misruns, but is likely to cause other defects, such as porosity. One common approach is to increase the mold temperature at critical locations by applying heat from an external source (antichill) or by using an insulating type of mold coating in the specific location of the mold to prevent the liquid metal from chilling in a specific area.

Shrinkage porosity associated with gating can be extremely difficult to eliminate because casting design sometimes precludes ideal metal feeding. This may necessitate complete redesign of the gating system and a change in the casting operation.

Dross. Gating systems often must be revised to eliminate excessive formation of dross. Fiberglass, metals, and ceramics are used in gating systems to remove dross, slow metal velocity, and help prevent further oxide generation.

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## Permanent Mold Casting

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## Cores

The cores used in the permanent mold process can be of gray iron, steel, sand, or plaster. Metal cores can be movable or stationary. Stationary cores must be perpendicular to the parting line to permit removal of the casting from the mold, and they must be shaped such that the casting is readily freed. Metal cores not perpendicular to the parting line must be movable so that they can be withdrawn from the casting before it is removed from the mold.

When sand or plaster cores are used in a permanent mold, the process is referred to as semipermanent molding. With sand or plaster cores, which are expendable, more complex shapes can be produced than with metal cores.

The two cored passageways shown in Fig. 8 illustrate the limitations of cores in permanent mold castings. The cored passageway shown in Fig. 8(a) could be produced with metal cores. Sand or plaster cores would be needed to provide the radius of the passageway shown in Fig. 8(b), which would also be more expensive to produce.

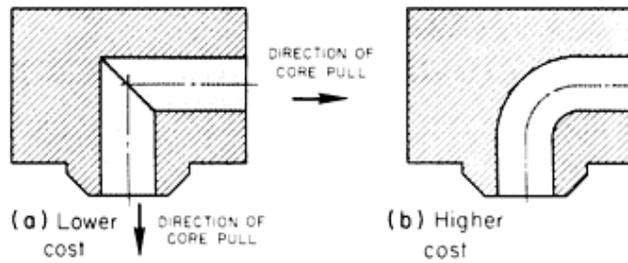


Fig. 8 Two types of cavities requiring different coring methods. (a) Corner radii must be sacrificed if metal cores are to be used. (b) Corner radii can be obtained with sand or plaster cores, but casting cost will be higher than in (a).

Cored holes in permanent mold castings can usually be held to closer tolerances, on both size and location, than in sand castings. Movable cores and stationary cores can both be machined to close dimensions and can be accurately located. Draft requirements for holes formed by steel cores are:

Hole dimensions, mm (in.)		Draft allowance per side, degrees
Depth	Diameter	
6.4 ( $\frac{1}{4}$ )	6.4 ( $\frac{1}{4}$ )	10
12.7 ( $\frac{1}{2}$ )	25.4 (1)	5
25.4 (1)	51 (2)	3
51 (2)	102 (4)	3

These drafts apply to all nonferrous metals cast in permanent molds.

Steel cores require the same coating as that applied to the mold; the dimensional accuracy of cavities made from coated steel cores is affected by the same factors that affect the accuracy of dimensions formed by coated metal molds. Unless a core is stationary, the clearance that must be provided to permit its withdrawal from the mold permits core movement, which may affect dimensions.

In terms of dimensional accuracy, sand cores have approximately the same limitations in permanent molds as in sand molds. However, when a sand core is located in a sand mold, some mold material may be disturbed or displaced. Because a permanent mold is more rigid, it provides a more accurate seat for locating a core.

Sand cores permit the casting of tortuous passages or of chambers or passages that are larger in section than the opening through the wall of the casting. Because sand cores are expendable, their removal presents no major problem.

Plaster cores are used in semipermanent molds to provide a surface finish better than that obtainable with sand or coated metal cores. For example, in a wave-guide casting requiring a smooth inside surface, the use of permeable plaster cores provides a surface finish better than that which could be obtained with coated metal cores. Plaster also has excellent insulating qualities and does not prematurely chill the metal in thin sections. With regard to dimensional accuracy, plaster cores offer no superiority over sand cores.

**Collapsible Cores.** It is preferable to avoid designs that require the use of collapsible metal cores (multiple-piece cores) in permanent molds. These cores add to the cost of the castings, and their assembly and removal increase production time. Furthermore, dimensional variations can result from the use of collapsible cores because they cannot be positioned as securely in the mold as single-piece cores or because of movement of core segments when the casting metal is poured. When castings must be designed to be made with collapsible cores, the designer should allow the loosest tolerances possible.

Despite the disadvantages of collapsible cores, they are extensively used in making certain castings. For example, nearly all of the aluminum pistons made for the automobile industry in the United States are cast in permanent molds using five-piece collapsible metal cores.

## Permanent Mold Casting

Revised by Charles E. West and Thomas E. Grubach, Aluminum Company of America

## Selection of Mold and Core Materials

Four principal factors affect the selection of materials for permanent molds and cores:

- The pouring temperature of the metal to be cast
- The size of the casting
- The number of castings per mold
- Cost of the mold material

These variables form the basis for the recommendations given in Tables 1, 2, and 3.

**Table 1 Recommended permanent mold materials**

Casting alloy	Number of pours		
	1000	10,000	100,000
<b>For small castings (25 mm, or 1 in., maximum dimension)</b>			
Zinc	Gray iron; 1020 steel	Gray iron; 1020 steel	Gray iron; 1020 steel
Aluminum, magnesium	Gray iron; 1020 steel	Gray iron; 1020 steel	Gray iron with AISI H14 inserts; 1020 steel
Copper	Gray iron	Gray iron	Alloy cast iron

Gray iron	Gray iron <sup>(a)</sup>	Gray iron <sup>(a)</sup>	Quantity not poured
<b>For medium and large-size castings (up to 915 mm, or 36 in., maximum dimension)</b>			
Zinc	Gray iron; AISI H11 <sup>(b)</sup>	Gray iron; AISI H11 <sup>(b)</sup>	Gray iron; AISI H11 <sup>(b)</sup>
Aluminum, magnesium	Gray iron	Gray iron	Gray iron; AISI H11 or H14 <sup>(c)</sup>
Copper	Alloy cast iron	Alloy cast iron	Alloy cast iron <sup>(d)</sup>
Gray iron	Gray iron <sup>(a)</sup>	Gray iron <sup>(a)</sup>	Quantity not poured

(a) Same composition as being poured.

(b) AISI H11 is used when polish is required on medium-size castings.

(c) For medium-size parts; recommended materials for large parts are gray iron with H11 inserts or solid H11 die steel.

(d) For medium-size parts; large parts are not poured in this quantity.

**Table 2 Recommended materials for small cores (<76 mm, or 3 in., in diameter and 255 mm, or 10 in., long) for permanent molds**

<b>Casting alloy</b>	<b>Recommended core materials<sup>(a)</sup></b>
Zinc	<b>Sand, plaster, gray iron, 1020 steel</b>
Aluminum, magnesium	<b>1010 or 1020 steel, sand, plaster, H11 die steel or equivalent<sup>(b)</sup>, carbon<sup>(c)</sup></b>
Copper	<b>Sand, 1020 steel, gray iron, plaster<sup>(d)</sup>, graphite<sup>(c)</sup></b>
<b>Gray iron</b>	<b>Sand, graphite, carbon, gray iron</b>

(a) Materials are listed in descending order of preference.

(b) Hardened to 42-45 HRC.

(c) For use with relatively few pours.

(d) For casting of aluminum bronzes

**Table 3 Recommended materials for large cores (>76 mm, or 3 in., in diameter and 255 mm, or 10 in., long) for permanent molds**

Casting alloy	Material for indicated number of pours <sup>(a)</sup>		
	1000	10,000	100,000
Zinc	Gray iron, 1020 steel	Gray iron, 1020 steel	Gray iron, 1020 steel
Aluminum, magnesium	Gray iron, gray iron with 1020 steel inserts <sup>(b)</sup> , sand, plaster <sup>(b)</sup>	Gray iron <sup>(b)</sup> , gray iron with 1020 or H11 inserts <sup>(b)</sup> , sand, plaster <sup>(b)</sup>	Gray iron <sup>(b)</sup> , gray iron with H11 inserts <sup>(b)</sup> , H11 die steel
Copper	Sand	Sand	Quantity not poured

(a) Materials are listed in descending order of preference.

(b) Except for openings with complex shapes, which require expendable sand cores

As indicated in Table 1, gray iron is the most commonly used mold material. Aluminum or graphite molds are sometimes used for the small-quantity production of aluminum and magnesium castings, and graphite or carbon liners on steel are sometimes used for molds for casting copper alloys (see the section "Solid Graphite Molds" in this article).

With aluminum or magnesium casting alloys, it is not unusual to obtain 100,000 castings, or more, per mold; however, molds for copper or gray iron casting alloys have a shorter life because of the higher pouring temperatures required. Gray iron molds without tool steel inserts are satisfactory for long production runs of aluminum and magnesium castings that will be machined extensively and for which surface finish is not a major consideration. In the casting of zinc, well over 100,000 pours are possible in a gray iron mold (die casting is usually selected to produce zinc castings in such large quantities).

**Mold Inserts.** Full or partial mold cavity inserts of the same material as the mold, or of a different material, are sometimes used to obtain longer mold life, or to simplify machining, handling, or replacement. Inserts can also be used for venting, cooling thin walls, and heating portions of the mold or the full cavity area. Inserts made of cast-to-shape gray iron are used for casting complex aluminum and magnesium parts that range in surface area from 320 to 2900 cm<sup>2</sup> (50 to 450 in.<sup>2</sup>). Tolerances on these parts range from ±0.76 to ±1.5 mm (±0.030 to ±0.060 in.). Inserts last for 5000 to 20,000 pours, depending on casting complexity.

Core materials are recommended in Tables 2 and 3 on the basis of performance over a wide range of coring requirements for small and large cores. An expendable core is used when the location or shape of the core does not permit its removal from the casting or when an intricate design can be obtained at less cost with materials for such cores. These materials are listed below in order of increasing preference:

- Sand (oil-bonded or resin-bonded, shell, carbon dioxide-silicate)
- Plaster
- Graphite and carbon

Mold parts can be cast to shape when the castings to be made are not complicated. Cast molds are suitable for applications for which gray iron or AISI H11 die steel is recommended in Table 3. Such cast molds are most often used when production requirements are large and when mold replacement or shipping schedules require several of the same molds.

Machining of the mold cavity is often a more significant factor in the cost of a mold than the cost of the mold material. The relative machining costs of identical molds fabricated from different materials increase as shown below. In this listing, machining costs for a gray-iron mold are taken as 1.0, and the costs include heat treatment when required:

Gray iron	1.0
Cast low-alloy steel	1.44
Gray iron with tool steel inserts	1.73
Cast tool steel	2.16

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### Mold Life

Mold life can vary from as few as 100 pours to as many as 250,000 pours (or even more), depending on the variables discussed later in this section. A mold for an aluminum piston, for example, can be expected to produce 250,000 castings before requiring repair. After the production of 250,000 more castings, the repaired mold will require a major overhaul. With repeated repairs and overhauls, the mold can produce as many as 3.5 million castings before being discarded. However, a piston mold, with its relatively simple design, will have a much longer life than a mold that requires elaborate internal coring and external inserts, such as a cylinder-head mold.

Mold life is likely to be longer in the casting of magnesium alloys than in the casting of aluminum alloys of similar size and shape; this is because molten magnesium does not attack ferrous metal molds. However, the difference in mold life for magnesium alloys depends to a great extent on the effectiveness of the mold coating used. In the casting of gray iron, mold life is expected to be short compared to the casting of similar shapes from aluminum alloys.

Molds are often fabricated from cast iron because casting the mold close to the finished shape can decrease machining costs. In addition, cast iron is much more resistant to attack by molten aluminum than steel. Steel, however, is weldable and easier to repair than cast iron. Therefore, steel molds are often used for high-production castings.

Major variables that affect the life of permanent molds are:

- *Pouring temperature:* The hotter the casting metal is poured, the hotter the mold is operated, which leads to rapid weakening of the mold metal
- *Weight of casting:* Mold life decreases as casting weight increases
- *Casting shape:* Mold walls are required to dissipate more heat from castings having thick sections than from those having thin sections. When there is a significant variation in the section thickness of a casting, a temperature differential is set up among different portions of the mold. As the temperature

differential increases, mold life decreases

- *Cooling methods:* Water cooling is more effective than air cooling, but it substantially decreases mold life
- *Heating cycles:* Generally, a continuous run, in which the mold is maintained at a uniform temperature, provides maximum mold life. Repeated heating and cooling over a wide temperature range will shorten mold life
- *Preheating the mold:* This is done to operating temperature with a gas flame or electric heaters, and it greatly increases mold life. Thermal shock is one of the principal causes of mold failure
- *Mold coating:* This protects the mold from erosion and soldering by preventing the metal from contacting mold surfaces, thus increasing mold life
- *Mold materials:* See Table 1
- *Storage:* Improper storage can lead to excessive rusting and pitting of mold surfaces, which will reduce mold life
- *Cleaning:* The common practices for cleaning molds are abrasive blasting, dipping in caustic solution, and wire brushing. Dipping in caustic can be hazardous to the operator. Wire brushing and abrasive blasting can cause excessive mold wear if not carefully controlled. Glass beads are the safest abrasive blast material; their use minimizes dimensional changes due to erosion from the abrasive blast
- *Gating:* A poor gating system can greatly reduce mold life by causing excessive turbulence and washout at the gate areas
- *Method of mold operation:* Although the same materials are used to make molds and cores for both automatically operated equipment and hand-operated equipment, the life of the tool materials on hand-operated equipment is shorter because of the abuse the tooling must withstand. Tools for automatic equipment may last up to twice as long as for hand-operated equipment
- *End use of casting:* If the structural function of a casting is more important than its appearance, a mold can be used for more pourings before being discarded

Influence of Mold Design. In addition to the above factors, mold design has a marked effect on mold life. Variation in mold wall thickness causes excessive stress to develop during heating and cooling, which in turn causes premature mold failure from cracking. Abrupt changes in thickness without generous fillets also cause premature mold failure. Small fillets and radii lead to reduced mold life because checking and cracking, as well as ultimate failure, often start at these points.

Usually, less draft is required on external mold surfaces than on internal mold surfaces because of the shrinkage in the casting. A 5° draft is desirable, but 2° on external and 3° on internal mold surfaces can be used. Lower draft angles, however, decrease the number of castings that can be made between mold repairs. The effect of draft angle on the life of cores and molds used for producing aluminum alloy castings is shown in Fig. 9.

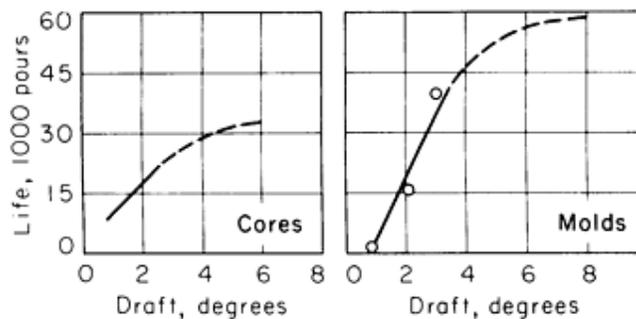


Fig. 9 Effect of draft angle on core and mold life in the permanent mold casting of aluminum alloys

Projections in the mold cavities contribute greatly to reduced mold life. These projections become extremely hot, which increases the possibility of extrusion, deformation, and mutilation when the casting is removed. It is sometimes possible to extend mold life by using inserts to replace worn or broken projections.

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## Mold Coatings

A mold coating is applied to mold and core surfaces to serve as a barrier between the molten metal and the surfaces of the mold while a skin of solidified metal is formed. Mold coatings are used for five purposes:

- To prevent premature freezing of the molten metal
- To control the rate and direction of solidification of the casting and therefore its soundness and structure
- To minimize thermal shock to the mold material
- To prevent soldering of molten metal to the mold
- To vent air trapped in the mold cavity

Types. Mold coatings are of two general types: insulating and lubricating. Some coatings perform both functions. A good insulating coating can be made from (by weight) one part sodium silicate to two parts colloidal kaolin in sufficient water to permit spraying. The lubricating coatings usually include graphite in a suitable carrier. Typical compositions of 15 mold coatings are listed in Table 4. Coatings are available as proprietary materials.

**Table 4 Typical compositions of coatings for permanent molds**

Coating No.	Composition, % by weight (remainder, water)									
	Sodium silicate	Insulators				Lubricants				Boric acid
		Whiting	Fire-clay	Metal oxide	Diatomaceous earth	Soap-stone <sup>(a)</sup>	Talc <sup>(a)</sup>	Mica <sup>(a)</sup>	Graphite	
1	2	...	4	...	...	...	...	...	1	...
2	8	...	4	...	...	...	...	...	...	...
3	...	7	...	...	...	...	...	...	...	7
4 <sup>(b)</sup>	12	9	...	...	...	...	...	...	...	...
5	5	11	...	2	...	...	5	...	...	...

6	9	...	4	...	...	14	...	...	...	...
7	11	...	...	17	...	...	...	...	...	...
8	...	...	4	...	...	23	...	5	...	...
9	7	...	1	...	...	23	...	2	...	...
10	23	...	...	...	...	...	20	...	...	...
11	30	...	...	...	5	...	10	...	...	...
12	18	...	...	...	41	...	...	...	...	...
13	8	...	...	60	...	...	...	...	...	...
14	7	...	...	...	...	...	62	...	...	...
<b>15</b>	<b>20</b>	<b>53</b>	...	...	...	...	...	...	...	...

(a) Serves also as an insulator.

(b) Plus silicon carbide, 2% by weight, for wear resistance

The various requirements of a mold coating are not always obtained with one coating formulation. These requirements are often met by applying different coatings to various locations in the mold cavity.

Coating Requirements. To prolong mold life, a coating must be noncorrosive. It must adhere well to the mold and yet be easy to remove. It must also keep the molten metal from direct contact with the mold surfaces.

A mold coating must be inert to the cast metal and free of reactive or gas-producing materials. If insulation is needed to prevent thin sections, gates, and risers from solidifying too quickly, fireclay, metal oxides, diatomaceous earth, whiting (chalk), soapstone, mica, vermiculite, or talc can be added to the mold coating. Graphite is added if accelerated cooling is needed. Lubricants, which facilitate removal of castings from molds, include soapstone, talc, mica, and graphite (Table 4).

Coating Procedure. The mold surface must be clean and free of oil and grease. The portions to be coated should be lightly sand blasted. If the coating is being applied with a spray, the mold should be sufficiently hot (205 °C, or 400 °F) to evaporate the water immediately.

For optimum coating retention, a primer coat of water wash should be applied before spraying the mold coating. Water wash is a very dilute solution of a mold coating. Dilute kaolin makes an excellent primer. An acceptable alternative is a 20 to 1 dilution of the coating to be sprayed. The high water content of the water wash very lightly oxidizes the mold surface and provides a substrate strate for subsequent layers to stick to. The water wash should be sprayed until the dark color of the mold starts to disappear. Lubricating materials or coatings are not acceptable as primers. Lubricants can be sprayed over insulating coatings, but insulating coatings will not adhere to lubricants.

The coating can be applied by spraying or brushing. It must be thick enough to fill minor surface imperfections, such as scratches. It should also be able to dry with a smooth texture on mold areas of light draft that form ribs and walls in the casting, and it must dry with a rough texture on large, flat areas of the mold to permit entrapped air to escape. The most pleasing cast surfaces are obtained when the coating has a matte or textured finish, which is most often obtained by spraying. Extremely smooth coatings should be avoided because they increase the formation of oxide skins. Thin successive layers are applied until the coating reaches the desired thickness, up to a maximum of 0.8 mm ( $\frac{1}{32}$  in.).

Thick coatings are especially useful on the surfaces of sprues, runners, and risers because they provide more insulation than thinner coatings and result in slower metal freezing. However, they are more likely to flake off and should not be used on the surfaces of casting cavities. Thick coatings are applied by dabbing with a paint brush and adhere better if applied over an initial thin spray coat. It is mandatory that the coating be thoroughly dry before a casting is made, or an explosion will result.

Coating life varies considerably with the temperature of the metal being cast, the size and complexity of the mold cavity, and the rate of pouring. Some molds require recoating at the beginning of each shift; others may run for several shifts with only spot repairs or touchups before recoating is needed. Light abrasive blasting is used to prepare the coating for touchup or to remove old coats. To maintain maximum feeding with the mold, risers, runners, and gates should be recoated about every second time the casting cavity is recoated.

Mold Coatings for Specific Casting Alloys. The metal being cast has a major influence on the type of coating selected. Lubricating coatings are usually used for the casting of aluminum and magnesium. Relatively complex mixtures are sometimes used. For the casting of copper alloys, because of their high pouring temperatures and their solidification characteristics, an insulating type of mold coating is generally required.

The mold coatings used in the production of gray iron castings are divided into two categories: an initial coating, which is applied before the mold is placed in production, and a subsequent coating of soot (carbon), which is applied prior to each pouring. The initial coating consists of sodium silicate (water glass) and finely divided pipe clay, mixed in a ratio of about 1 to 4 by volume with enough water (usually about 15 parts by volume) to allow spraying or brushing. This mixture is applied to molds heated to 245 to 260 °C (475 to 500 °F).

The secondary coating is a layer of soot (carbon) deposited on the mold face and cavities each time the mold is to be poured. The soot is formed by burning acetylene gas delivered at low pressure (3.5 to 5.2 kPa, or 0.5 to 0.75 psig) so that a maximum amount of soot is produced and a minimum of heat is generated. It can be applied either manually or by automatic burners. This soot layer provides insulation between the mold and the casting, permitting easy removal of the castings from the mold, and it prevents chilling of the castings. It also provides a seal between the mold faces to minimize leakage. The thickness of the soot deposit is 0.10 to 0.25 mm (0.004 to 0.010 in.).

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## Mold Temperature

If the mold temperature is too high, excess flash develops, castings are too weak to be extracted undamaged, and mechanical properties and casting finish are impaired. When mold temperature is too low, cold shuts and misruns are likely to occur, and feeding is inhibited, which generally results in shrinkage, hot tears, and sticking of the casting to molds and cores.

The variables that determine mold temperature include:

- *Pouring temperature:* The higher the pouring temperature, the higher the temperature of the mold
- *Cycle frequency:* The faster the operating cycle, the hotter the mold
- *Casting weight:* Mold temperature increases as the weight of molten metal increases
- *Casting shape:* Isolated heavy sections, cored pockets, and sharp corners not only increase overall mold

temperature but also set up undesirable thermal gradients

- *Casting wall thickness*: Mold temperature increases as the wall thickness of the casting increases
- *Mold wall thickness*: Mold temperature decreases as the thickness of the mold wall increases
- *Thickness of mold Coating*: Mold temperature decreases as the thickness of the mold coating increases

After the processing procedure has been established for a given casting operation, mold coating, cycle frequency, chills, and antichills have significant effects on mold temperature. Mold coating is difficult to maintain at an optimum thickness, primarily because the coating wears during each casting cycle and because it is difficult to measure coating thickness during production. The most widely used method for controlling coating thickness is periodic inspection of the castings. Improper coating thickness is reflected by objectionable surface finish and loss of dimensional accuracy.

### *Preheating of Molds*

In many casting operations, molds are preheated to their approximate operating temperature before the operation begins. This practice minimizes the number of unacceptable castings produced during establishment of the operating temperature.

Molds can be preheated by exposure to direct flame, although this method can be detrimental to the molds because of the severity and nonuniformity of heat distribution. Customized heaters are often built for molds. Preheating of the mold face in an oven is the best method because the thermal gradients are of smaller magnitude. Unfortunately, this is usually impractical for larger molds. Final mold operating temperatures are achieved after the first few production cycles.

### *Control of Mold Temperature*

Optimum mold temperature is the temperature that will produce a sound casting in the shortest time. For an established process cycle, temperature control is largely achieved through the use of auxiliary cooling or heating and through control of coating thickness.

Auxiliary cooling is often achieved by forcing air or water through passages in mold sections adjacent to the heavy sections of the casting. Water is more effective, but over a period of time scale can coat the passages, thus necessitating frequent adjustments in water flow rates. Without cleaning, the flow of water eventually stops. Water passages should be checked and cleaned each time a mold is put into use.

The problem of scale formation has been solved in some plants by the use of recirculating systems containing either demineralized water or another fluid such as ethylene glycol. However, such systems are rarely used.

Water flow is regulated manually to each mold section with the aid of a flowmeter. A main shutoff valve is used to stop the water flow when the casting process is interrupted. Adjusting the rate of water flow to control the solidification rate of a heavy section permits some leeway in the variation of wall thickness that can be designed into a single casting. In addition to the control of water flow, the temperature of the inlet water (or any other coolant that might be used) affects the performance of the mold cooling system.

If water or another liquid coolant is used, it must never be allowed to contact the metal being poured, or a steam explosion will result. The intensity of a steam explosion increases as metal temperature increases. In addition, water will react chemically with molten magnesium.

A mold coating of controlled thickness can equalize solidification rates between thin and heavy sections. Chills and antichills can be used to adjust solidification rates further, so that freezing proceeds rapidly from thin to intermediate sections and then into heavy sections, and finally into the feeding system.

Chills are used to accelerate solidification in a segment of a mold. This can be done by directing cooling air jets against a chill inserted in the mold (Fig. 10) or, more simply, by using a metal insert without auxiliary cooling. Chilling can also be achieved by removing some or all of the mold coating in a specific area to increase thermal conductivity. Chills can be used to increase production rate, to improve metal soundness, and to increase mechanical properties.

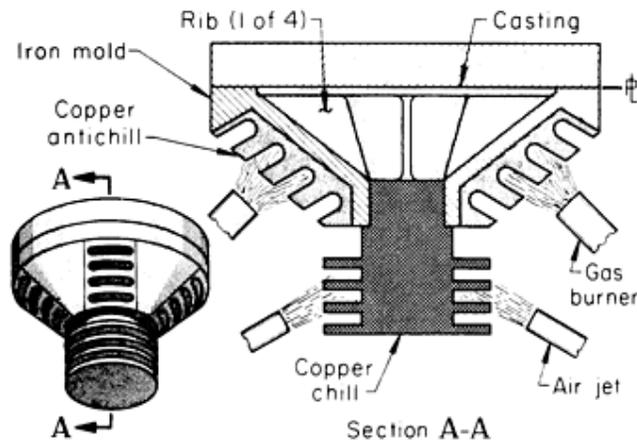


Fig. 10 Use of air-cooled chills and flame-heated antichills to equalize cooling rates in casting sections of varying thickness

**Antichills.** An antichill serves to slow the cooling in a specific area. Heat loss in a segment of a permanent mold can be reduced by directing an external heating device, such as a gas burner, against an antichill inserted in the mold (Fig. 10). The same effect can be produced by the use of insulating mold coatings.

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## Pouring Temperature

Permanent mold castings are generally poured with metal that is maintained within a relatively narrow temperature range. This range is established by the composition of the metal being poured, casting wall thickness, casting size and weight, mold cooling practice, mold coating, and gating systems used.

**Low Pouring Temperature.** If pouring temperature is lower than optimum, the mold cavity will not fill, inserts (if used) will not be bonded, the gate or riser will solidify before the last part of the casting, and thin sections will solidify too rapidly and interrupt directional solidification. Low pouring temperature consequently results in misruns, porosity, poor casting detail, and cold shuts. Sometimes only a small increase in pouring temperature is needed to prevent cold shuts.

**High pouring temperature** causes casting shrinkage and mold warpage. Warpage leads to loss of dimensional accuracy. In addition, variations in metal composition may develop if the casting metal has components that become volatile at a high pouring temperature. High pouring temperature also decreases solidification time (thus decreasing production rate) and almost always shortens mold life.

**Pouring Temperatures for Specific Metals.** The pouring temperature for aluminum alloys usually ranges from 675 to 790 °C (1250 to 1450 °F), although thin-wall castings can be poured at temperatures as high as 845 °C (1550 °F). Once established for a given casting, pouring temperature should be maintained within  $\pm 8$  °C ( $\pm 15$  °F). If this control of pouring temperature cannot be maintained, the cooling cycle must be adjusted for the maximum temperature used. Internal mold cooling can be controlled by means of solenoid valves actuated by thermocouples inserted in the mold walls.

For magnesium alloys, the normal temperature range for pouring is 705 to 790 °C (1300 to 1450 °F). Thin-wall castings are poured near the high side of the range; thick-wall castings, near the low side. However, as for any permanent mold casting, pouring temperature is governed by the process variables listed in the section "Mold Temperature" in this article,

and some experimentation is often required to establish the optimum pouring temperature for a specific casting. Once established, the pouring temperature should be controlled within  $\pm 8$  °C ( $\pm 15$  °F).

Copper alloys are poured at 980 to 1230 °C (1800 to 2250 °F), depending on the alloy as well as the process variables discussed in the section "Mold Temperature" in this article. Once the temperature is established for a specific set of conditions, it should be controlled within  $\pm 15$  °C ( $\pm 25$  °F).

The fluidity of gray iron is excellent, and little difficulty is experienced at pouring temperatures of 1275 to 1355 °C (2325 to 2475 °F). Excessive pouring temperatures can cause flashing and leaking due to mold distortion. As the pouring temperature increases, there is a rapid increase in defects caused by local hot spots on the cavity surface and insufficient soot coverage.

Because the temperature of the molten iron decreases considerably between the time that the first and last machines are serviced, it is usually necessary to deliver the metal to the casting area in a transfer ladle. The metal in this transfer ladle is delivered at a higher temperature than that suitable for pouring. To obtain the desired pouring temperature, small amounts of chill (foundry scrap of the same metal) are added to the pouring ladle as needed. If several machines are being serviced, the metal may have cooled sufficiently so that no chilling is required by the time the last machine is serviced.

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## Removal of Castings From Molds

After a casting has solidified, the mold is opened and the casting is removed. To facilitate release of the casting from the mold, a lubricant is often added to or sprayed over the mold coating. The use of as much draft as permissible on all portions of the casting facilitates ejection. For many castings, ejector pins or pry bars must be used. Core pins and cores should be designed so that they do not interfere with the removal of castings from the mold.

Aluminum alloy castings require at least a 1° draft for mechanical ejection from the mold prior to manual removal (the more draft, the easier the ejection). For castings with low draft angles, the mold coating usually contains a lubricating agent (usually graphite) to prevent sticking.

Magnesium alloy castings are subject to cracking when removed from the mold because the metal is hot short. Therefore, the use of adequate draft is mandatory. On ribs, a draft of 5° is an absolute minimum. However, 10° is recommended and will result in fewer ejection difficulties. In addition, because of the danger of cracking, extreme care should be taken to avoid side thrust when removing cores that must be retracted before the mold is opened.

Copper alloy castings will stick in the molds for any of several reasons, but insufficient draft is usually the primary reason. Draft requirements vary from less than  $\frac{1}{2}$ ° to as much as 5°, depending on alloy, depth of cavity, dimensional and tolerance requirements, and general mold layout (location and number of parting planes). Normally, if draft angles of 4 to 5° are acceptable, castings do not stick in the mold. If tighter dimensional control is required (necessitating smaller draft angles), castings may stick. Sticking can be prevented by providing for mechanical ejection or by increasing draft on noncritical areas.

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## Casting Design

The design of permanent mold castings for production to acceptable quality at the lowest cost involves many considerations that apply to any method of casting (see the article "Casting Design" in this Volume). For example, casting sections should be as uniform as possible, without abrupt changes in thickness. Heavy sections should not be isolated and should be fed by risers. Tolerances should be no closer than necessary. In addition to these general considerations, the following aspects of design are particularly applicable to the low-cost production of sound permanent mold castings:

- Insofar as possible, all locating points should be in the same half of the mold cavity; in addition, locating points should be kept away from gates, risers, parting lines, and ejector pins
- The use of cored holes less than 6.4 mm ( $\frac{1}{4}$  in.) in diameter should be avoided, even though cored holes 3.2 mm ( $\frac{1}{8}$  in.) in diameter or smaller are sometimes possible
- Draft angles in the direction of metal flow on outside surfaces may vary from 1 to more than 10°, and internal draft from slightly less than 2 to 20°. However, using minimum draft increases casting difficulty and cost. Internal walls can be cast without draft if collapsible metal cores are used, but this practice increases cost
- Nuts, bushings, studs, and other types of inserts can often be cast in place. The bond between inserts and casting can be essentially mechanical, metallurgical, or both
- Under conditions of best control, in small molds, allowance for machining stock can be less than 0.8 mm ( $\frac{1}{32}$  in.). However, maintaining machining allowance this low usually increases cost. Generally, it is more practical to allow 0.8 to 1.6 mm ( $\frac{1}{32}$  to  $\frac{1}{16}$  in.) of machining stock for castings up to 250 mm (10 in.) in major dimension and to allow up to 3.2 mm ( $\frac{1}{8}$  in.) for larger castings
- The designer should not expect castings to have a surface finish of better than 2.5  $\mu\text{m}$  (100  $\mu\text{in.}$ ) under optimum conditions. Ordinarily, casting finish ranges from 3 to 7.5  $\mu\text{m}$  (125 to 300  $\mu\text{in.}$ ), depending on the metal being cast

The producibility of a casting can often be improved by avoiding abrupt changes in section thickness. Heavy flanges adjacent to a thin wall are especially likely to cause nonuniform freezing and hot tears; in such cases, redesign of the casting may be necessary. The minimum section thickness producible at reasonable cost varies considerably with the size of the casting and the uniformity of wall thicknesses in the casting.

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## Permanent Mold Casting

Revised by Charles E. West and Thomas E. Grubach, Aluminum Company of America

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## Dimensional Accuracy

The dimensional accuracy of permanent mold castings is affected by short-term and long-term variables. Short-term variables are those that prevail regardless of the length of run:

- Cycle-to-cycle variation in mold closure or in the position of other moving elements of the mold
- Variations in mold closure caused by foreign material on mold faces or by distortion of the mold elements
- Variations in thickness of the mold coating
- Variations in temperature distribution in the mold
- Variations in casting removal temperature

Long-term variables that occur over the life of the mold are caused by:

- Gradual and progressive mold distortion resulting from stress relief, growth, and creep
- Progressive wear of mold surfaces primarily due to cleaning

Dimensional variations can be minimized by keeping heating and cooling rates constant, by operating on a fixed cycle, and by maintaining clean parting faces. It is particularly important to select mold cleaning procedures that remove a minimum of mold material.

Mold Design. The mold thickness and the design of the supporting ribs both affect the degree of mold warpage at operating temperatures. Supporting ribs on the back of a thin mold will warp the mold face into a concave form. This mold design error can alter casting dimensions across the parting line by as much as 1.6 mm ( $\frac{1}{16}$  in.). Adequate mold lockup will contribute to the control of otherwise severe warpage problems.

Mold erosion resulting from metal impingement and cavitation due to improper gating design both contribute to rapid weakening of the mold metal and to heat checking. These mold design errors contribute to rapid dimensional variation during a long run. Mechanical abrasion due to insufficient draft or to improperly designed ejection systems also contributes to the rapid variation of casting dimensions.

Sliding mold segments require clearance of up to 0.38 mm (0.015 in.) to function under varying mold temperatures. This clearance and other mechanical problems associated with sliding mold segments contribute to variations in casting dimensions. Sand cores further aggravate the problem.

Mold Operation. Metal buildup from flash can prevent the mold halves from coming together and can cause wide variations in dimensions across the parting line, even in a short run. Mold coatings on the cavity face are normally applied in thicknesses from 0.076 to 0.15 mm (0.003 to 0.006 in.). Poor mold maintenance can allow these coatings to build to more than 1.5 mm (0.060 in.) thick, causing extreme variation in casting dimensions. Inadequate lubrication of sliding mold segments and ejector mechanisms will contribute to improper mold lockup and consequent variation in casting dimensions. Variation in the casting cycle and in metal temperature will contribute to dimensional variations.

Wear Rates. The dimensions of many mold and core components change at a relatively uniform rate; therefore, it is possible to estimate when rework or replacement will be required. To maintain castings within tolerances, it is sometimes necessary to select mold component materials on the basis of their wear resistance.

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## Permanent Mold Casting

Revised by Charles E. West and Thomas E. Grubach, Aluminum Company of America

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## Surface Finish

The surface finish on permanent mold castings depends mainly on:

- *Surface of the mold cavities:* The surface finish of the casting will be no better than that of the mold cavity. Heat checks and other imperfections will be reproduced on the casting surface
- *Mold coating:* Excessively thick coatings, uneven coatings, or flaked coatings will degrade casting finish
- *Mold design:* Enough draft must be provided to prevent the galling or cracking of casting surfaces. The location of the parting line can also affect the surface finish of the casting
- *Gating design and size:* These factors have a marked effect on casting finish because of the influence on the rate and smoothness of molten metal flow
- *Venting:* The removal of air trapped in mold cavities is important to ensure smooth and complete filling
- *Mold temperature:* For optimum casting surface finish, mold temperatures must be correct for the job and must be reasonably uniform
- *Casting design:* Surface finish is adversely affected by severe changes of section, complexity,

requirements for change in direction of metal flow, and large flat areas

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## Permanent Mold Casting

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## Casting Defects

The defects that can occur in permanent mold castings are porosity, dross, nonmetallic inclusions, misruns, cold shuts, distortion, and cracking. Aluminum alloy castings are subject to all of these defects.

Magnesium alloy castings can have the same defects as aluminum alloy castings. In addition, magnesium alloys are more likely to be hot short.

Copper alloy castings are also susceptible to most of the defects common to aluminum and magnesium. Because of the high pouring temperatures, heat checking of the mold cavities is an added problem. Copper alloy castings often stick in the molds; this can sometimes be prevented by redesigning the mold cavity.

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## Cost

The total cost of a permanent mold casting includes the cost of metal, labor, fuel, supplies, maintenance of molds and other equipment, and inspection.

Manual Versus Automated Methods. Manually operated equipment is generally more economical for low production quantities, but automated molding invariably costs less for medium-to-high production quantities.

Cost Versus Quantity. Permanent mold casting is primarily used for medium and high production, although the process is sometimes used advantageously for low production. Cost per casting or per pound invariably decreases as quantity increases.

Permanent Mold Versus Sand Casting. The permanent mold process is often selected in preference to sand casting or another alternative process primarily because of the lower cost per casting, but there are often added benefits. For some castings, a minor design change can permit a change from sand casting to permanent mold casting that results in a considerable cost savings.

When castings must be machined, the significant cost is often not that of the casting itself but of the final machined product. Permanent mold casting is often economical because it permits a reduction in the number of machining operations required or in the amount of metal removed.

## Solid Graphite Molds\*

Permanent molds can be machined from solid blocks of graphite instead of steel. The low coefficient of thermal expansion and superior resistance to distortion of graphite make it attractive for the reproducible production of successive castings made in the same mold.

Because graphite oxidizes at temperatures above 400 °C (750 °F), molds would wear out quickly even if used for nonferrous casting. To protect the molds and to extend their service lives, they are usually coated with a wash, which is normally made of ethyl silicate or colloidal silica. Molds typically show wear by checking or by forming minute cracks in their surface.

Graphite permanent molds are used for a variety of products (notably bronze bushings and sleeves), and graphite chills are often inserted in molds to promote progressive or directional solidification. The use of graphite as a permanent mold material is perhaps best demonstrated in the casting of chilled iron railroad car wheels (the Griffin wheel casting process), as shown in Fig. 11. Graphite is a particularly suitable mold material for this process. It produces castings with closer tolerances than can be achieved with sand molding, and the high thermal conductivity of graphite chills the metal next to the mold face very efficiently, giving it a wear-resistant white iron structure.

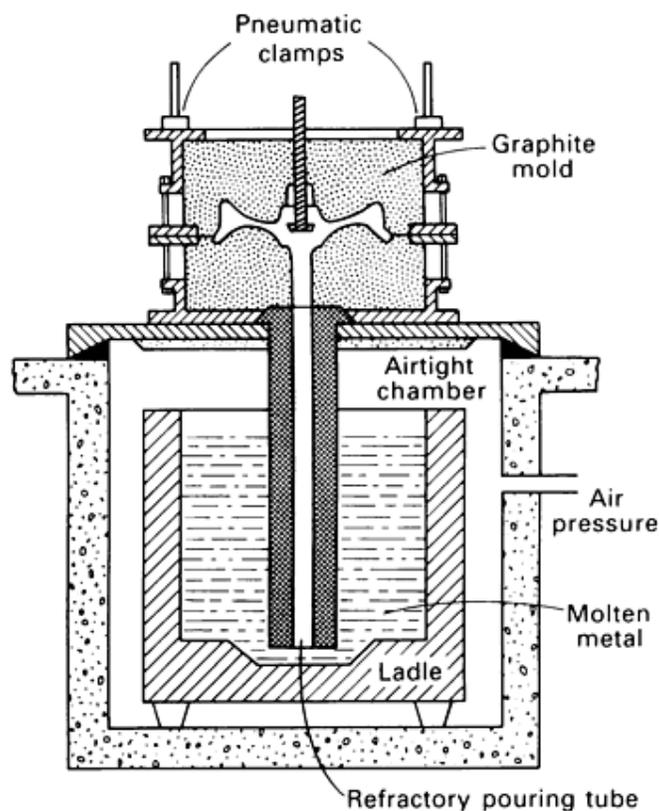


Fig. 11 Schematic of the Griffin wheel casting process. See text for details.

However, because graphite erodes easily, pouring the metal into molds from the top under the influence of gravity causes unacceptable mold wear. As a result, the process was developed so that the mold is positioned over a ladle of molten

metal placed in an airtight chamber. A refractory pouring tube extends from deep in the ladle up to the bottom of the graphite mold. Pouring is carried out by pressurizing the metal in the ladle by means of increasing the pressure in the chamber. This forces metal up the pouring tube into the mold. When the casting is filled, a plunger blocks the pouring tube, the air pressure is released, and the metal that remains in the pouring tube drains back into the ladle. The mold and casting are then transferred to a cooling conveyor, and another mold is placed in position over the ladle.

The process is highly automated, and it has a high casting yield with little gate removal required. Because metal is drawn from the bottom of the ladle, there is little chance for slag to be entrained in the castings, which are clean and have excellent surfaces. Casting quality is further controlled by the ease of regulating the flow of metal into the mold. The technique has been used to make ferrous castings weighing up to 410 kg (900 lb).

Note cited in this section

\* This section was prepared by Thomas S. Piwonka, University of Alabama.

Die Casting

Lionel J.D. Sully, Edison Industrial Systems Center

Introduction

DIE CASTING is characterized by a source of hydraulic energy that imparts high velocity to molten metal to provide rapid filling of a metal die. The die absorbs the stresses of injection, dissipates the heat contained in the metal, and facilitates the removal of the shaped part in preparation for the next cycle. The hydraulic energy is provided by a system that permits control of actuator position, velocity, and acceleration to optimize flow and force functions on the metal as it fills the cavity and solidifies.

Die Casting

Lionel J.D. Sully, Edison Industrial Systems Center

Die Casting Processes

The variety in die casting systems results from trade-offs in metal fluid flow, elimination of gas from the cavity, reactivity between the molten metal and the hydraulic system, and heat loss during injection. The process varieties have many features in common with regard to die mechanical design, thermal control, and actuation. Four principal alloy families are commonly die cast: aluminum, zinc, magnesium, and copper-base alloys (Table 1). Lead, tin, and, to a lesser extent, ferrous alloys can also be die cast. The three primary variations of the die casting process are the hot chamber process, the cold chamber process, and direct injection.

**Table 1 Compositions of selected die casting alloys**

Alloy	Principal alloying elements <sup>(a)</sup> , %								
	Al	Cu	Fe	Mg	Mn	Pb	Si	Sn	Zn
<b>Aluminum alloys</b>									

A360	rem	0.60	1.0	0.40-0.60	...	...	9.0-10.0	...	0.40
A380	rem	3.0-4.0	1.0	0.10	...	...	7.5-9.5	...	2.9
A383	rem	2.0-3.0	1.0	0.10	...	...	9.5-11.0	...	2.9
A384	rem	3.0-4.5	1.0	0.10	...	...	10.5-12.0	...	2.9
B390	rem	4.0-5.0	1.0	0.5-0.65	...	...	16.0-18.0	...	1.4
A413	rem	1.0	1.0	0.10	...	...	11.0-13.0	...	0.40
518	rem	0.25	1.1	7.6-8.5	...	...	0.35	...	0.15
<b>Copper alloys</b>									
C85800	0.25	57 min	0.50	...	0.25	1.5	0.25	1.50	31 min
C87900	0.15	63 min	0.40	...	0.15	0.25	0.75-1.25	0.25	rem
C87800	0.15	80 min	0.15	0.01	0.15	0.15	3.75-4.25	0.25	rem
<b>Magnesium alloys</b>									
AZ91B	8.3-9.7	0.35	...	rem	0.13	...	0.50	...	0.13
AM60A	5.5-6.5	0.35	...	rem	0.13	...	0.50	...	0.22
AS41A	3.5-5.0	0.06	...	rem	0.20	...	0.50	...	...
<b>Zinc alloys</b>									
AC40A	3.9-4.3	0.10	0.075	0.025-0.05	...	0.004	...	0.002	rem
AG41A	3.5-4.3	0.25	0.10	0.02-0.05	...	0.005	...	0.003	rem
Alloy 7	3.9-4.3	0.75-1.25	0.075	0.03-0.06	...	0.004	...	0.002	rem
ILZRO 16	3.5-4.3	0.75-1.25	0.10	0.03-0.08	...	0.005	...	0.003	rem

More detail on composition ranges and minor constituents is available in *Properties and Selection: Irons, Steels, and High-Performance Alloys*, Volume 1 of the *ASM Handbook*. rem, remainder

(a) Maximum, unless range is given or otherwise indicated.

The hot chamber process is the original process invented by H.H. Doehler. It continues to be used for lower-melting materials (zinc, lead, tin, and, more recently, magnesium alloys). Hot chamber die casting places the hydraulic actuator in intimate contact with the molten metal (Fig. 1). The hot chamber process minimizes exposure of the molten alloy to turbulence, oxidizing air, and heat loss during the transfer of the hydraulic energy. The prolonged intimate contact between molten metal and system components presents severe materials problems in the production process.

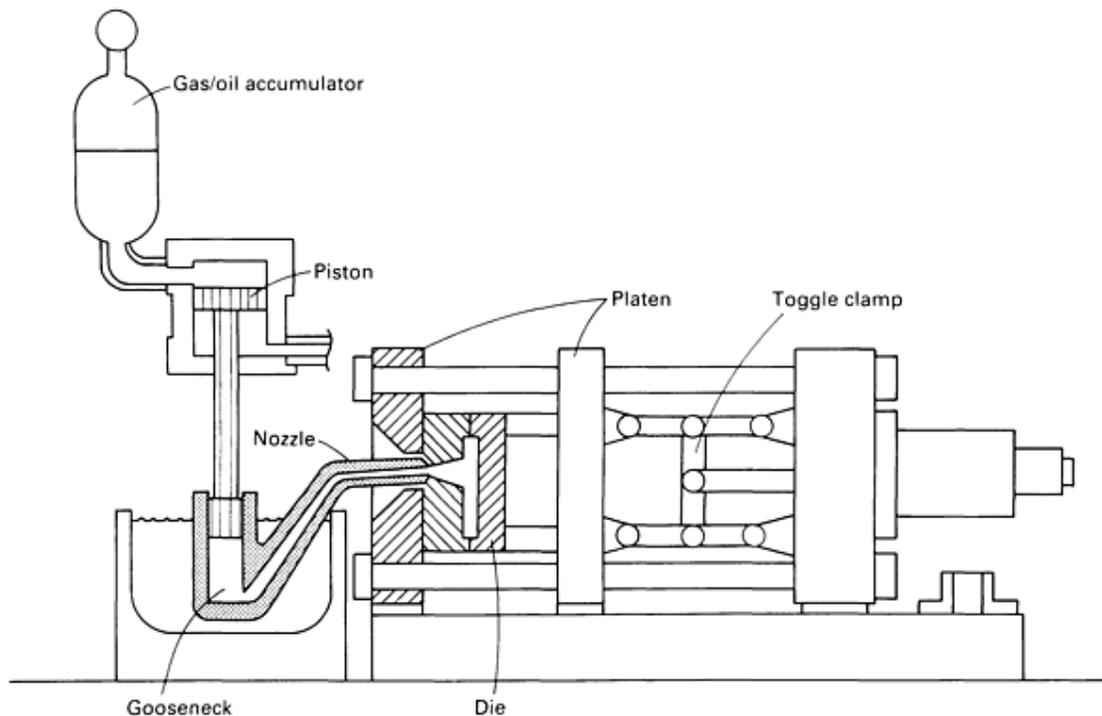


Fig. 1 Schematic showing the principal components of a hot chamber die casting machine

The cold chamber process solves the materials problem by separating the molten metal reservoir from the actuator for most of the process cycle. Cold chamber die casting requires independent metering of the metal (Fig. 2) and immediate injection into the die, exposing the hydraulic actuator for only a few seconds. This minimal exposure allows the casting of higher-temperature alloys such as aluminum, copper, and even some ferrous alloys.

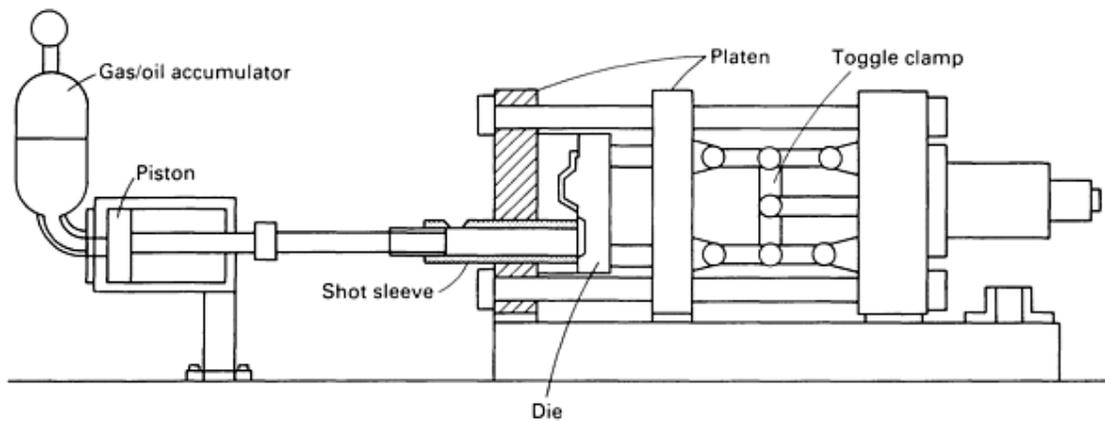


Fig. 2 Schematic showing the principal components of a cold chamber die casting machine

Direct injection extends the technology used for lower-melting polymers to metals by taking the hot chamber intimacy to the die cavity with small nozzles connected to a manifold, thus eliminating the gating and runner system. This process, however, is still under development.

Process control in die casting to achieve consistent high quality relates to timing, fluid flow, heat flow, and dimensional stability. Some features are chosen in die and part geometry decisions and are therefore fixed; others are defined by the process at the machine and can be adjusted in real time. All are related and therefore must be dealt with in parallel; the best die castings result from an intimate interrelationship between product design and process design.

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## Die Casting

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## Product Design for the Process

Product design and die design are intimately related. The principal features of a die casting die are illustrated in Fig. 3. The high-speed nature of the process allows the filling of thin-wall complex shapes at high rates (of the order of 100 parts per hour per cavity). This capability places additional demands on the casting designer because traditional feeding of solidification shrinkage is almost impossible. The inability to feed in the traditional sense demands that machining stock be kept to a minimum; high-integrity surfaces should be preserved.

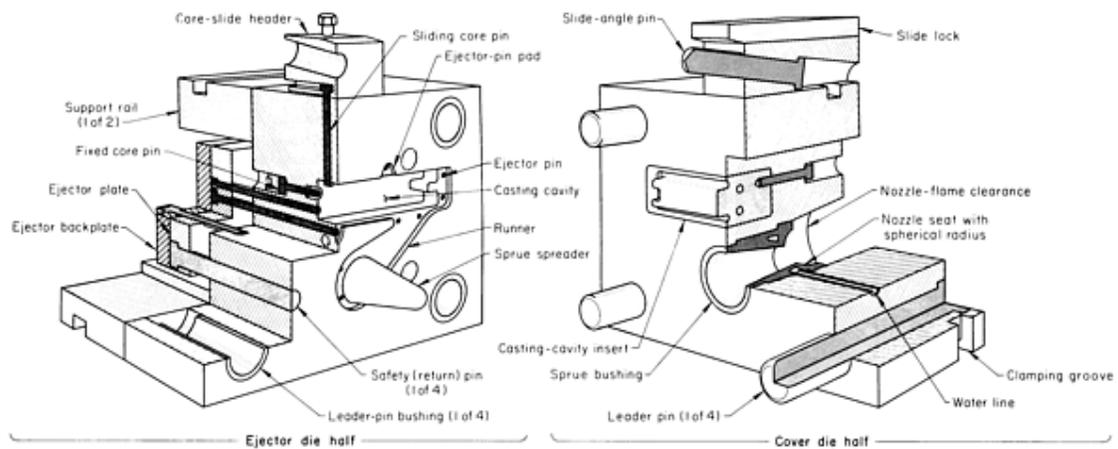


Fig. 3 Components of a single-cavity die casting die for use in a hot chamber machine

A factor in cost is the parting line topology. The parting line is the line on the casting generated by the separation between one die member and another. The simplest and lowest-cost die has a parting line in one plane. Casting design should be adjusted if possible to provide flat parting lines. Draft is required on the die casting walls perpendicular to the parting line or in the direction of die motion (Fig. 4). An important characteristic of good design is uniform wall thickness, which is necessary for obtaining equal solidification times throughout the casting. Die castings have wall thicknesses of about 0.64 to 3.81 mm (0.025 to 0.150 in.), depending on casting shape and size (Table 2). Bosses, ribs, and filleted corners always cause local increases in section size. In particular, bosses that must be machined require consideration of the entire product-manufacturing cycle. The machinist will find it easier to drill into a solid boss; cored bosses may require floating drill heads in order to align the drill with the cast tapered hole that preserves the high-integrity skin of the casting.

**Table 2 Minimum section thicknesses for die castings**

Surface area of casting <sup>(a)</sup>		Minimum section thickness for:					
		Tin, lead, and zinc alloys		Aluminum and magnesium alloys		Copper alloys	
cm <sup>2</sup>	in. <sup>2</sup>	mm	in.	mm	in.	mm	in.
Up to 25	Up to 3.875	0.635	0.025	0.81	0.032	1.52	0.060
25-100	3.875-15.5	1.02	0.040	1.27	0.050	2.03	0.080
100-500	15.5-77.5	1.52	0.060	1.78	0.070	2.54	0.100

(a) Area of a single main plane

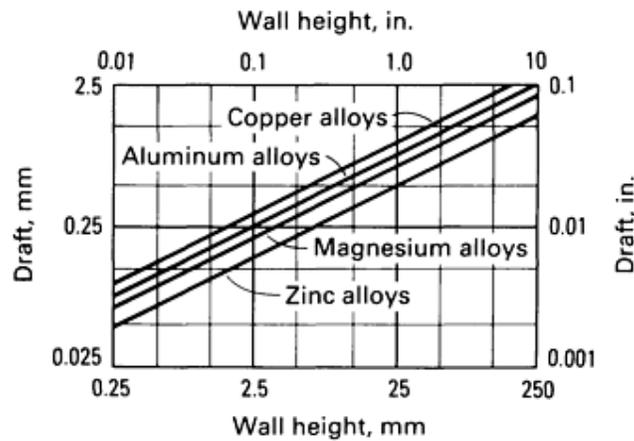


Fig. 4 Minimum drafts required for inside walls of die castings made from four different types of casting alloys

Cores and slides provide side motions for undercuts. A core body is generally round and buried within the cover or ejector die. A slide body has a rectangular or trapezoidal shape and crosses the parting line of the die. As with the cover and ejector dies, the impression steel is often separate from the holder steel. Cores and slides are actuated by various methods, including hydraulic cylinders, rack and pinion, and angle pins. Innovative die design permits radial die motion at a price of die expense. There are die casting processes that use complex-shaped disposable cores similar to those in other gravity casting processes. Cores and slides provide the casting designer with tremendous flexibility at the expense of an increase in die complexity. A standard set of cores--fixed core pins for small holes that are screwed in, or bolted-in inserts--can be used to reduce die construction cost and to permit rapid replacement.

Loose Pieces and Inserts. In certain cases, a reentrant shape needs to be cast into the part where there is no space for core/slide mechanisms. In such a case, the die designer can use a loose piece. A loose piece is placed in the die before each shot is made. It is then ejected from the die with the casting and separated manually or by fixture. Although it provides design flexibility, the load/unload sequence required for loose pieces slows the process, thus increasing cost.

Similarly, the die casting process can allow the part designer great flexibility in local material properties by the use of cast-in inserts of other materials, such as steel, iron, brass, and ceramics. The bond between insert and casting is physical, not chemical, in nature. Therefore, the insert should be clean and preheated. The insert should be designed to prevent pullout or rotation under working loads; knurling, grooves, hexagons, or flats are commonly used for this purpose. Proper support of hollow inserts will prevent crushing of the insert under the high metal injection pressure. The wall thickness of the casting surrounding an insert should be no less than 2.0 mm (0.080 in.) to prevent cracking by shrinkage, hot tearing, and excessive residual stresses.

Trimming. The die cast part is ejected from the die with a variety of appendages (gates, overflows, vents, flash, and robot grasping lugs) that must then be removed. This secondary process is called trimming. Although trimming can be done manually, the high production rates characteristic of die casting demand automation. Trim presses are used to remove the excess material. Castings are often trimmed immediately after the casting process because their higher temperature reduces the strength of the metal.

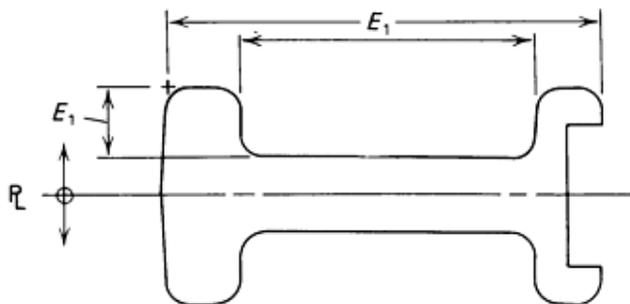
Trimming conditions directly influence the design of the part and the die casting process, especially gating and parting line definition. Trimming is facilitated by flat parting lines. The relatively rough edge that results from trimming may be acceptable and is often left as is. In some cases, this rough edge is not acceptable and must be removed by machining or grinding. The direction of flash must be such that the edge is machinable.

Dimensional variation is determined by die design, the accuracy of die construction, and process variation. The most accurate dies are those machined using computer numerical control methods. Close control of alloy composition, temperature casting, time, and injection pressure will lead to more consistent casting dimensions. The minimum variation in dimensions is required for those features contained entirely within one die half. Table 3 lists the tolerances on linear dimensions recommended by the American Die Casting Institute (ADCI); Tables 4 and 5 list additional tolerances recommended by ADCI. Therefore, machining locators should ideally be placed in the same die half. Tolerances are a

function of casting size and projected area. Features across parting lines have added variation because of the accuracy of repeated die closing. Die temperature, machine hydraulic pressures, and die cleanliness are the principal factors to be controlled. Finally, further dimensional variation occurs if the feature is in a moving die member such as a slide or core.

**Table 3 Recommended tolerances on as-cast linear dimensions of die castings**

Additional tolerances are listed in Tables 4 and 5.



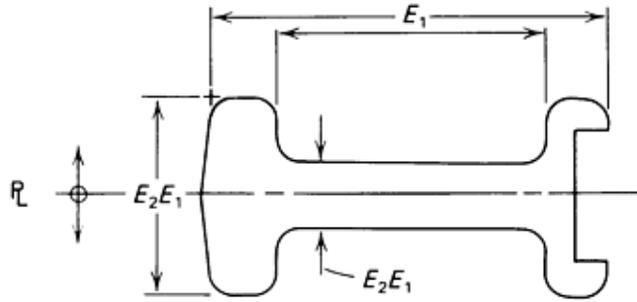
The tolerance on a dimension  $E_1$  will be the value shown in the tables for dimensions between features formed in the same die part. The tolerance must be increased for dimensions of features formed between moving die parts (see Tables 4 and 5).

Length of dimension $E_1$ , in.	Basic tolerance (in.) for:			Additional tolerance <sup>(a)</sup> (in.) for each additional inch of dimension $E_1$ for:		
	Zinc alloy castings	Aluminum and magnesium alloy castings	Copper alloy castings	Zinc alloy castings	Aluminum and magnesium alloy castings	Copper alloy castings
<b>Noncritical dimensions</b>						
Up to 1	±0.010	±0.010	±0.014	...	...	...
1-12	...	...	...	±0.0015	±0.002	±0.003
Above 12	...	...	...	±0.001	10.001	...
<b>Critical dimensions</b>						
Up to 1	±0.003	±0.004	±0.007	...	...	...
1-12	...	...	...	±0.001	±0.0015	±0.002
Above 12	...	...	...	±0.001	±0.0015	...

(a) Example: an aluminum alloy casting would have a tolerance of ±0.010 in. on a critical 5.000 in. dimension  $E_1$  (that is, the basic tolerance of ±0.004 in. + 4 (0.0015) = ±0.010 in.).

**Table 4 Recommended parting line tolerances for die castings**

Tolerances given in this table are to be added to the basic tolerances given in Table 3. See also Table 5.



The tolerance on dimensions such as  $E_2E_1$ , which are perpendicular to the parting plane, will be the value shown in the table plus the linear tolerance from Table 3. The value chosen from the table depends on the projected area of the part. Additional tolerances in the case of other moving die parts are shown in Table 5.

Projected area of casting <sup>(a)</sup> , in. <sup>2</sup>	Additional tolerance <sup>(b)</sup> (in.) for:		
	Zinc alloy castings	Aluminum and magnesium alloy castings	Copper alloy castings
Up to 50	±0.004	±0.005	±0.005
50-100	±0.006	±0.008	...
100-200	±0.008	±0.012	...
200-300	±0.012	±0.015	...
300-500	±0.016	±0.020	...
500-800	±0.020	±0.025	...
800-1200	±0.025	±0.030	...

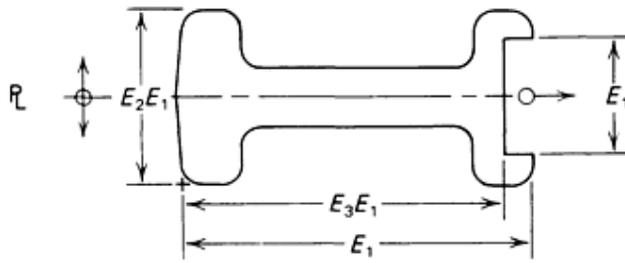
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(a) Projected area is the area of the part in the parting plane.

(b) Example: an aluminum die casting with a projected area of 75 in.<sup>2</sup> would have a tolerance of ±0.018 in. on a critical 5.000 in. dimension  $E_2E_1$  (that is, ±0.008 in. for 75 in.<sup>2</sup> plus the basic linear tolerance of 0.010 in.). See Table 3.

**Table 5 Recommended additional tolerances for die castings produced in dies with moving parts**

Tolerances in this table should be used in conjunction with those listed in Table 3. See also Table 4.



The tolerance on dimensions such as  $E_3E_1$  will be the value shown in the table plus the linear tolerance from Table 3. The value chosen from the table depends on the projected area of the portion of the die casting formed by the moving die part perpendicular to the direction of movement.

Projected area of die casting, in. <sup>2</sup>	Additional tolerance <sup>(a)</sup> (in.) for:		
	Zinc alloy castings	Aluminum and magnesium alloy castings	Copper alloy castings
Up to 10	±0.004	±0.005	±0.010
10-20	±0.006	±0.008	...
20-50	±0.008	±0.012	...
50-100	±0.012	±0.015	...
100-200	±0.016	±0.020	...
200-350	±0.020	±0.025	...
350-600	±0.025	±0.030	...
600-1000	±0.030	±0.035	...

(a) Example: An aluminum alloy casting formed using a moving die part and having a projected area of 75 in.<sup>2</sup> would have a tolerance of ±0.025 in. on a critical 5.000 in. dimension  $E_3E_1$  (that is, ±0.015 in. for 75 in.<sup>2</sup> plus ±0.010 in. on linear dimensions). See Table 3.

In summary, a cost-effective die casting demands proper attention to the dimensional variation of the process. Inattention to dimensional factors will lead to an inability to provide consistent products within economic process conditions. The product designer signer and the die caster must therefore initiate a dialog early in the product cycle.

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#### References cited in this section

1. "Linear Dimension Tolerances for Die Castings," ADCI-E1-83, American Die Casting Institute
2. "Parting Die Tolerances," ADCI-E2-83, American Die Casting Institute

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## Die Casting

Lionel J.D. Sully, Edison Industrial Systems Center

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### Gating

The first step in the process sequence is the supply of the molten alloy to the casting machine and its injection into the die. The fluid flow is divided into three considerations: metal injection, air venting, and feeding of shrinkage.

#### *Metal Injection*

The distinguishing characteristic of the die casting process is the use of high-velocity injection. The short fill time (of the order of milliseconds) allows the liquid metal to move a great distance despite a high rate of heat loss. The elements of a typical metal gating system are illustrated in Fig. 5.

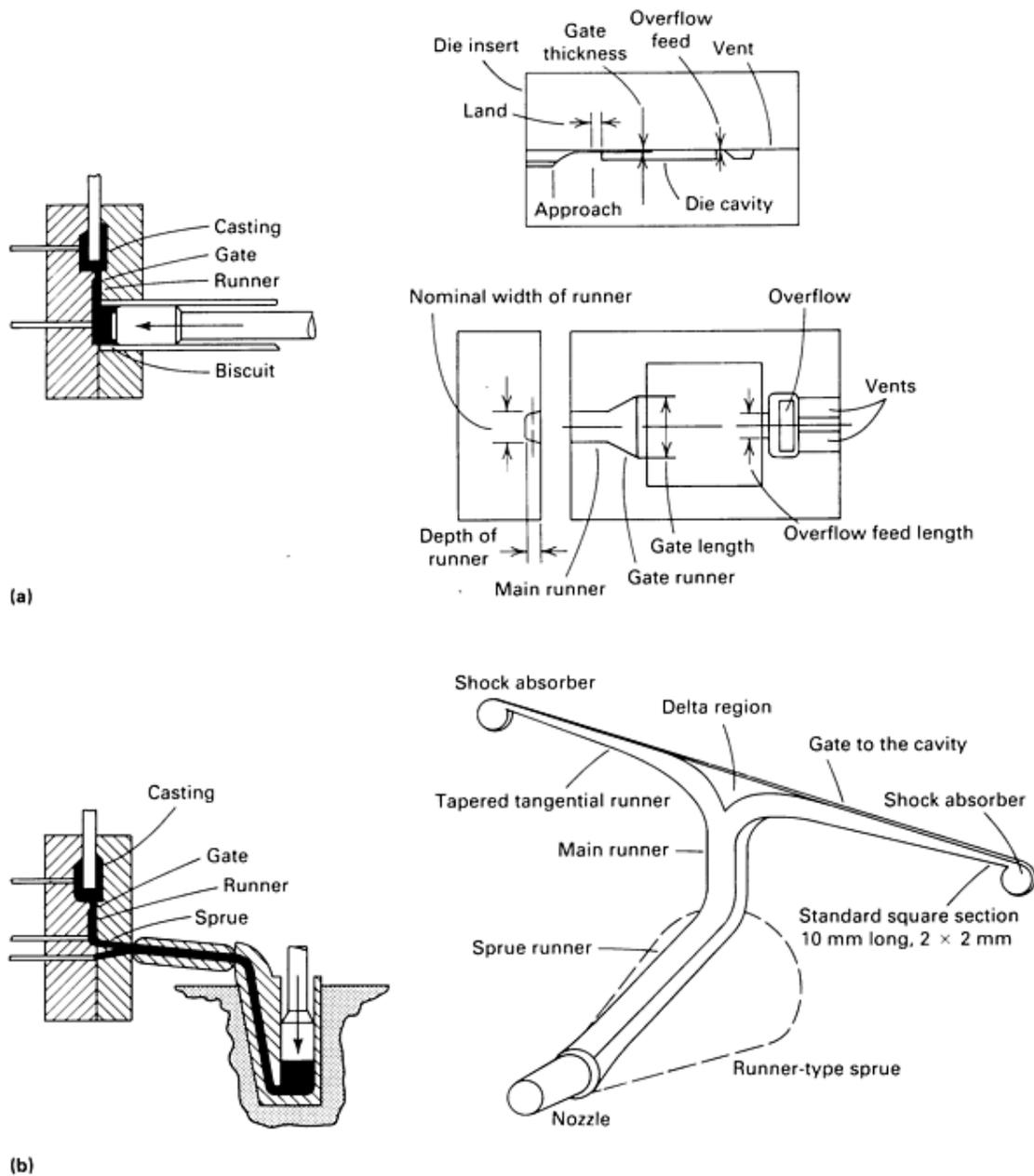


Fig. 5 Schematics showing gating systems for cold chamber (a) and hot chamber (b) die casting machines

Proper process performance depends on the delivery of molten metal with high quality as defined by temperature, composition, and cleanliness (gas content and suspended solids). The molten alloy is prepared from either primary ingot or secondary alloys. A melting furnace is used to provide the proper temperature and to allow time for chemistry adjustment and degassing. The alloy is often filtered during transfer to a holding furnace at the casting machine.

The Injection Chamber. Three components make up the injection chambers used for the three types of die casting: the shot sleeve, the gooseneck, and the nozzle (Fig. 1, 2). The cold chamber shot sleeve (Fig. 2) is unique. Initially, it is only partially filled to prevent splashing and to allow for metering error, and it must be filled by slow piston movement to avoid wave formation and air entrainment. Then, for all three chambers, the hydraulic piston rapidly accelerates the molten metal to the desired velocity for injection (Fig. 6). Most die casting machines provide the ability to control the piston acceleration in a linear fashion. Parabolic velocity curves are also available on some controls. This phase of injection can be accomplished in several steps. The third phase of injection is activated as the cavity is close to being filled. This intensification phase draws on an accumulator of high-pressure hydraulic fluid or multiplies pressure using

conventional piston intensifiers. This increases the pressure on the metal to force the rapidly freezing alloy into incipient shrinkage cavities.

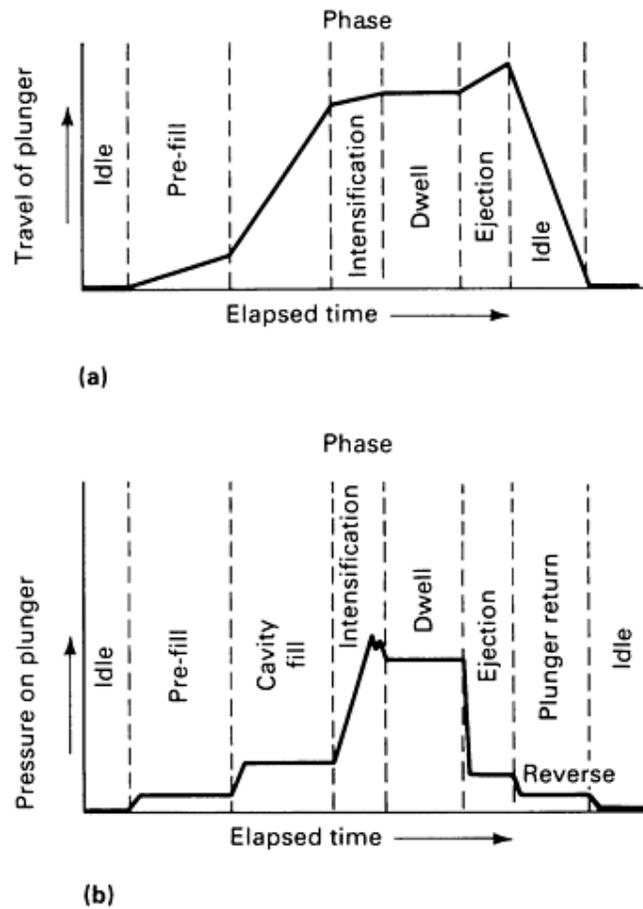


Fig. 6 Curves for plunger travel versus time (a) and plunger pressure versus time (b) indicating the various phases of a shot

Sprues and Runners. The sprue provides a smooth transition from the shot sleeve or nozzle and promotes high cooling heat flow after injection is complete. The runner carries the flowing metal from the injection chamber to the desired location(s) on the casting periphery. Runners are not used in direct injection. Heat loss, unnecessary turbulence, and die erosion can be minimized by proper attention to basic hydraulic principles when designing runners. Typical runners are therefore round or nearly square trapezoidal in section to minimize surface area and heat loss. There is a distinct change in section from the thick runner to the thin gate. A change in flow direction also often occurs. The approach section is the means for achieving these two needs. The shape of this section of the flow channel often provides the name of the gate, for example, chisel gate or fan gate. The use of tapered tangential runners eliminates this approach feature.

The gate is the controlling entry point into the casting. The gate serves a fluid flow need, but it must later be removed from the casting by trimming. Therefore, the gate cross section should be the smallest in the gating system. The cross section is determined by the desired fill time and flow rate that the casting machine can provide. A number of methods are available for calculating gate area; these are discussed below.

The shape of the part is primarily governed by the end use, not by fluid flow considerations. Indeed, the die casting process excels in very complex near-net shape configurations. The high-velocity inertia-driven flow, combined with rapid heat loss and partial freezing during fill, eliminates the possibility of a rigorous fluid mechanics solution. However, the die caster must always attempt to understand the flow in the part cavity.

The overflow is the final component in the fluid flow system. Although they add to the weight of remelt, overflows do serve a variety of purposes. They can act as a reservoir for metal to be removed from the cavity, and they can provide an off-casting location for ejection pins, robot holds, or instrumentation points.

Gating System Design. Several methods are available for designing gating systems. Design of the gating system is always a compromise. Unlike the flow of polymers or metal flow in forging, the high-velocity metal flow of die casting, combined with heat loss and simultaneous solidification, cannot be rigorously solved with computational methods. Therefore, various methods have been developed to provide the die caster with tools to address the problem on a sound, consistent basis. All of these methods attempt to take into account the influence of the following key variables:

- Part shape
- Internal quality
- Surface quality
- Mechanical properties
- Die temperature
- Die erosion
- Die material
- Die venting
- Metal temperature
- Metal fluidity
- Metal heat content
- Metal microstructure

Since the invention of the die casting process, many die castings have been successfully made with gating systems designed by experience only. Each company has a reservoir of this closely guarded experience. Trial-and-error adjustments at the casting machine are frequently part of the learning. However, the decline of the presence of the artisan in the foundry is forcing a move toward analytically based gating design, but the analysis base is still tempered with the fine tuning of experience. This is especially true in gate location and local angle of entry, which are directly affected by part shape and secondary operations.

One of the first analysis methods was the ADCI/DCRF Nomograph (Fig. 7), which solves geometric relationships for the bulk flow design. The selection of a fill time for the casting is based on experience and experiment. The limited selection of plunger diameters for a given machine restricts the design. The cold chamber process links the volume of metal to plunger diameter by filling the shot sleeve about two-thirds full. The nomograph is used to develop a required volume fill rate  $Q$ .

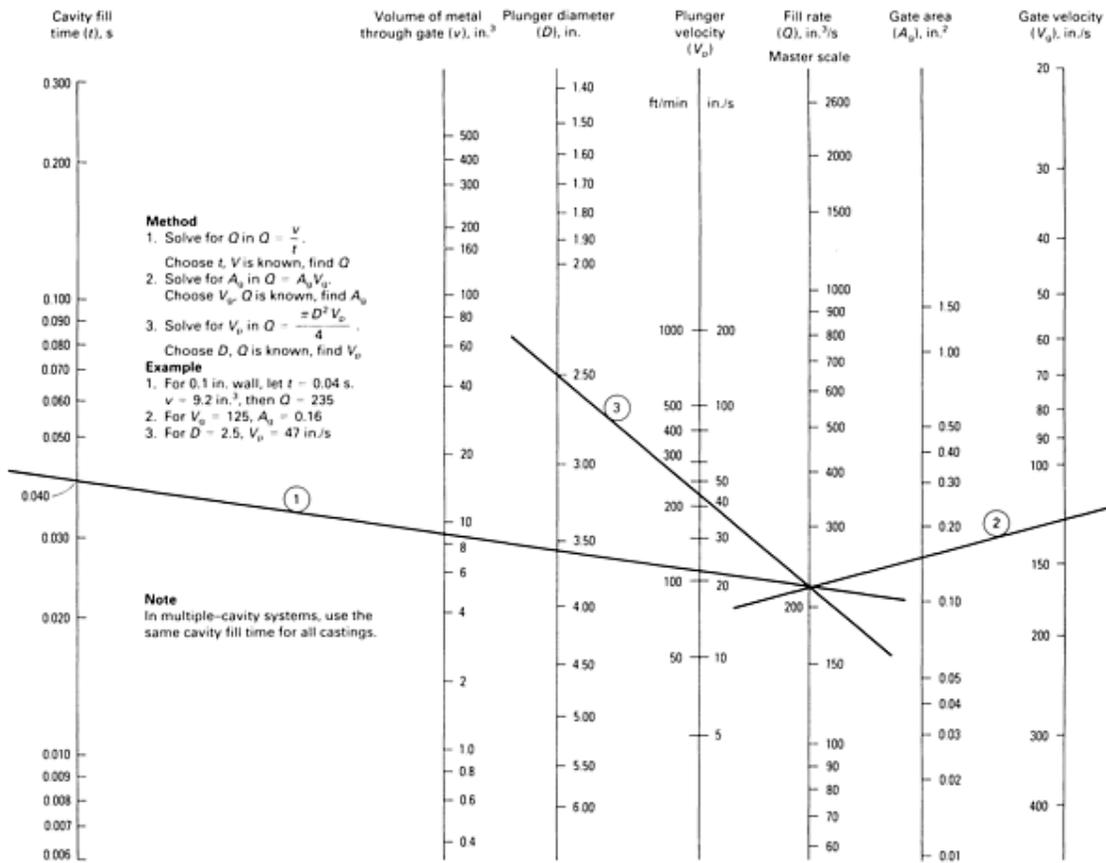


Fig. 7 Nomograph used to determine the volume fill rate  $Q$  required for different casting process parameters

It has recently been recognized that the ability of the casting machine to provide this metal volume flow, while keeping the dies closed during injection, must be considered. The tool that has been developed for this purpose is called the  $P-Q^2$  diagram (Fig. 8). It can be shown that the pressure  $P$  on the metal and hydraulic system is proportional to the square of the injection velocity and therefore the volume flow rate  $Q$ . The line with the negative slope is the machine characteristic line. The characteristic line moves as shown with changes in hydraulic pressure, shot valve throttling, and plunger diameter. The line that starts at the origin of the graph is a measured relationship of pressure to flow rate for the particular casting and gate being cast. The effect of adjusting the gate area is shown.

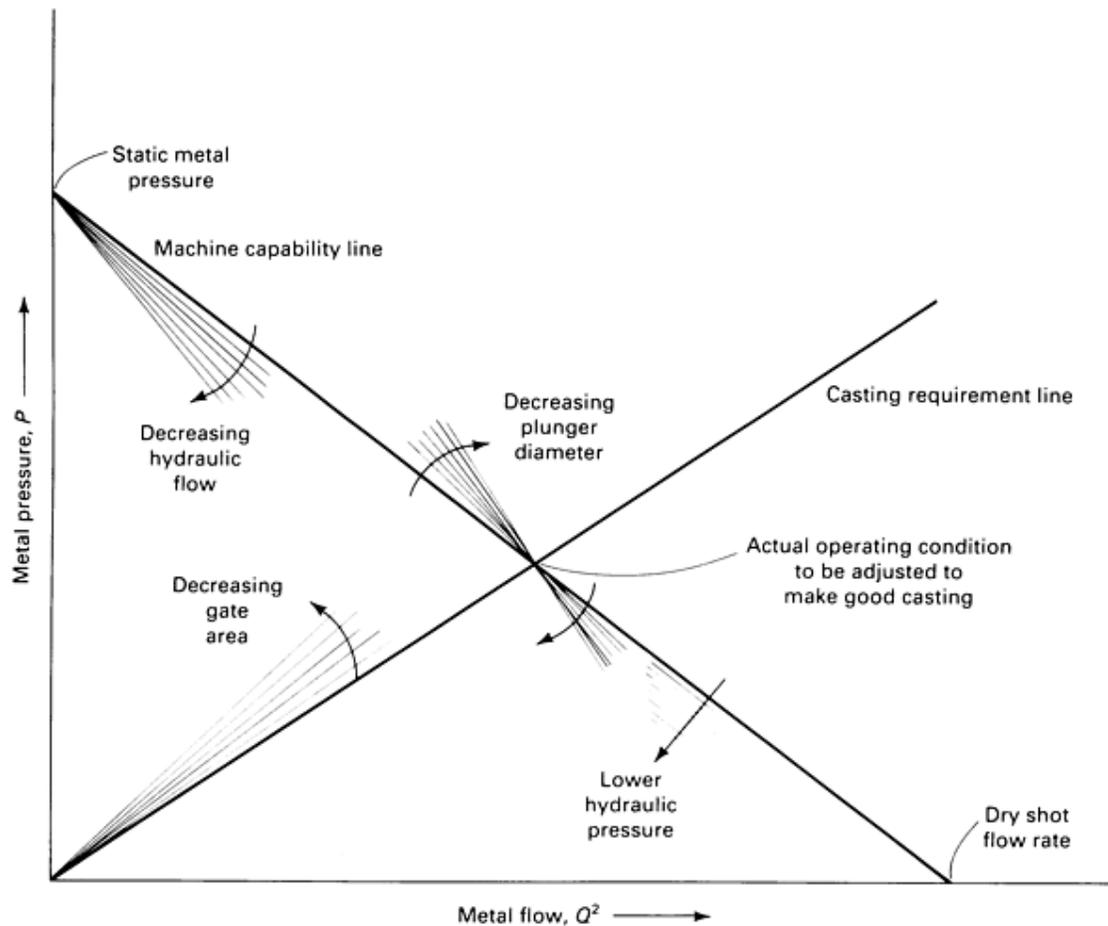


Fig. 8 Metal pressure versus metal flow ( $P-Q^2$ ) diagram used to determine or optimize process parameters in die casting

Optimization of these various parameters for the casting and machine provides the process engineer with a powerful tool for process definition and debugging. A number of microcomputer programs are available to base gate design on this hydraulic approach (see the Selected References at the end of this article).

### *Air Venting*

The subject of air venting is often neglected in die casting texts, but it can have a profound effect on product quality. Back pressure directly affects fluid flow. The molten metal injected into the die must displace the gas initially within the die cavity or absorb it as compressed bubbles. The common belief that die castings cannot be heat treated is an indication that they often contain entrained high-pressure gas pockets. Effective air removal eliminates entrained gas, resulting in optimum metal properties and even heat-treatable castings.

**Gas Displacement.** The most common method of gas displacement is the use of thin channels called vents that are open to the outside of the die. The total area of vents should be approximately 20% of the gate area. The machined channels are no more than 0.18 to 0.38 mm (0.007 to 0.015 in.) thick to ensure that the metal will freeze off before the edge of the impression block is reached. The turbulence of flow makes complete removal of cavity gases difficult by displacement venting. Vent placement is a matter of experience, with final design often done by trial and error on the casting machine.

An alternative to displacement venting is the extraction of the air ahead of the metal by a vacuum system using an accumulator. Once the die is closed and the shot hole sealed, the vacuum valve is opened and the air in the cavity is drawn

into the accumulator. The vacuum valve is either closed after a preset time or by metal impingement, which shuts the valve to prevent metal from filling the vacuum system. The accumulator is then pumped down for the next cycle.

Another method of eliminating entrained gas bubbles is to rely on the reactivity of the molten alloy with oxygen. The normal air in the cavity can be displaced by a pure oxygen purge. When the molten metal is injected, the gaseous oxygen combines with the metal to form a finely distributed solid oxide. This is known as the pore-free process.

The overflow can also act as a reservoir for molten alloy that has flowed through the cavity. One method of removing entrained gas from the cavity relies on the transfer of some of the gas into the overflow. However, for this method to be effective, the proportion of overflow volume to casting volume must be relatively large.

### *Feeding of Shrinkage*

Practically all casting processes except die casting and squeeze casting rely on a massive reservoir or riser of molten metal to feed incipient shrinkage. There is no such riser in a die casting die. Metal pressure intensification at the end of the injection cycle is the only force used to feed shrinkage. The largest thermal section in cold chamber die casting is the biscuit and the runner adjacent to the shot sleeve and up to the gate (see Fig. 5a). Given the very thin walls of many die castings, the effective feeding distance from the gate is very short. Therefore, the die caster must rely on other techniques to assist in minimizing shrinkage.

For example, near-eutectic alloys with short freezing ranges are preferred. Inoculation (grain refinement) ensures a small eutectic cell size for well-dispersed micro-shrinkage that is not interconnected. The remnant shrinkage might also be moved to an uncritical area. This is accomplished by manipulating metal flow and die temperatures. A mechanical solution is the use of pressure pins, which are small, hydraulically actuated cores that are driven into the freezing casting. Timing and pressure are critical to the proper use of pressure pins. This approach adds to the complexity of the die.

### *Interaction of Fluid Flow with Dies and Machines*

The forces generated by injection of the molten metal are a key factor in die design. Although the forces are highly dynamic in nature, most dies are designed for peak static loads. The geometric factor that usually determines the size of the casting machine that must be used is the combined projected area of the casting, runner, and gating system. The force that must be contained by the machine is this area multiplied by the peak metal pressure during the injection cycle. This is the peak of the intensification pressure (Fig. 6b). Because metal pressures under intensification can exceed 69 MPa (10 ksi), the force pushing the die open can be more than 450,000 kg (over 1 million lbf) for a large casting, based on projected area. This force determines the locking capacity needed to keep the die closed. Die casting machines are available with locking forces ranging from 450 kN to 35 MN (50 to 4000 tonf). The tooling cost and process cost increase with projected area and machine size. The distribution of forces within the tie bars is also important; the objective is to load each tie bar equally.

If the die uses slides and cores, these must also resist the force of the metal. This is usually accomplished by a mechanical lock. The closing actuator should not be expected to perform this function.

The thermal effects of molten metal flow in the die are a major factor in determining die life, casting surface quality, and many internal quality parameters. Impingement of metal upon the die, excessive turbulence, and cavitation in the flow increase the local heat load on the die. The result can be premature die failure from thermal fatigue.

In summary, the fluid flow aspects of die casting are a major determinant in product quality and die life. Therefore, fluid flow, or gating, can control the economic success of a particular die casting product. The flow is complex, and success depends on experience to aid an evolving analysis technology.

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## Die Casting

Lionel J.D. Sully, Edison Industrial Systems Center

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## Heat Removal

Once the molten alloy is in the die cavity, the heat in the alloy must be removed to allow solidification and subsequent cooling to occur; the die acts as a heat exchanger. A number of heat flow paths are available for this transfer, as shown in Fig. 9. As with any heat flow problem, the geometry of the heat exchanger is critical; in this case, heat exchanger geometry is dictated by the part geometry. Longer cooling times are achieved by utilizing heavy sections, distance from cooling lines, and shapes with large volume-to-surface-area ratios (or large section modulus). Another critical result of shape is the possibility of large differences in cooling times creating stresses within the die casting. If cooling stresses become too high under the rigid constraint of the die, hot tears and cracks can result.

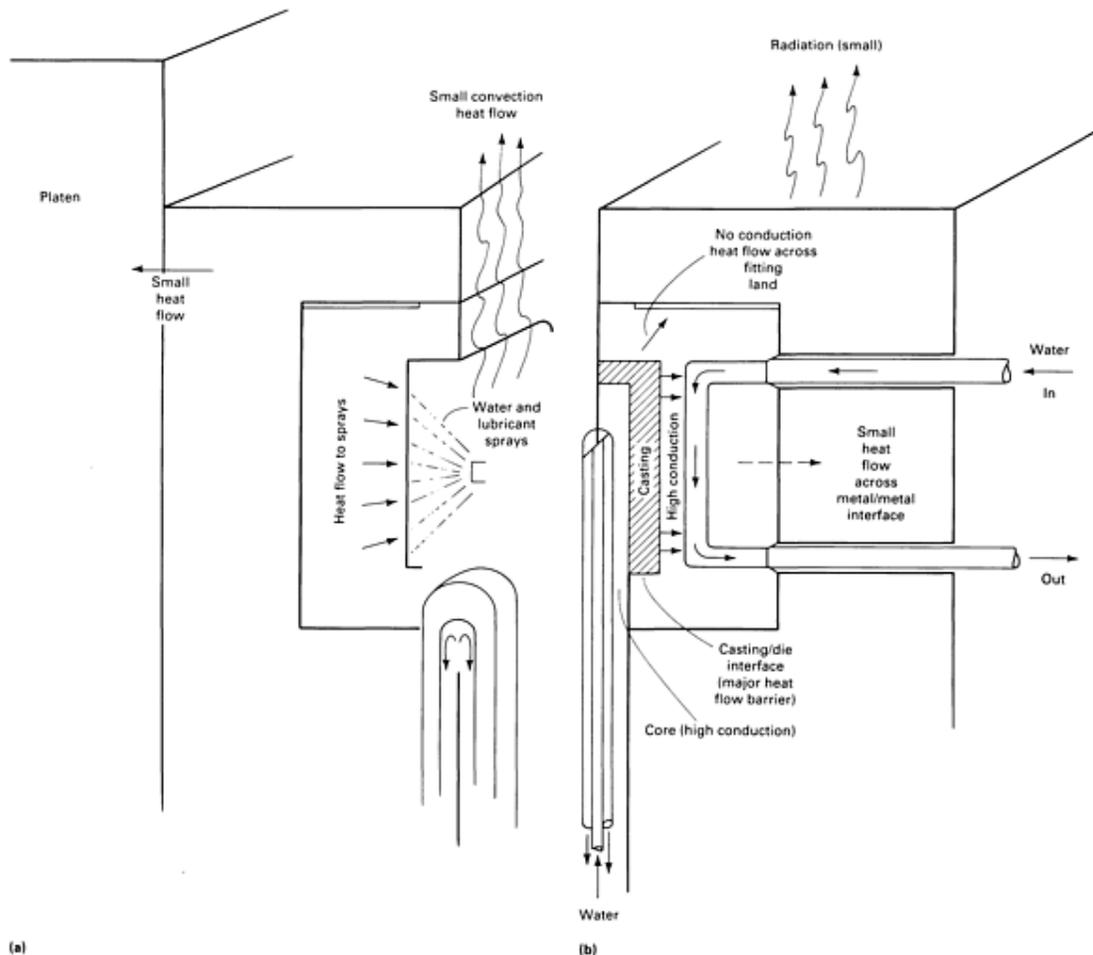


Fig. 9 Various heat flow paths available in die casting. (a) Die open for service. (b) Die closed after shot

The rate of heat removal is such that cooling is significant even during the filling process. Therefore, superheat and latent heat are transferred to the die before the alloy is stationary. The metal remote from the gate will be partially solid before the end of die filling. This transient heat flow results in more heat being transferred to the die near the gate.

**Control of Heat Flow.** The most important factor in controlling heat flow is the die/casting interface. The interface heat transfer coefficient is affected by a number of factors, such as shape, surface finish, lubrication, and steel oxide state. However, die material can also be used to influence heat flow. Conductive materials such as tungsten-base alloys and beryllium copper are used as inserts to promote high heat flow rates in local areas.

The location of waterlines is a key control of heat flow. The complex shapes of many die castings restrict the die designer in the placement of cooling lines. The basic factors controlling waterline effectiveness are location, coolant flow rate, temperature and pressure, and scale buildup. Placement of waterlines must be done in design. Coolant flow is a process control tool; scale buildup in waterlines is routinely controlled as part of preventive maintenance.

Cooling water can be replaced by hot oil to provide a source of heat in a die. Heat is often needed in configurations that suffer from excess temperature loss in filling. Hot oil and hot water systems can be effectively used to preheat a die before casting begins. This will promote longer die life.

In contrast, external die sprays between shots are one method of obtaining rapid heat flow where internal cooling is insufficient. As in the case of preheating by making shots, external sprays are very detrimental to die life. The trade-off in this case is between the cost required to maintain the die steel (including downtime) and the reduced cycle time for each part.

**Analysis of Cooling Requirements.** Several analytical methods are available for analyzing the cooling requirements of a die for a particular part. These tools vary widely in the detail and the time required for analysis. There are very simple methods that can be done quickly, and these are used for preliminary analysis. There are also methods that require more time and effort but provide the die designer with the detail necessary to obtain effective process definition.

A simple overall heat balance is the most basic tool that is used. In this technique, the heat content is calculated for one molten alloy shot between the injection temperature and the ejection temperature. This is the heat that must be removed within one cycle from the casting and the die. The proportion of the heat removed by cooling lines can then be determined. The size of preheating units required can also be found by using this simple method and taking into account the die properties.

There are also methods that use purely geometric considerations. In this case, the geometric shapes of part and die segments are considered in the conduction equation for the die. Computer-aided design (CAD) software is available to make this method simple to use once a surface model is created.

Analysis of cooling channel placement, along with hydraulic considerations for circuiting, is in general use for plastic injection molds. This method can also be adapted for die casting cooling design, and again, software is available in conjunction with a number of CAD packages.

Diffusion solutions, such as finite-element and finite-difference methods, represent the most detailed solution to the heat transfer design problem in die casting die design. The use of these tools will become more common as the cost of computation decreases. The sophistication of automated mesh generation must also improve if models are to be created and run within the short lead times often required for die design. The increased use of CAD for product design, where three-dimensional geometry is available to the die designer from the beginning, will also promote the use of these tools for initial design and for process improvement and optimization.

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## Ejecting the Casting

After the casting has solidified and cooled, it must be removed from the die. Slides and cores generally must be withdrawn first, followed by opening of the die by ejector die motion. As the die opens, the casting is ejected from the die by the ejector pin. This is done by stopping the ejector plate while the die continues to retract or by using an actuator driven by hydraulic cylinder or rack and pinion. The casting is then taken from the pins manually, by dropping through the base of the machine under gravity, or by a robot or extractor.

Ejector pin size and location are governed by part geometry, especially depth of draw, draft, and surface contact area. The function of the casting can have considerable bearing on the allowable ejector pin location, and this is a subject for negotiation between the caster and the product designer. Bosses are often provided to ensure that there is a flat surface upon which the ejector pin can push. The mechanical design aspects of the ejection system must address stability and guidance during travel. Similarly, the die base in which the ejection system is contained must be strong enough to withstand the locking forces of the casting machine and metal flexure without undue deflection. Support pillars under the cavity may be required.

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## Preparation for the Next Cycle

With the casting removed from the die, external water sprays can be used to cool the die. Compressed air blow off is used to blow residual water and any other loose flash from the internal die surfaces. This is followed by a lubricant spray to provide an insulating release agent between metal and die. A lubricant is also applied to the shot cylinder. The die can then be closed in preparation for the next cycle. The combined ejection and preparation phases can be up to 40 to 50% of the process cycle, as compared to 20% for plastic injection molding. The time required for ejection and preparation depends on casting size and die complexity.

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## Die Casting Defects

Effective die design (fluid flow, heat flow, and mechanical design) and a well-defined process capability will combine to produce quality die castings. Proper attention to die casting process control will result in consistently high quality parts. The establishment of a stable process is the combined result of a partnership in casting design, die design, and process engineering.

Defects will occur if process variation is too broad. Defects are caused by three basic sources:

- Mechanical problems in the die
- Metallurgical problems in the molten alloy
- The interaction of heat flow and fluid flow

Care is necessary in order to identify the cause of a specific defect because several outward appearances can have different sources.

Mechanically induced defects such as galling or drag marks on the casting surface occur during ejection of the casting and are usually caused by insufficient draft in the die. Galling will be aligned with the direction of relative motion of the casting and its adjacent die segment. Lack of draft can be an error in die building, but it is readily corrected. Die design can cause lack of draft by inadequate specification, poor ejector system alignment, and inadequate slide or core alignment. Improper machine setup with uneven tie bar loading can cause the die to shift upon closing and opening and therefore create galling. Distorted or cracked castings are the result of extreme cases of poor mechanical design. Although a new die may be free of such mechanical defects, the normal wear and tear of the process may eventually lead to these defects. Proper attention to preventive maintenance will minimize such behavior.

Another class of mechanically induced defects can result from improper injection system performance. Machine-monitoring systems are available to measure and control critical timing, pressures, and velocities. These can be monitored on a shot-by-shot basis or on a periodic audit plan. In the event of loss of process control, these injection parameters should be the first to be checked. Changes to the die should be the last to be checked because they are the most difficult to diagnose and the most costly to implement.

Metallurgical Defects. Proper control of the quality of the molten metal is of primary importance with regard to metallurgical defects. The four principal factors are alloy composition, dissolved gas content, entrained solids (such as oxides and intermetallic compounds), and improper temperatures. The results can be poor fluidity, die soldering, shrinkage porosity, hot cracking, and gas porosity. Metallurgical factors interact directly with the primary causes of

casting defects: heat flow and fluid flow. A die casting process that experiences unexplained variations over time in the quantity of defects may be receiving poor-quality metal. As with a deterioration in the mechanical behavior of the die, metal quality is one of the first process parameters to be checked.

**Interaction of Heat Flow and Fluid Flow.** The die casting die is primarily a means of shaping a molten volume of metal and removing enough heat to permit ejection. Improper interaction of fluid and heat flow can lead to poor casting quality. The rapid fill time, the complex part geometries, and the high heat transfer rates of die casting combine to form a complex set of potential causes of defects. Flow/heat defects can be built into the die by poor design of the gating, venting, and thermal die layout. However, once the process is proven and the die is properly maintained, these parameters should not produce variations in the process.

*Cold shuts* are seams in the casting where two streams of metal have come together but have not fused. Cold shuts occur when solidification progresses too far in the flow streams, resulting in insufficient fluidity at the seam for mixing. The fixed causes of cold shuts are poor flow patterns due to inappropriate gating, excessive back pressure due to inadequate venting, and excessively thin walls in the part design. Process variables that cause the appearance of cold shuts are low die or metal temperatures, inadequate injection pressures, and excessive fill times.

Accurate volume measurement is important for precise process control. Insufficient volume can result in a very short biscuit (the cylinder left in the shot sleeve), premature freezing, and loss of effectiveness in injection pressure intensification. Excess volume can prolong cold chamber casting cycles because the biscuit is the last section of the casting to solidify.

*Gas porosity* consists of discrete, separate holes that have two sources: entrained air and, less frequently, dissolved gas. The latter source is entirely a metallurgical control problem, while the former has a variety of process causes. Built-in causes of excessive entrained gas are:

- Too empty a shot sleeve (excessive diameter or length)
- Inadequate venting
- Excessive use of lubricant
- Residual moisture from sprays
- Poor metal flow patterns that prevent venting

If the gas porosity is adjacent to the surface, a blister may form immediately following ejection as the high-pressure gas deforms the weak metal. The secondary factor is excessive die temperature on the blister side.

*Shrinkage porosity* is a series of interconnected holes created by a lack of feed metal at the end of solidification. Shrinkage is confined to the thermal center of a section, which can extend to the casting surface if local die temperatures are excessive. Shrinkage porosity can be built in by poor casting design that contains large sections, excessive die heating from poor metal flow distribution, and inadequate internal die cooling. Process variations in metal temperature, die temperature, inadequate injection pressures, and poor cooling from clogged cooling lines can result in shrinkage porosity.

*Soldering* is the adherence of the molten metal to the die surface; this results in tearing of the casting surface upon ejection. The condition appears where impingement of the flowing metal causes local overheating of the die. If the overheating is extreme, the molten metal stream will erode the die surface. This is most often seen at or near the gate. Poor gate design is the primary cause of soldering, combined with inadequate die cooling; poor die surface polishing can aggravate the problem. Process variations in lubricant application, die surface maintenance, or temperature control can lead to soldering and die erosion.

Molten aluminum is very aggressive toward unprotected die steels. If the iron content of the aluminum alloy is too low, the molten material tends to dissolve the die steel during injection. This tendency is especially pronounced under conditions that promote soldering and die erosion. This special soldering problem can be avoided by maintaining the iron content of aluminum die casting alloys between 0.8 and 1.1%.

*Heat check fins* are replica die cracks created by thermal fatigue. Thermal fatigue cracking (heat checking) is the result of the temperature cycles experienced at the die surface. High stresses may be built into the die by the design of the casting. Sharp corners and other stress raisers should be removed if at all possible. Excessive temperatures, combined

with local plastic deformation, creep, and phase changes in the steel, eventually lead to crack formation. Improper heat treatment will aggravate phase-induced failure. Dies for the low-melting metals rarely fail by thermal fatigue. Copper-base and ferrous castings rapidly cause checking of the die surface. Two process abuses are the most frequent irritants: making shots in a cold die, and excessive use of external water sprays.

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## Die Casting

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## Postcasting Operations

**Die Trimming.** There are two postcasting operations that are unique to die casting. Die castings are taken from the die with flash, gates, and overflows attached to them. Trimming of these extraneous elements can be done by hand for low production volumes but is usually done with a hydraulic trim press for high-production parts. The press is set up with two handswitch interlocks to ensure that the operator's hands are out of the press after loading/unloading. Robot operation is also possible. Two types of trim dies are used: push-through and reverse-trim. Commercially available die sets are often used. The trim knives are hardened to greater than 50 HRC, and provision is made for self-cleaning or blow-off of flash to keep the trim dies clean.

**Impregnation.** Porosity in a die casting can lead to a lack of pressure tightness. Although porosity can be minimized by proper process design or control, it is sometimes necessary or cost effective to fill voids by using an impregnation process. Sodium silicate and anaerobic organic compounds are among the impregnants available. The typical procedure is as follows:

- Clean the casting
- Place in an autoclave and draw a vacuum of 710 mm (28 in.) of mercury for 15 min
- Introduce the sealant and apply hydrostatic pressure for 15 min
- Pump out and remove the castings
- Wash and dry

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## Centrifugal Casting

### *Horizontal Centrifugal Casting*

Alain Royer and Stella Vasseur, Pont-à-Mousson S.A., France

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HORIZONTAL CENTRIFUGAL CASTING is used to cast pieces having an axis of revolution. The technique uses the centrifugal force generated by a rotating cylindrical mold to throw the molten metal against the mold wall and form the desired shape.

The first patent on a centrifugal casting process was obtained in England in 1809. The first industrial use of the process was in 1848 in Baltimore, when centrifugal casting was used to produce cast iron pipes. In the 1890s, the principles already known and proved for liquids in rotation about an axis were extended to liquid metals, and the mathematical theory of centrifugal casting was developed in the early 1920s.

Horizontal centrifugal casting was first used mainly to manufacture thin-wall gray iron, ductile iron, and brass tubes. Improvements in equipment and casting alloys made possible the development of a flexible and reliable process that is both economical and capable of meeting stringent metallurgical and dimensional requirements. Cylindrical pieces produced by horizontal centrifugal casting are now used in many industries. Of particular importance are large-diameter thick-wall bimetallic and specialty steel tubes used in the chemical processing, pulp and paper, steel, and offshore petroleum production industries.

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## Centrifugal Casting

### Equipment

A horizontal centrifugal casting machine must be able to perform four operations accurately and with repeatability:

- The mold must rotate at a predetermined speed
- There must be a means to pour the molten metal into the rotating mold
- Once the metal is poured, the proper solidification rate must be established in the mold
- There must be a means of extracting the solidified casting from the mold

Figure 1 shows a common design for a horizontal centrifugal casting machine. Many variations of this basic design are in use. Details may vary; for example, there are different types of drive systems, carrying rollers, and so on.

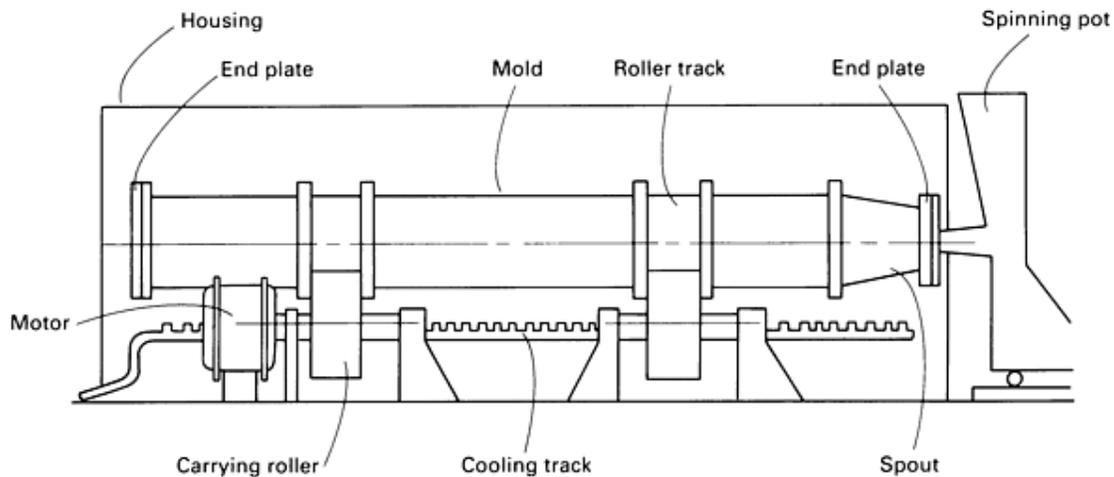


Fig. 1 Schematic of a common design for a horizontal centrifugal casting machine.

### Molds

Molds consist of four parts: the shell, the casting spout, roller tracks, and end heads. The mold assembly is placed on interchangeable carrying rollers that enable the use of different mold diameters and fine adjustments. Molds are cooled by a water spray, which can be divided into several streams for selective cooling.

Different types of molds are generally used according to the geometry and quantity of castings needed and the characteristics of the metal or alloy being cast. Molds can be either expendable (a relatively thin case lined with sand) or permanent.

Expendable molds lined with sand are widely used in centrifugal casting, especially for producing relatively few castings. A single mold case can be used with different thicknesses of sand linings to produce tubes of various diameters within a limited range.

*Green sand* is commonly used as the liner in expendable molds. Various mixtures and binders are used--for example, a mixture of 60% silica sand and 40% calcined and crushed asbestos or sand bound with resin. Phenolic binders are also used with silica sand. One proprietary process uses a mixture of sand, silica flour, bentonite, and water.

*Dry sand molds* can also be employed; in this case, the sand is pressed down around a pattern having the same dimensions as the casting. Hardening is sometimes accomplished with carbon dioxide.

*Mold washes* of various compositions are used with sand molds. The wash hardens the mold surface and minimizes erosion of the mold by molten metal.

**Permanent Molds.** The most common materials for permanent molds are steel, copper, and graphite.

*Steel molds* are used to cast large quantities and for some casting alloys that require specific solidification conditions. Steel molds are sensitive to thermal shock; alumina- or zirconia-base mold sprays are used to lessen thermal shocks to the mold and to improve the mold surface. Mold coatings are also important in regulating the solidification rates of some casting materials. Other ceramic coating materials are beginning to be employed.

*Copper molds* are sometimes used for their high thermal conductivity. Their relatively high cost and the difficulty of calculating the correct dimensions of these molds limit their field of application.

*Graphite Molds.* Because of their relatively low cost, graphite molds can be an economical alternative to sand in the production of small quantities of parts. Graphite is the mold material of choice in the casting of 80% Cu bronzes, high-phosphorus bronzes, and other copper alloys. Graphite has excellent thermal conductivity and resistance to thermal shock,

and it is easily machined. Care must be taken, however, to maintain the mold well below the oxidation temperature of graphite.

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## Centrifugal Casting

### Casting Techniques

**Pouring.** Molten metal can be introduced into the mold at one end, at both ends, or through a channel of variable length. Pouring rates vary widely according to the size of the casting being produced and the metal being poured. For example, a pouring rate of 1 to 2 Mg/min (1.1 to 2.2 tons/min) has been used to cast low-alloy steel tubes 5 m (200 in.) long and 500 mm (20 in.) in outside diameter with 50 mm (2 in.) thick walls. Pouring rates that are too slow can result in the formation of laps and gas porosity, while excessively high rates slow solidification and are one of the main causes of longitudinal cracking.

**Casting Temperatures.** The degree of superheat required to produce a casting is a function of the metal or alloy being poured, mold size, and physical properties of the mold material. The following empirical formula has been suggested as a general guideline to determine the degree of superheat needed:

$$L = 2.4\Delta T + 110 \qquad \text{(Eq 1)}$$

where  $L$  is the length of spiral fluidity (in millimeters) and  $\Delta T$  is the degree of superheat (in degrees centigrade). The use of Eq 1 for ferrous alloys results in casting temperatures that are 50 to 100 °C (120 to 212 °F) above the liquidus temperature. In practice, casting temperatures are kept as low as possible without the formation of defects resulting from too low a temperature.

A high casting temperature requires higher speeds of rotation to avoid sliding; low casting temperatures can cause laps and gas porosity. Casting temperature also influences solidification rates and therefore affects the amount of segregation that takes place.

**Mold Temperature.** Numerous investigators have studied the relationship between initial mold temperature and the structure of the resultant casting. Initial mold temperatures vary over a wide range according to the metal being cast, the mold thickness, and the wall thickness of the tube being cast. Initial mold temperature does not affect the structure of the resultant casting as greatly as the process parameters discussed above do.

**Speed of Rotation.** Generally, the mold is rotated at a speed that creates a centrifugal force ranging from 75 to 120  $g$  (75 to 120 times the force of gravity). Speed of rotation is varied during the casting process; Fig. 2 illustrates a typical cycle of rotation. The cycle can be divided into three parts:

- At the time of pouring, the mold is rotating at a speed sufficient to throw the molten metal against the mold wall
- As the metal reaches the opposite end of the mold, the speed of rotation is increased
- Speed of rotation is held constant for a time after pouring; the time at constant speed varies with mold type, metal being cast, and required wall thickness

The ideal speed of rotation causes rapid adhesion of the molten metal to the mold wall with minimal vibration. Such conditions tend to result in a casting with a uniform structure.

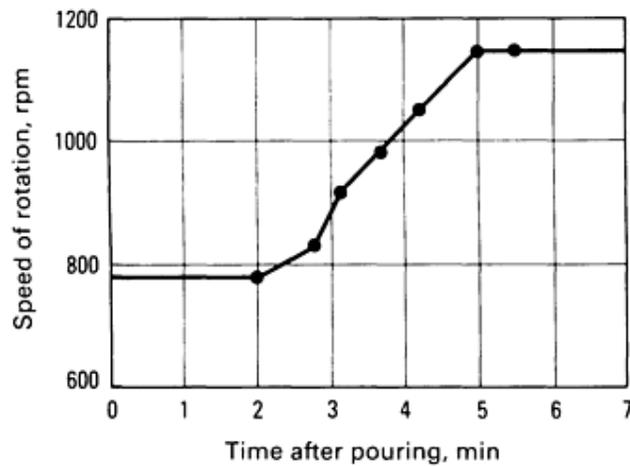


Fig. 2 Typical cycle of rotation in horizontal centrifugal casting.

As the molten metal enters the mold, a pressure gradient is established across the tube thickness by centrifugal acceleration. This causes alloy constituents of various densities to separate, with lighter particles such as slags and nonmetallic impurities gathering at the inner diameter. The thickness of these impurity bands is usually limited to a few millimeters, and they are easily removable by machining.

Too low a speed of rotation can cause sliding and result in poor surface finish. Too high a speed of rotation can generate vibrations, which can result in circumferential segregation. Very high speeds of rotation may give rise to circumferential stresses high enough to cause radial cleavage or circular cracks when the metal shrinks during solidification.

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## Centrifugal Casting

### Solidification

In horizontal centrifugal casting, heat is removed from the solidifying casting only through the water-cooled mold wall. Solidification begins at the outside diameter of the casting, which is in contact with the mold, and continues inward toward the casting inside diameter. Several parameters influence solidification:

- The mold, including the mold material, its thickness, and initial mold temperature
- The thickness and thermal conductivity of the mold wash used
- Casting conditions, including degree of superheat, pouring rate, and speed of rotation
- Any vibrations present in the casting system

Thermal Aspects of Solidification. It appears that the mold-related parameters listed above have relatively little influence on solidification. Large variations in mold thickness, however, could become significant.

The parameters with the greatest effect are the degree of superheat in the molten metal and the thickness of the mold wash employed. Both of these process variables affect local solidification conditions and therefore modify the structure of the casting. Figure 3 illustrates the general effects of mold wash thickness and degree of superheat on solidification rates. Charts such as Fig. 3 can be used to predict total solidification time. They are especially useful in determining the optimal casting conditions for bimetallic tubes based on the type of bond required.

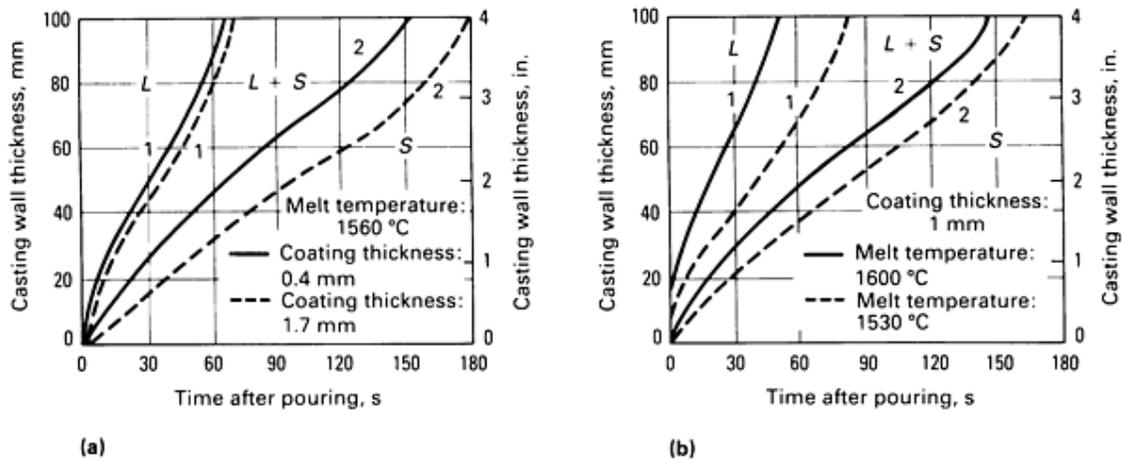


Fig. 3 Effect of mold coating thickness (a) and molten metal temperature (b) on solidification in horizontal centrifugal casting. Numbers 1 and 2 indicate liquidus and solidus curves, respectively.

Metallurgical Aspects of Solidification. The as-cast structures obtained in the horizontal centrifugal casting of steels vary according to composition. Regardless of the phase or phases that solidify first, certain features are common to the structures of centrifugally cast ferrous alloys (Fig. 4a):

- Very thin, fine columnar skin
- Well-oriented columnar structure adjacent to the skin
- More or less fine equiaxed structure

In the case of steels that solidify as ferrite, the columnar areas may be nonexistent if superheat and mold wash thickness are low (Fig. 4b). In steels that solidify as austenite, it is relatively easy to obtain well-oriented 100% columnar structures.

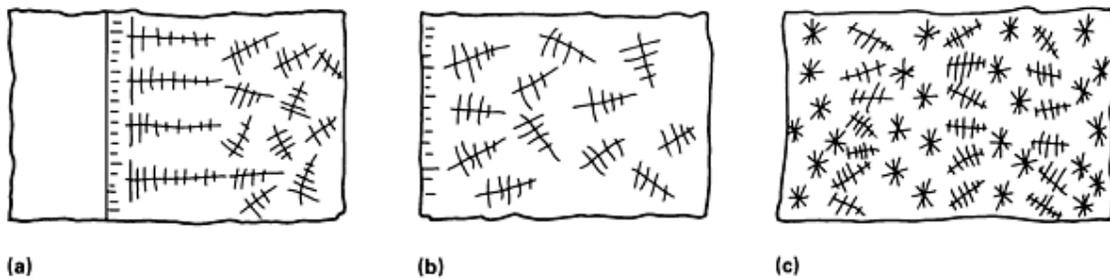


Fig. 4 Three types of as-cast structures seen in centrifugally cast ferrous alloys. (a) Fine columnar skin, large well-oriented columnar grains, and equiaxed area. (b) Completely equiaxed structure sometimes observed in ferritic steels. (c) Equiaxed bands of varying grain size. This type of structure is thought to be caused by machine vibrations.

A phenomenon specific to horizontal centrifugal casting is the formation of equiaxed bands through the entire thickness of the casting (Fig. 4c). A plausible explanation for this phenomenon is linked to machine vibrations, which may cause recirculation of the molten metal during solidification.

As in static casting, the rejection of solute ahead of the solidification front leads to microsegregation and to a progressive enrichment of the remaining liquid. Carbon steels are particularly sensitive to this effect; carbon, sulfur, and phosphorus contents must be limited to avoid local precipitation of carbides and sulfides.

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## Centrifugal Casting

### Process Advantages

**Flexibility in Casting Composition.** Horizontal centrifugal casting is applicable to nearly all compositions with the exception of high-carbon steels (0.40 to 0.85% C). Carbon segregation can be a problem in this composition range.

**Wide Range of Available Product Characteristics.** The metallurgical characteristics of a tubular product are mainly characterized by its soundness, texture, structure, and mechanical properties. Centrifugal castings can be manufactured with a wide range of microstructures tailored to meet the demands of specific applications.

The high degree of microstructural control possible with horizontal centrifugal casting results in great flexibility in selecting properties for specific applications. Tubes can be manufactured with resistance to elevated temperatures, corrosion resistance, thermal fatigue resistance, low-temperature ductility, and so on. Centrifugally cast parts have a high degree of metallurgical cleanliness and homogeneous microstructures, and they do not exhibit the anisotropy of mechanical properties evident in rolled/welded or forged tubes.

**Dimensional Flexibility.** Horizontal centrifugal casting allows the manufacture of pipes with maximum outside diameters close to 1.6 m (63 in.) and wall thicknesses to 200 mm (8 in.). Tolerances depend on part size and on the type of mold used.

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## Centrifugal Casting

### Materials

As mentioned at the beginning of this article, any material that can be statically cast can also be centrifugally cast. Materials that are currently being processed by horizontal centrifugal casting include high-strength low-alloy steels, duplex stainless steels, and chromium-molybdenum alloy steels. Also of importance are bimetallic tubes. These materials will be discussed briefly in this section. Specific applications for centrifugally cast tubes are discussed in the section "Applications" in this article.

High-strength low-alloy steels are important in offshore structures that must withstand extreme climatic conditions, for example, offshore drilling equipment in the North Sea. These materials must be weldable, with ductile-to-brittle transition temperatures below  $-40\text{ }^{\circ}\text{C}$  ( $-40\text{ }^{\circ}\text{F}$ ). Likely candidate materials for use under such conditions are manganese-molybdenum steels with microalloying additions of vanadium, nickel, or niobium. Heavy-wall weldable pipes with good mechanical properties can be produced from such materials by horizontal centrifugal casting. Several proprietary alloys have been approved for use in offshore oil applications in the North Sea.

Duplex stainless steel tubes can be readily produced by horizontal centrifugal casting in any section size. Castings retain strength at temperatures to  $600\text{ }^{\circ}\text{C}$  ( $1110\text{ }^{\circ}\text{F}$ ), have good ductility, and are weldable without special precautions.

Chromium-molybdenum alloy steel tubes produced by horizontal centrifugal casting have homogeneous structures and are metallurgically sound. They are resistant to thermal fatigue and wear and have good toughness.

Bimetallic tubes with metallurgical (rather than mechanical) bonds can be readily produced by horizontal centrifugal casting. They are most commonly produced by successively casting one alloy inside the other. Bimetallic tubes are used for two primary reasons: to reduce cost by using an exotic material bonded to a less expensive backing material, and to obtain combinations of properties that could not be achieved by other methods.

There are no general rules regarding what materials can be combined in centrifugally cast bimetallic tubes, although it may be beneficial to cast the inner layer of such tubes from a material that is more fusible than the outer material. In addition, relatively thin inner layers should be manufactured from alloys with coefficients of thermal expansion smaller

than that of the outer alloy. In this way, the thin inner layer is put into compression, making it more resistant to cracking. Table 1 lists materials that are commonly combined in bimetallic tubes, as well as their applications.

**Table 1 Common material combinations used in bimetallic centrifugally cast tubes**

<b>Outer material</b>	<b>Inner material</b>	Typical applications
Chilled iron	Gray iron	<b>Bearing rollers</b>
27% Cr cast iron	Ni-Resist cast iron	<b>Mill rollers</b>
Low-alloy steel	Manganese-molybdenum steel	<b>Continuous casting rollers</b>
Low-alloy steel	Ni-Hard cast iron, martensitic or 27% Cr white iron	<b>Wear-resistant applications</b>
Chromium-nickel white iron	Gray ductile iron	<b>Mill rollers</b>
Chromium white iron	Gray iron	<b>Mill rollers</b>
Stainless steel	Gray iron	<b>Rollers for pulp and paper industry</b>
<b>Low-alloy steel</b>	<b>Pearlitic gray iron, stainless steel, or superalloy</b>	<b>Liners, pipelines for corrosives</b>

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## Centrifugal Casting

### Applications

The flexibility of the horizontal centrifugal casting process, in terms of both materials and the wide range of part sizes that can be produced, has led to the application of centrifugally cast parts in many industries. Some of the most common applications are outlined briefly in this section.

**Iron and Steel Industry.** Centrifugally cast parts are used in the production of iron and steel for continuous casting rollers, rolling mill rolls, furnace rollers, special pipelines, winding spools, and other applications. Some of these uses are shown in Fig. 5.

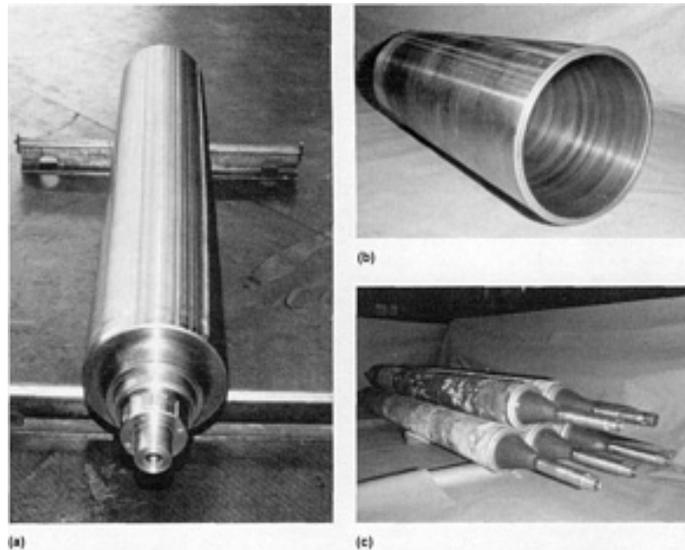


Fig. 5 Three applications for centrifugally cast parts in the iron and steel industry. (a) Continuous casting roller. (b) Winding spool. (c) Annealing furnace rollers.

Petroleum Production. Offshore production platforms in the oil and gas industry use centrifugally cast tubes in various applications (Fig. 6). Hot extruded bimetallic tubes are used in pipelines and gathering systems.

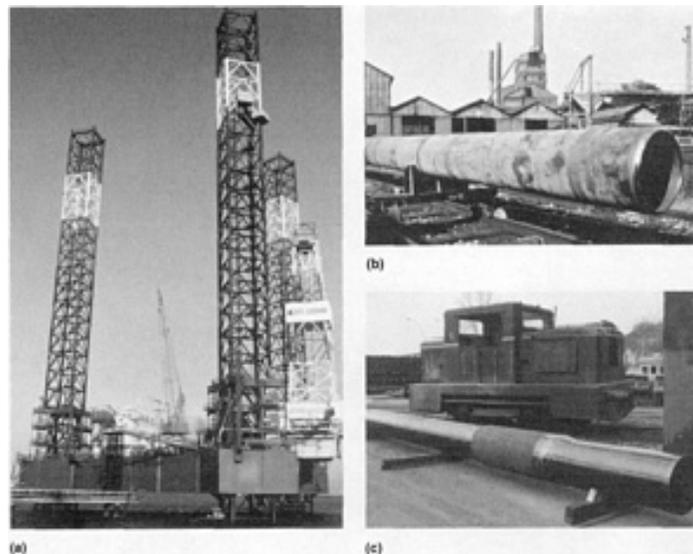


Fig. 6 Offshore petroleum production applications for centrifugally cast parts. (a) Jackup leg. (b) Risers. (c) Buckle-crack arrestor.

Other applications for centrifugally cast tubes include hydraulic cylinders, rollers for glass production, pipelines for the transport of abrasive materials, rollers in the pulp and paper industry, tubes for the chemical processing industry, foundation piles, and building columns. Some of these applications are shown in Fig. 7.

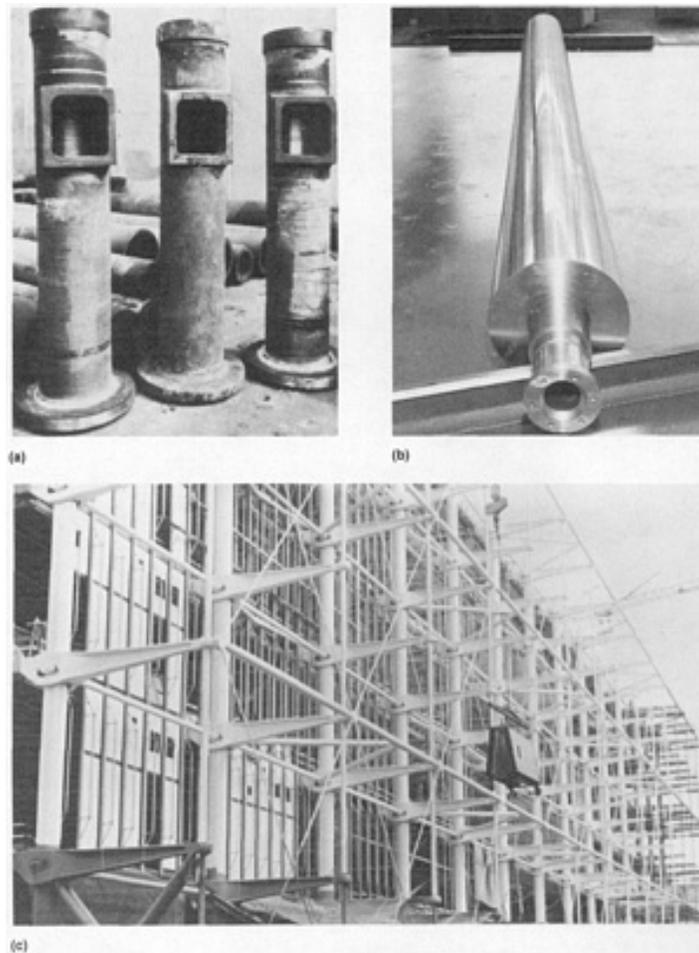


Fig. 7 Miscellaneous applications for centrifugal castings. (a) Hydraulic cylinders. (b) Float glass roller. (c) Exterior columns of Beaubour Museum, Paris.

## Centrifugal Casting

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### *Vertical Centrifugal Casting*

R.L. Dobson, The Centrifugal Casting Machine Company

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There are essentially two basic types of centrifugal casting machines: the horizontal type, which rotates about a horizontal axis, and the vertical type, which rotates about a vertical axis. Horizontal centrifugal casting machines are generally used to make pipe, tubes, bushings, cylinder sleeves (liners), and cylindrical or tubular castings that are simple in shape (see the previous section "[Horizontal Centrifugal Casting](#)" in this article). The range of application of vertical centrifugal casting machines is considerably wider. Castings that are not cylindrical, or even symmetrical, can be made using vertical centrifugal casting. The centrifugal casting process uses rotating molds to feed molten metal uniformly into the mold cavity. Directional solidification provides for clean, dense castings with physical properties that are often superior to those of the static casting processes.

Centrifugal castings are produced by pouring molten metal into a rotating or spinning mold. The centrifugal force of the rotating mold forces the molten metal against the interior cavity (or cavities) of the mold under constant pressure until the molten metal has solidified. Cylindrical castings are generally preferred for the centrifugal casting process. Tubular castings produced in permanent molds by centrifugal casting usually have higher yields and higher mechanical properties

than castings produced by the static casting process. Centrifugal casting is the most economical method of producing a superior-quality tubular or cylindrical casting with regard to casting yield, cleaning room cost, and mold cost.

Centrifugal castings can be best described as isotropic, that is, having equal properties in all directions. This is not true of a forging. By utilizing the outstanding advantage created by the centrifugal force of rotating molds, castings of high quality and integrity can be produced because of their high density and freedom from oxides, gases, and other nonmetallic inclusions. An economic advantage of centrifugal castings is the elimination or minimization of gates and risers.

All metals that can be cast by static casting can be cast by the centrifugal casting process, including carbon and alloy steels, high-alloy corrosion- and heat-resistant steels, gray iron, ductile and nodular iron, high-alloy irons, stainless steels, nickel steels, aluminum alloys, copper alloys, magnesium alloys, nickel- and cobalt-base alloys, and titanium alloys. Nonmetals can also be cast by centrifugal casting, including ceramics, glasses, plastics, and virtually any material that can be made liquid or pourable.

Sand molds, semipermanent molds, and permanent molds can be used for the centrifugal casting process. Selection of the type of mold is determined by the shape of the casting, the degree of quality needed, and the production (number of castings) required.

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## Centrifugal Casting

### Centrifugal Casting Processes

There are three types of centrifugal casting:

- True centrifugal casting
- Semicentrifugal casting
- Centrifuge centrifugal casting

True centrifugal casting is used to produce cylindrical or tubular castings by spinning the mold about its own axis. The process can be either vertical or horizontal, and the need for a center core is completely eliminated. Castings produced by this method will always have a true cylindrical bore or inside diameter regardless of shape or configuration. The bore of the casting will be straight or tapered, depending on the horizontal or the vertical spinning axis used. Castings produced in metal molds by this method have true directional cooling or solidification from the outside of the casting toward the axis of rotation. This directional solidification results in the production of high-quality defect-free castings without shrinkage, which is the largest single cause of defective sand castings.

Semicentrifugal casting is used to produce castings with configurations determined entirely by the shape of the mold on all sides, inside and out, by spinning the casting and mold about its own axis. A vertical spinning axis is normally used for this method. Cores may be necessary if the casting is to have hollow sections. Directional solidification is obtained by proper gating, as in static casting. Castings that are difficult to produce statically can often be economically produced by this method, because centrifugal force feeds the molten metal under pressure many times higher than that in static casting. This improves casting yield significantly (85 to 95%), completely fills mold cavities, and results in a high-quality casting free of voids and porosity. Thinner casting sections can be produced with this method than with static casting. Typical castings of this type include gear blanks, pulley sheaves, wheels, impellers, and electric motor rotors.

Centrifuge centrifugal casting has the widest field of application. In this method, the casting cavities are arranged about the center axis of rotation like the spokes of a wheel, thus permitting the production of multiple castings. Centrifugal force provides the necessary pressure on the molten metal in the same manner as in semicentrifugal casting. This casting method is typically used to produce valve bodies and bonnets, plugs, yokes, brackets, and a wide variety of various industrial castings.

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## Centrifugal Casting

### Mold Design

Gating Practice. The practicality of casting a part using the semicentrifugal or centrifuge centrifugal process is determined by casting configuration. The gating system of centrifugal castings usually employs a single gate, which combines the function of gate and riser. Centrifugal force greatly magnifies the feeding action of the riser and produces a greater metal density in the casting than would otherwise result. Figure 8 shows that a centrifugal casting mold spinning at a peripheral velocity of 305 m/min (1000 ft/min) at the outer diameter of the casting(s) will have an equivalent head of 9 m (30 ft). This is equivalent to a pressure of 703 kPa (102 psi). A typical static casting has a head less than 0.3 m (1 ft) high. The centrifugal force acting on the molten metal will provide better feeding action than a static cast head; therefore, it is possible to feed molten metal into and through lighter and thinner mold sections into heavier mold sections much more easily than in static casting.

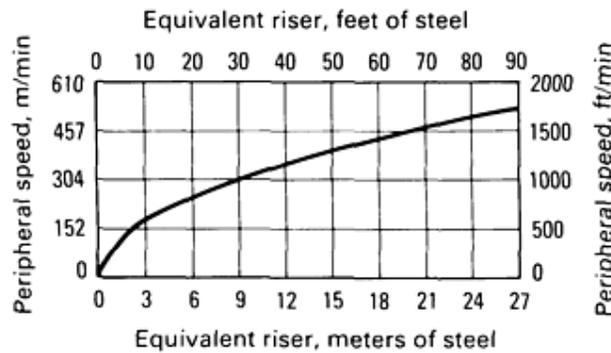


Fig. 8 Relationship between peripheral speed in centrifugal casting and equivalent riser.

Certain casting configurations that do not inherently produce directional solidification can be made to directionally solidify by certain molding practices. Pads, auxiliary gates, chills, or blind heads can be used. However, a casting of nonuniform section thickness might require such elaborate mold methods that molding and cleaning costs become too high.

**Sand Molds.** When sand molds are used, particularly green sand, it is usually necessary to begin pouring the molten metal at a slow mold-spinning speed. When the mold is partially or wholly poured, the spinning speed is increased to that required to prevent or reduce erosion of the mold cavities from the molten metal. Molds should almost always be poured while rotating, even if the speed of rotation is only 5 rpm. This ensures the proper distribution of hot and cold metal in the mold for the optimum feeding action.

**Green Sand Molds.** Centrifugal castings can be made in green sand or dry sand molds. When green sand molds are used, flasks (preferably round) are required. Three methods can be used to fasten the green sand mold to the table of the centrifugal casting machine.

In the first method, two pins are fastened to the table over which the flask is lowered. The cope and drag are held together by clamps in the usual manner of static casting.

In the second method, a device similar to a lathe chuck is fastened to the table. The cope and drag are clamped together as in static casting. The green sand mold is lowered onto the table, and the clamps are tightened to secure the mold.

In the third method, the green sand mold is transported on a roller conveyor into a flask body, which is fastened to the table. Rollers are also used in the casting machine to facilitate movement of the green sand mold. The flask body opens in half on a hinge. A cover, which holds a runner cup, serves to distribute equally the pressure from the clamping arrangement to the mold. The clamping arrangement, which is part of the flask body, keeps the cope and drag in firm contact.

**Dry Sand Molds.** Flasks are not required when dry sand molds are used. Two methods are available for handling dry sand molds on the casting machine.

In the first method, the dry sand molds are placed in a jacket somewhat similar to that used in conjunction with snap flasks. The jacketed mold is then carried to the casting machine and lowered to the table. Clamps are used to hold the cover onto the mold and to fasten the mold firmly to the table.

In the second method, the dry sand molds are transported on a roller conveyor into the casting machine, in which rollers are incorporated. Using a flask body of this type, both dry sand and green sand molds can be used interchangeably in the same casting machine.

*Molding Costs.* A green sand mold prepared for static casting generally costs the same as a green sand mold prepared for centrifugal casting. If dry sand molds are used for centrifugal casting rather than green sand, the molding cost may be higher, resulting in a reduced cost savings. There is an appreciable cost savings in the cleaning room because risers need not be removed from castings. This reduces the amount of cutting, chipping, and grinding required to clean the castings. The additional cleaning room savings might be offset by operating costs, depreciation of the centrifugal casting equipment, and possible increased molding costs due to the use of dry sand molds. An increase in yield primarily due to the elimination of riser heads is indicated in Table 2, which compares casting yields for static and centrifugal processes.

**Table 2 Comparison of casting yields for miscellaneous static and centrifugal castings**

Casting	Casting weight		Static yield, %	Centrifugal yield, %
	kg	lb		
A	27.7	61	39.0	<b>79.7</b>
B	18.1	40	53.4	<b>74.1</b>
C	7.7	17	49.2	<b>75.5</b>
D	14.1	31	38.0	<b>67.4</b>
E	27.2	60	36.3	<b>77.0</b>
F	14.3	31.5	41.5	<b>64.3</b>
G	28.6	63	40.0	<b>79.3</b>
H	20.0	44	36.4	<b>73.3</b>

*Other Sand Molding Considerations.* The requirements for a centrifugal sand mold or flask are more stringent than those for static cast molds because concentricity with the spinning axis must be more exact to prevent an imbalance that could cause vibration. However, most casting speeds required for centrifugal sand molding are relatively slow compared to true centrifugal casting in permanent molds. Molds made up of sections using dry sand cores are also used for centrifugal casting. The sand used can be sodium silicate, dry sand, chromite sand, or any molding material with sufficient strength to withstand the forces imposed by the spinning speed. It is desirable to use a suitable mold wash with most sand molds to reduce or minimize mold erosion from the molten metal. Excessive mold erosion generally does not occur, because of the relatively slow spinning speeds used.

Permanent Molds. Two basic types of permanent molds are in use: metal molds and graphite or carbon molds. Because of the faster heat extraction from permanent molds, there is usually an increase in the quality (especially properties) of the castings produced in this type of mold.

Metal Molds. A large number of cast iron molds are still used for centrifugal casting. However, steel molds are more common and much safer. Cast iron molds can be dangerous because of defects that may occur during the mold casting process and the fact that cast iron has relatively low tensile strength. In addition, when cast iron molds are water cooled, there is always the danger of cracking, rupture, or breakage. Most metal molds used in centrifugal casting are water cooled on the outside diameter using high-velocity water jets to increase solidification rates.

Steel molds are recommended for centrifugal casting. It is very important that the molds be perfect and free of any defects. The molds are machined all over to obtain a smooth surface and to ensure dynamic balance. A machined surface finish of  $3\ \mu\text{m}$  (125  $\mu\text{in.}$ ) RMS is recommended on the mold bore and outside diameter. If there are any defects on the portion of the mold that contacts the casting, it will be difficult, if not impossible, to remove the casting from the mold. Steel molds should always be thoroughly stress relieved (minimum temperature of  $620\ ^\circ\text{C}$ , or  $1150\ ^\circ\text{F}$ ) before the finish-machining operations. In the case of small, simple molds machined from heavy-wall seamless steel tubing, it has been standard practice not to stress relieve, because there is no apparent difference in the operational life of the mold. Stress relieving effectively prevents warpage in most molds and therefore prolongs the service life of the mold.

A molybdenum disulfide lubricant is recommended for all threaded fasteners used on a mold, such as mold lock clamps, end plate bolts, mold attaching bolts, and mold centering bosses.

Various mold end plate designs (Fig. 9) can be used, depending on individual preference and the size of the mold being used.

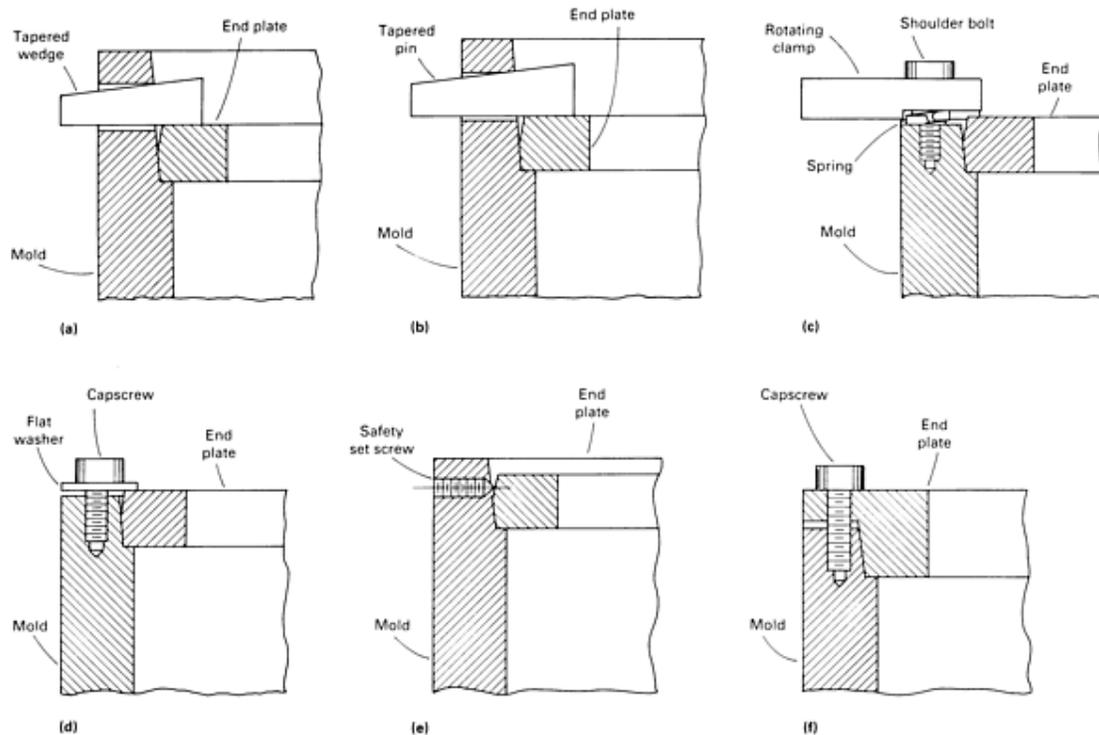


Fig. 9 Six end plate designs used in centrifugal casting. (a) through (c) are the most common.

It is recommended that low-carbon steels be used for centrifugal molds. Alloy steels and steels with more than 0.30% should not be used, because they are subject to cracking due to thermal shock and heat stresses from the casting of the molten metal. Satisfactory mold materials are 1018, 1020, or ASTM A106, grade A, steel. It is usually most convenient to make small molds from either hot-rolled solid bar stock or from heavy-wall seamless steel tubing. Larger-diameter molds

can be made from forgings or hot-rolled bar stock with the center trepanned or from centrifugally cast heavy-wall steel tubing.

*Metal Mold Design.* Machining allowances for castings depend on melting practices, the condition and thickness of the mold insulation coating, the volumetric shrinkage of the metal being cast, and the susceptibility of the metal to casting defects such as dross formation. The suggested machining allowances given in Table 3 can be used as a basis for mold design. With these minimum allowances, the mold can be remachined to allow for more machining allowance as determined by experience and the specific melting practices used.

**Table 3 Minimum machining allowances for design of centrifugal casting molds**

Casting size		Allowance on casting OD (each side)		Allowance on casting ID (each side)					
				Irons		Bronzes		Steels	
mm	in.	mm	in.	mm	in.	mm	in.	mm	in.
50-200	2-8	1.6	$\frac{1}{16}$	1.6	$\frac{1}{16}$	3.2	$\frac{1}{8}$	4.8	$\frac{3}{16}$
200-300	8-12	2.5	$\frac{3}{32}$	2.5	$\frac{3}{32}$	5	$\frac{3}{16}$	7.5	$\frac{9}{32}$
300-500	12-20	4	$\frac{5}{32}$	4	$\frac{5}{32}$	8	$\frac{5}{16}$	12	$\frac{5}{32}$
500-700	20-28	6	$\frac{7}{32}$	6	$\frac{7}{32}$	12	$\frac{7}{16}$	18	$\frac{21}{32}$
700-900	28-353	8	$\frac{5}{16}$	8	$\frac{5}{16}$	16	$\frac{5}{8}$	24	$\frac{15}{32}$

Patternmaker's shrinkage is the shrinkage allowance built into the pattern to compensate for the change in dimensions caused by the contraction of the cast metal as it cools. This shrinkage allowance is the factor with which the moldmaker is concerned. Different casting alloys have different shrinkage rates. Although average values for unrestricted cooling conditions are available (Table 4), it must be remembered that these can vary considerably according to the resistance offered by molds and cores.

**Table 4 Guidelines for shrinkage allowances for various metals and alloys**

Metal or alloy	Shrinkage allowance	
	in./ft	mm/m

Aluminum alloys	$\frac{5}{32}$	<b>13</b>
Aluminum bronze	$\frac{1}{4}$	<b>21</b>
Yellow brass (thick sections)	$\frac{5}{32}$	<b>13</b>
Yellow brass (thin sections)	$\frac{3}{16}$	<b>16</b>
Gray cast iron <sup>(a)</sup>	$\frac{1}{10} - \frac{5}{32}$	<b>8-13</b>
White cast iron	$\frac{1}{4}$	<b>21</b>
Tin bronze	$\frac{3}{16}$	<b>16</b>
Gun metal	$\frac{1}{8} - \frac{3}{16}$	<b>11-16</b>
Lead	$\frac{5}{16}$	<b>26</b>
Magnesium	$\frac{1}{4}$	<b>21</b>
Magnesium alloys (25%)	$\frac{3}{16}$	<b>16</b>
Manganese bronze	$\frac{1}{4}$	<b>21</b>
Copper-nickel	$\frac{1}{4}$	<b>21</b>
Nickel	$\frac{1}{4}$	<b>21</b>

Phosphor bronze	$\frac{1}{8} - \frac{3}{16}$	<b>11-16</b>
Carbon steel	$\frac{3}{16} - \frac{1}{4}$	<b>16-21</b>
Chromium steel	$\frac{1}{4}$	<b>21</b>
Manganese steel	$\frac{5}{16}$	<b>26</b>
Tin	$\frac{1}{4}$	<b>21</b>
<b>Zinc</b>	$\frac{5}{16}$	<b>26</b>

(a) Shrinkage in cast iron depends mainly on the speed with which the casting cools. Greater shrinkage results in more rapid cooling, less shrinkage from slower cooling.

*Mold Wall Thickness.* Figure 10 can be used as a general guideline for determining the proper mold wall thickness for water-cooled steel molds. Wall thicknesses may vary depending on the specific equipment and application involved. Mold wall thickness is independent of casting wall thickness for water-cooled steel molds. Casting wall thicknesses exceeding 305 mm (12 in.) have been made using these recommended mold wall thicknesses.

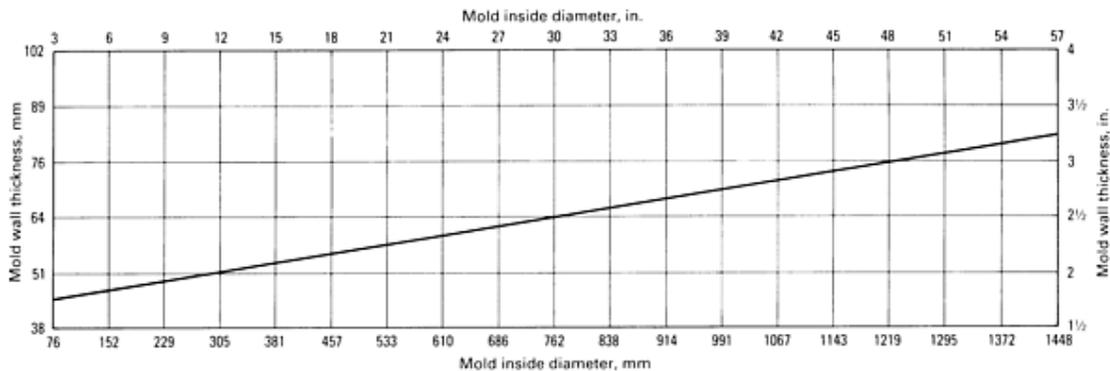


Fig. 10 Mold wall thickness as a function of mold inside diameter. Values are recommendations from one manufacturer for steel molds.

*End plate thicknesses* depend on casting wall thickness and end plate material. Commonly used end plate materials are ASTM A36 steel, 1015 steel, or 1018 steel plate. In cases of extremely large diameter plates (>450 mm, or 18 in.), the end plate material can be pressure vessel quality ASTM A285 grade C or A515 grade 70.

For maximum adhesion of the mold wash to flat surfaces of the mold top and bottom end plates, it is advisable to have a machined surface finish of about 9 to 13  $\mu\text{m}$  (350 to 500  $\mu\text{in.}$ ) RMS, with the lay approximately circular relative to the center of the plate. The opening in the top plate should be at least 13 mm ( $\frac{1}{2}$  in.) smaller in diameter than the casting inside diameter but large enough to permit the molten metal to enter the mold.

*The end plate recess* in the mold provides an effective seal to prevent leakage of the molten metal from the mold. The amount of end plate recess used depends on mold inside diameter and can be as high as the mold inside diameter plus 25 mm (1 in.) for mold inside diameters of 150 mm (6 in.) or more.

*End Plate Mold Lock Design.* Various removable end plates are shown in Fig. 9. These end plate types are recommended for all vertical molds. Preferred end plate types are those shown in Fig. 9(a), (b), and (c). Some end plates can be turned over to prolong their service lives, and it is recommended that they be turned over between each cast.

Mold end plate diametral clearance fit into the mold recess diameter should be a minimum of 1.2 mm ( $\frac{3}{64}$  in.). This clearance is effective for end plates up to about 380 mm (15 in.) in diameter. On larger end plates, clearances as large as 2.5 mm ( $\frac{3}{32}$  in.) may be necessary for easy removal and assembly. The standard draft angle of  $3^\circ$  will permit easy removal and assembly.

The number of fasteners or mold clamps or wedges used depends on mold diameter. Recommended numbers of fasteners are:

- Three for molds up to 250 mm (10 in.) bolt circle or outside diameter
- Four for molds from 250 to 380 mm (10 to 15 in.) bolt circle or outside diameter
- Five for molds from 380 to 480 mm (15 to 19 in.) bolt circle or outside diameter

Large diameter molds or molds for extremely heavy wall castings (>50 mm, or 2 in., in wall section) require additional fasteners for safe operation.

*End Plate Wedge and Pin Design.* Wedges for holding the end plate secure in the mold are principally of two different types: the tapered wedge and the tapered pin. The maximum allowable stress for tapered wedges and pins is 69 MPa (10 ksi). Wrought steel bar stock, such as cold-rolled carbon steel or stainless steel, can be used; cast pins or wedges should not be used.

The following allowable safe loads can be used regardless of the wedge or pin material:

Holder	Maximum safe load	
	kgf	lbf
Tapered wedge	1840	4060

*Mold Adapter Tables.* A mold adapter table (Fig. 11) is usually furnished or required with a vertical centrifugal casting machine to facilitate attachment of the molds to the machine. Also furnished or required with the mold adapter

table is a mold centering boss or index boss/plug for aligning and centering the mold so that it is concentric with the spinner shaft of the machine.

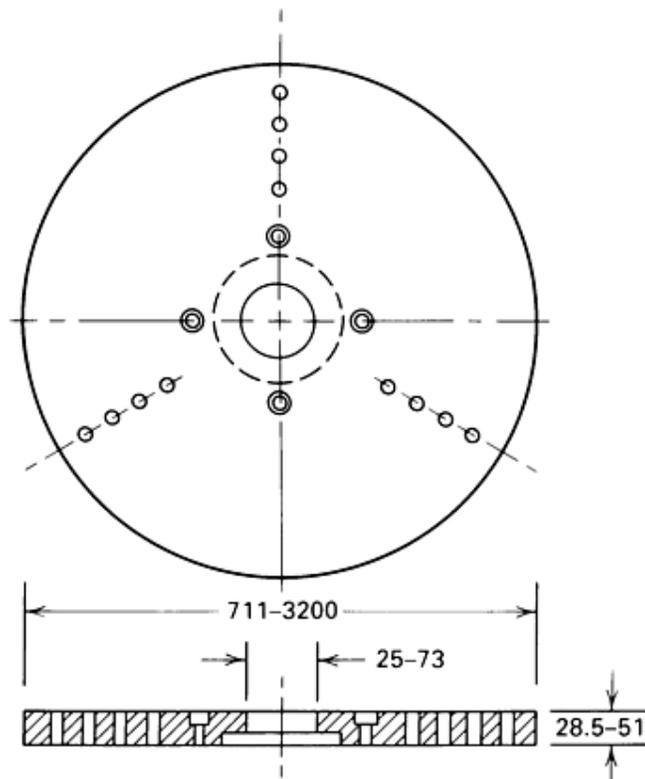


Fig. 11 Adapter table for mounting of molds on the centrifugal casting machine. Dimensional ranges are given in millimeters.

Two methods can be used to secure the mold to the adapter table. One method is to allow for a flanged extension of the bottom mold plate with holes for bolting directly into the table. The other method is to use a flanged extension of the mold bottom plate with dog clamps fastened to the table in the same manner in which a part is held on a mill table or vertical lathe.

The vertical centrifugal casting machine is available with a water-cooled bottom mold plate. Water cooling requires the machining of radial grooves or slots in the bottom of the bottom mold plate for water passage. Water cooling is sometimes advantageous for extremely heavy wall castings, which can transfer excessive heat into the bottom of the mold.

*Pretreatment for Metal Molds.* All molds, end plates, and surfaces to which mold wash is to be applied should be treated before use in the following manner:

- Preheat mold to approximately 150 °C (300 °F)
- Swab inside surface of mold with concentrated aqueous ammonium persulfate
- Flush mold with water to remove all contaminants. The mold can be put into service after this treatment

For new molds, the following treatment is recommended before use:

- Preheat mold to 205 to 260 °C (400 to 500 °F)

- Spray with a coating of mold wash approximately 0.8 mm ( $\frac{1}{32}$  in.) thick
- Brush out mold wash, and repeat spray procedure. The mold should then be brushed out and resprayed a third time

The mold is ready for use after this treatment. If the wash still does not adhere, the mold should be cleaned again with ammonium persulfate as described above.

*Mold Wash for Permanent Molds.* The mold wash, when used on a permanent mold, serves as a refractory insulating material. When applied in sufficient thickness, the mold wash insulates the mold, thus reducing the surface temperature of the mold and increasing its useful life. A wide variety of centrifugal casting mold washes are commercially available, including silica, zirconia, and alumina washes. The centrifugal mold wash must be inert to the molten metal being cast.

The insulating characteristic of the mold wash is necessary to retard or slow the initial solidification rate in order to eliminate the formation of cold shuts, laps, droplets, and so on, and to produce a high-quality homogeneous outside surface on the casting. In most cases, a mold wash coating thickness of 0.8 mm ( $\frac{1}{32}$  in.) is desired to obtain satisfactory castings. Spraying equipment is available for applying centrifugal casting mold washes.

*Water Cooling of Permanent Steel Molds.* The temperature of the mold increases with each casting poured. The mold can be operated at temperatures to 370 °C (700 °F). However, the usual operating temperatures of the mold should range from 150 to 260 °C (300 to 500 °F). To maintain this mold temperature for successive casting production, water cooling of the outside surface of the mold is generally employed. The high velocity of the water impinging upon the mold surface will prevent the formation of an insulating steam barrier, which would actually inhibit the extraction of heat from the mold. Quick-opening valves must be used to prevent warpage of the mold, and the spinning of the mold should be interlocked with the water valves to prevent spraying water on a mold that is not spinning and ultimately warping an expensive mold. In practice, the water cooling is usually activated immediately upon completion of the pouring and allowed to remain on long enough to permit the mold to be sprayed with the mold wash at the proper temperature range for the next casting cycle, after extracting the solidified casting.

*Graphite and Carbon Molds.* The choice between using a graphite or a carbon mold depends primarily on the availability to the user. Graphite has a higher rate of heat conductivity than carbon and is therefore sometimes used because of the desired metallurgical properties of the finished casting.

Graphite can be easily machined into a variety of intricate mold forms with a very good surface finish. Graphite molds have excellent chill characteristics, with thermal conductivity three times that of iron and a specific heat about double that of iron. The chilling ability of a material is roughly equal to the product of its mass multiplied by its specific heat. Graphite is nonreactive with most molten metals. In casting phosphorus bronze, graphite molds are not burned into as iron molds are. Carbon pickup is negligible in casting low-carbon stainless steel because of the quick chilling ability of the graphite, which almost instantaneously solidifies a skin layer of steel and therefore makes carbon pickup impossible. In certain cases where rapid chilling is not desired, an insulating mold wash is used. Graphite molds are extremely resistant to thermal shock, with a thermal conductivity about three times that of steel and a low Young's modulus. The strength of graphite molds increases with temperature.

Graphite molds are generally designed with two considerations: minimum wall thickness and weight ratio of mold to casting. A steel sleeve or master die holder is usually employed with a heat shrink-fit over the graphite mold. The steel is preheated to 425 °C (800 °F) for this shrink-fit; therefore, there is considerable compression upon the graphite mold. The graphite mold wall thickness must be sufficient to withstand the stress of the shrink-fit without breaking. For heat shrink-fit applications, the graphite mold wall should not be thinner than 19 mm ( $\frac{3}{4}$  in.). The second factor is the minimum weight ratio of mold to casting to reduce the effects of graphite oxidation and to obtain the proper chilling effect. There are many factors involved in arriving at this ratio, but in general the ratio should be a minimum of 0.75. The factors that would influence a larger ratio include the heavy load imposed because of rapid succession of casts, greater chill depth desired, availability of graphite mold stock, and general flexibility in machining.

The graphite mold can be machined before or after the metal jacket or steel sleeve has been encased around the graphite. The expected life of a graphite mold depends on three major factors: stripping time, total cycle time, and permissible rebores.

*Stripping time* should be as long as possible to permit the casting to shrink away from the mold, particularly if the casting diameter is less than 150 to 200 mm (6 to 8 in.). With this precaution, the casting, with burrs, will not score the graphite mold wall nearly as much as when extracting the casting immediately after solidification when there is only negligible casting shrinkage.

*Total cycle time* between pours should be as long as possible to allow the graphite mold to cool to 95 to 150 °C (200 to 300 °F), thus reducing the time that the graphite will be above its oxidizing temperature of 425 to 480 °C (800 to 900 °F).

*Permissible rebores* are very influential in determining total mold life. If a casting size is of such tolerance that rebored molds cannot be considered and if there is no larger size of bushing or casting for which the mold can be used, it is obvious that total mold life will be considerably shortened.

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## Centrifugal Casting

### Process Details

**Casting Inside Diameters.** When making castings on a vertical centrifugal casting machine, the inside diameter (bore) of the casting will be tapered in accordance with the following formula:

$$n = 264 \sqrt{\frac{h}{r_1^2 - r_2^2}} \quad \text{(Eq 2)}$$

where  $n$  is speed of rotation (in revolutions per minute),  $r_1$  is the inside radius at the top of the casting (in inches),  $r_2$  is the inside radius at the bottom of the casting (in inches), and  $h$  is casting height (in inches).

Actually, if the length of the casting does not exceed approximately twice its inside diameter, the amount of taper will be negligible. The optimal speed of rotation results in a centrifugal force of 75  $g$  (75 times the force of gravity) on the inside diameter. It can be seen from Eq 2 that too slow a speed of rotation will result in excessive taper on the inside diameter of the casting.

There are castings for which it is desirable to cast the inside diameter with a predictable taper. Using Eq 2, the exact speed can be calculated to produce an approximate given taper on the inside diameter of the casting.

**Speed of Rotation.** To establish a temperature gradient of the molten metal from the outside diameter toward the center of rotation (that is, directional solidification), it is usually necessary for the mold to be spinning when the metal is poured. In some cases, in order to eliminate defects such as erosion and dirt in sand molds, it is desirable to pour at a slow speed of rotation. However, true centrifugal castings having a wall section of 12.7 mm ( $\frac{1}{2}$  in.) or less must be poured at spinning speed because the metal in this thin section solidifies quickly.

Nomographs are available for determining the proper speed of rotation for centrifugal casting. However, Eq 3 can be used to calculate spinning speed:

$$g = 0.0000142Dn \quad \text{(Eq 3)}$$

where  $g$  is the centrifugal force (in pounds per pound or number of times gravity),  $D$  is the inside diameter of the casting (in inches), and  $n$  is the speed of rotation (in revolutions per minute). Equation 3 can be easily manipulated to solve for speed.

Mold Speed Curves. Mold speeds are determined by the inside diameter of the castings to be made. The mold speed curve shown in Fig. 12 is based on the inside diameter of the casting. The length of the casting is not considered in determining mold speed.

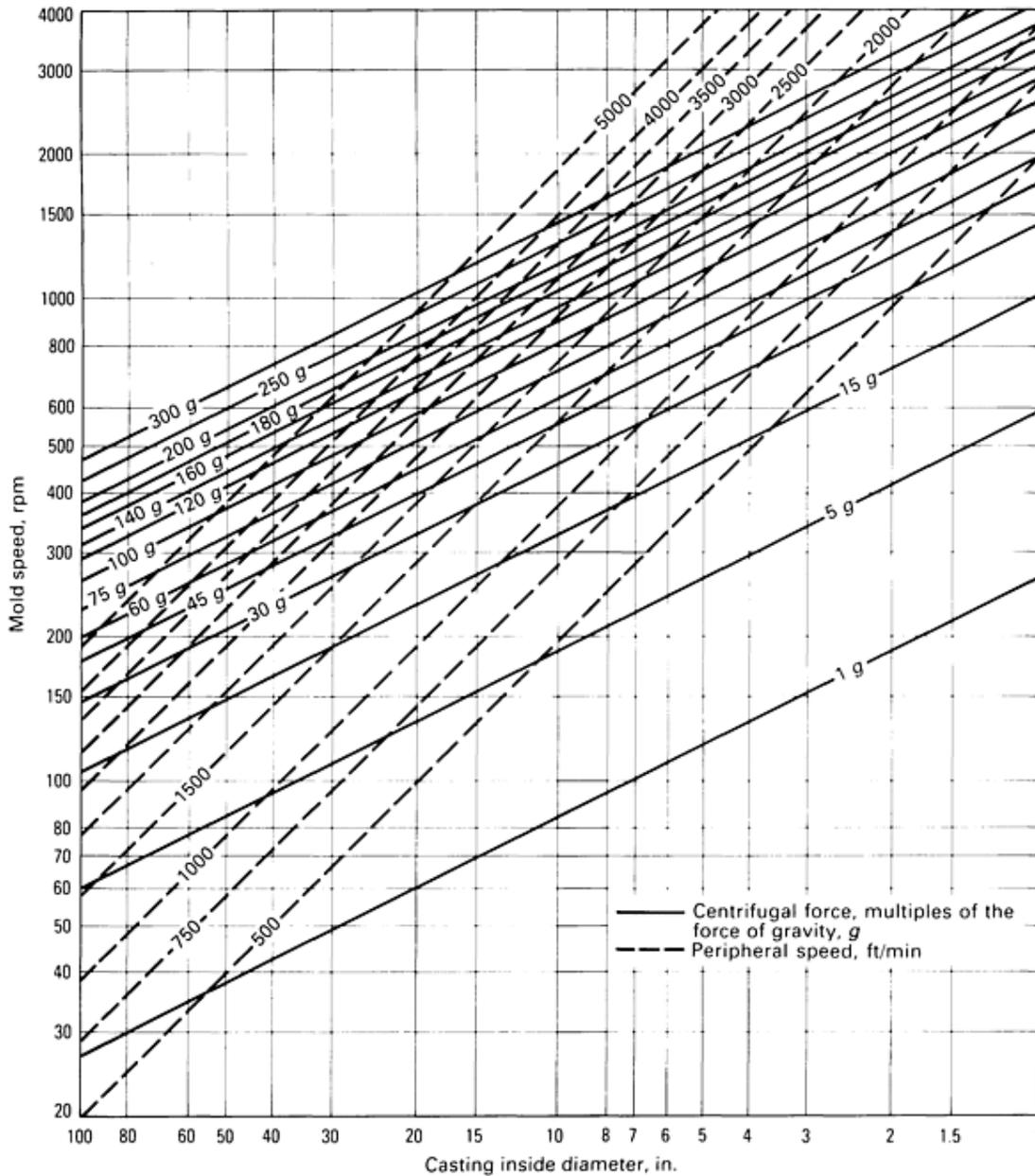


Fig. 12 Nomograph for determining mold speed based on the inside diameter of the casting and the required centrifugal force. See text for example of use.

For example, the mold speed for producing a casting 100 mm (4 in.) in outside diameter by 75 mm (3 in.) in inside diameter at a centrifugal force of 60  $g$  is calculated as follows. Find the 3 in. diameter at the bottom of the curve. Move vertically from this point until the 3 in. line intersects the diagonal line marked 60  $g$ . From this intersection, move directly to the right-hand edge of the curve; the speed of rotation of the mold in this case should be 1150 rpm.

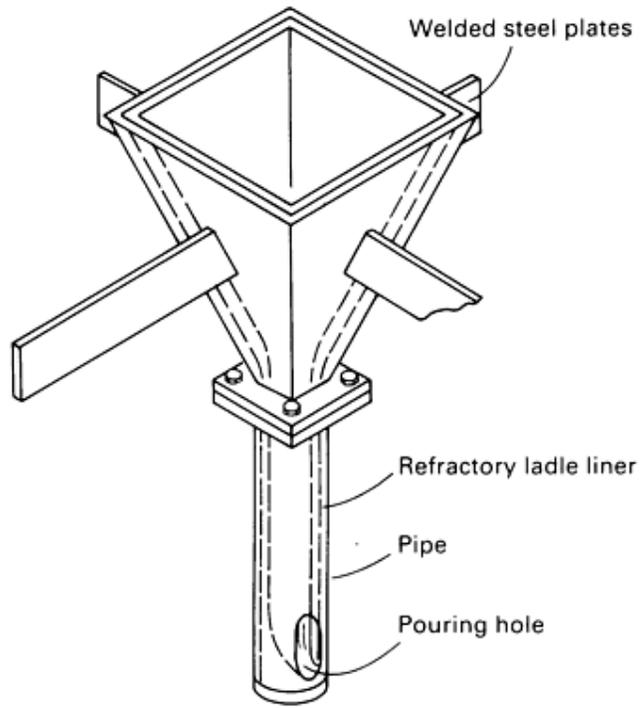
*Caution.* From the standpoint of safety for vertical centrifugal casting, it is highly recommended that the  $g$  force acting on the outside diameter of the mold be considered. It is safe practice to limit this force to approximately 200  $g$  on the outside diameter of the mold. After the proper mold speed is determined from the mold speed curve, this speed should be

checked with the mold outside diameter to limit the  $g$  force on the outside diameter to less than 200  $g$ . If it is found that the force is more than 200  $g$ , the speed of rotation should be slowed so that 200  $g$  is not exceeded on the mold outside diameter.

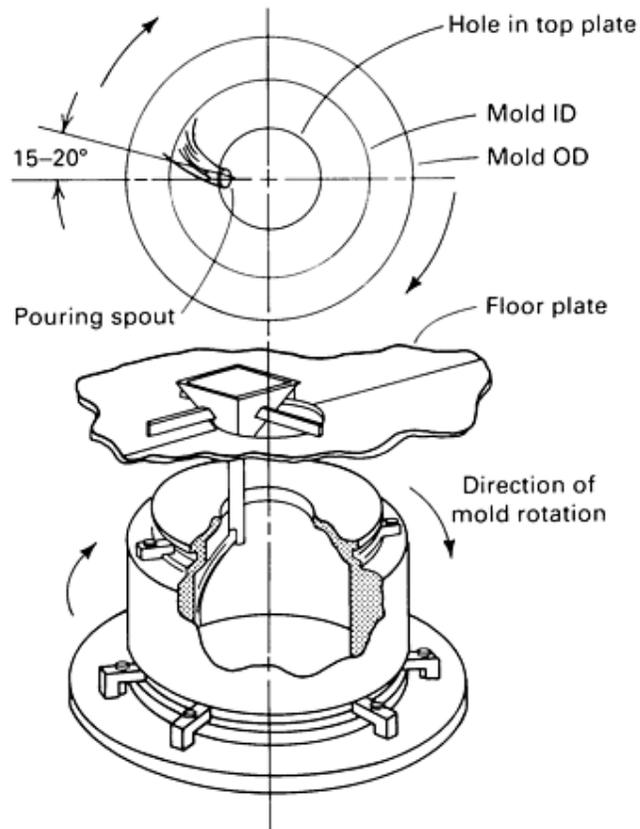
**Pouring Techniques.** For permanent molds, the metal is generally poured about 40 °C (100 °F) higher than the temperature used for the same casting if poured statically in a sand mold. This is because of the more rapid chilling effect of permanent molds.

The pouring rates required for successful permanent mold centrifugal casting are quite high compared to those for static casting in sand molds. It is particularly important that the initial rate of pour at the beginning be very high to prevent cold laps and cold shuts. For most types of centrifugal castings weighing less than 45 kg (100 lb), a pour rate of about 9 kg/s (20 lb/s) is recommended. For castings weighing up to 450 kg (1000 lb), an initial pour rate of 9 to 23 kg/s (20 to 50 lb/s) is recommended. For castings weighing more than 450 kg (1000 lb), pour rates of 45 to 90 kg/s (100 to 200 lb/s) are recommended. When pouring into a vertically spinning mold, it is important to introduce the molten metal into the mold in such a way as to prevent or minimize turbulence of the molten metal, which can cause splashing, spraying, or droplets and can result in undesirable casting defects.

Although many vertical centrifugal castings can be poured directly into the mold from the ladle to produce a quality centrifugal casting, it is more often desirable to use a pouring funnel. With a pouring funnel, the nozzle can be lined to the required diameter so that, with a certain riser height of molten metal in the funnel, a controlled pour rate can be obtained for a particular casting weight. In addition, with a pouring funnel, the entry of molten metal into the mold can be made to impinge upon the body of the mold with initial metal flow in the direction of mold rotation. This type of pouring will provide superior casting quality by minimizing or eliminating any upsetting turbulence in the flow of molten metal that might cause defects. Figure 13 shows a pouring funnel and funnel position.



(a)



(b)

Fig. 13 Typical pouring spout design (a) and pouring spout positioning during casting (b).

Extraction of Castings. Commercially available casting pulling tongs (Fig. 14) are recommended for extracting vertical centrifugally cast castings. These pullers engage onto the inside diameter of the casting and are used to lift the casting from the mold.

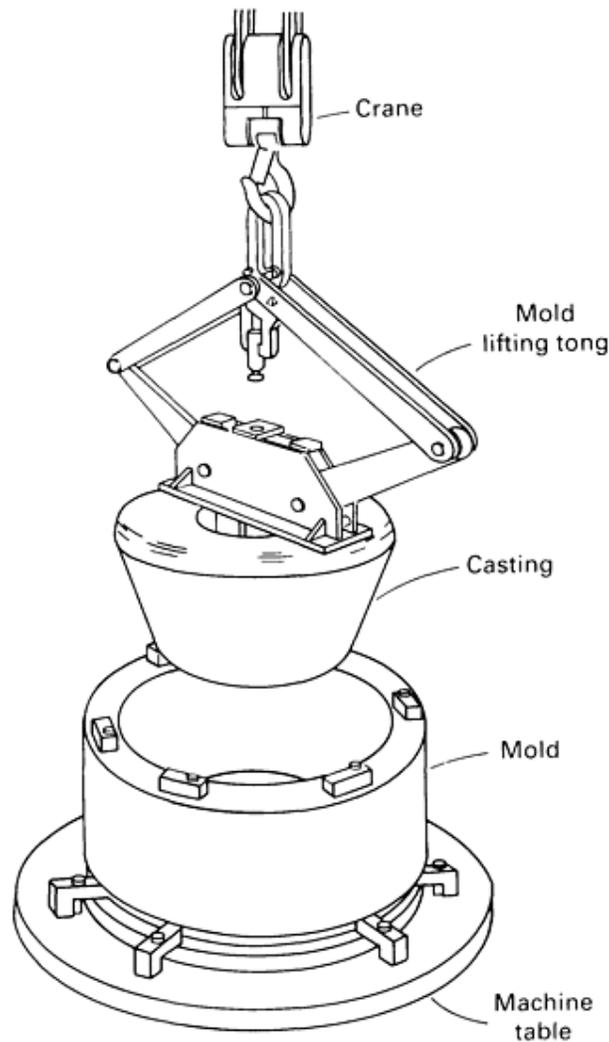


Fig. 14 Lifting tong assembly used to extract centrifugal castings from the mold.

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## Centrifugal Casting

### Defects in Centrifugal Casting

Segregation banding occurs only in true centrifugal casting, generally where the casting wall thickness exceeds 50 to 75 mm (2 to 3 in.). It rarely occurs in thinner-wall castings. Banding can occur in both horizontal and vertical centrifugal castings.

Bands are annular segregated zones of low-melting constituents, such as eutectic phases and oxide or sulfide inclusions. They are characterized by a hard demarcation line at the outside edge of the band that usually merges into the base metal of the casting.

Most alloys are susceptible to banding, but the wider the solidification range and the greater the solidification shrinkage the more pronounced the effects may be. Banding has been found when some critical level of rotational speed is attained, and it has been associated with very low speeds, which can produce sporadic surging of molten metal. Therefore, both mechanisms may be involved. Minor adjustments to casting operation variables, such as rotational speed, pouring rate, and metal and mold temperatures, will usually reduce or eliminate banding.

Various theories have been presented to account for banding. One holds that vibration is the principal cause and that during solidification a zone of low-melting liquid exists immediately adjacent to the main crystal growth. Nucleation can occur, and if disturbed by vibration, banding results. This theory further states that growth takes place from these new nuclei in such a manner as to form a sandwich of liquid metal surrounded by solid metal, which is isolated from the liquid bath at the bore.

Another theory proposes that banding can be caused by variations in gravitational force between the top and bottom of the mold and that centrifugal separation of the constituents of the metal occurs once per revolution during the period of solidification. This theory does not bear close examination because it assumes that solidification will occur in a matter of seconds even in very thick sections. In reality, solidification takes place over a period of many minutes in thick sections.

Another explanation for banding supposes that the process is far less complicated and that there are irregularities in the flow of the liquid metal (incipient laps) as it enters the rotating mold. As the metal enters the mold, it forms a tubular casting that tends to solidify in the normal manner; however, if the additional liquid metal arrives at a particular position too late, the initial liquid metal has already partially solidified. This would result in a distinct lap, cold shut, or lamination and/or banding.

Raining. In a horizontal machine, raining can occur if the mold is rotated at too low a speed or if the metal is poured into the mold too fast. In this phenomenon, the metal actually rains or falls from the top of the mold to the bottom. More information on raining is available in the section "Horizontal Centrifugal Casting" in this article.

Vibration Defects. Vibration can cause a laminated casting. It can be held to a minimum by proper mounting, careful balancing of the molds, and frequent inspection of rollers, bearings, and other vital parts.

## Centrifugal Casting

### Equipment

Vertical centrifugal casting machines are used for producing bushings and castings that are relatively large in diameter and short in length. The usual maximum length of the casting is two times the outside diameter of the casting. Vertical axis machines are also used for producing castings of odd or asymmetrical configurations. Table 5 lists the load capacities of vertical centrifugal casting machines from one manufacturer.

**Table 5 Load capacities of the vertical centrifugal casting machines of one manufacturer**

All loads are based on balanced loads for thrust loads only and are calculated based on an  $L_{10}$  bearing life of 100,000 h.

Machine speed, rpm	Capacity of indicated proprietary model number			
	Model AS, Model C		Model VS, Model VSC, Model E	
	kg	lb	kg	lb
100	6930	15,270	21,260	<b>46,875</b>

200	6930	15,270	17,275	<b>38,085</b>
300	6130	13,520	15,355	<b>33,850</b>
400	5620	12,395	14,025	<b>30,925</b>
500	5260	11,595	13,140	<b>28,970</b>
600	4980	10,980	12,400	<b>27,345</b>
700	4755	10,485	11,810	<b>26,040</b>
800	4570	10,075	11,370	<b>25,065</b>
900	4410	9,720	11,075	<b>24,415</b>
1000	4270	9,415	10,690	<b>23,565</b>
1100	4150	9,150	...	...
1200	4045	8,915	...	...
1300	3950	8,710	...	...
1400	3860	8,510	...	...
<b>1450</b>	<b>3825</b>	<b>8,430</b>	...	...

Safety. The importance of safety in machine design, mold design, installation, and operation cannot be overemphasized. A centrifugal casting machine and installation should incorporate all of the safety factors possible. Centrifugal force increases directly as the square of the speed of rotation and directly as the length of the radius from the axis of rotation. Centrifugal force can be tremendous and very destructive. Speeds of rotation should never exceed those required to produce the casting. Molds must be centered on the spinning axis as accurately as possible and must be statically or dynamically balanced if necessary.

The method of attachment of both bottom and top cover plates to the mold is of great importance for withstanding and containing the force of the molten fluid metal while spinning. All clamping arrangements should be designed to tighten with, or to be unaffected by, centrifugal force. Molds should be firmly clamped to the table because unbalanced molds may fly off the table during operation. Adequate safety guards with interlocks should be used around all machines to protect workers from molten metal, which can spray from the mold if too much metal is poured.

Heat expansion can occur suddenly and rapidly in the mold body, top and bottom mold plates, and even into the centrifugal casting machine. This sudden expansion can put bending and shearing stresses into fasteners and other retention and clamping devices. A thorough understanding of the forces involved in centrifugal casting is necessary to ensure the utmost in safety for all concerned.

Moisture in a sand mold or moisture in the mold wash can turn into steam when the molten metal contacts it, and the resulting forces would be incalculable. Most vertical centrifugal casting machines should be installed completely below floor level for maximum operator safety. Figure 15 illustrates such an installation.

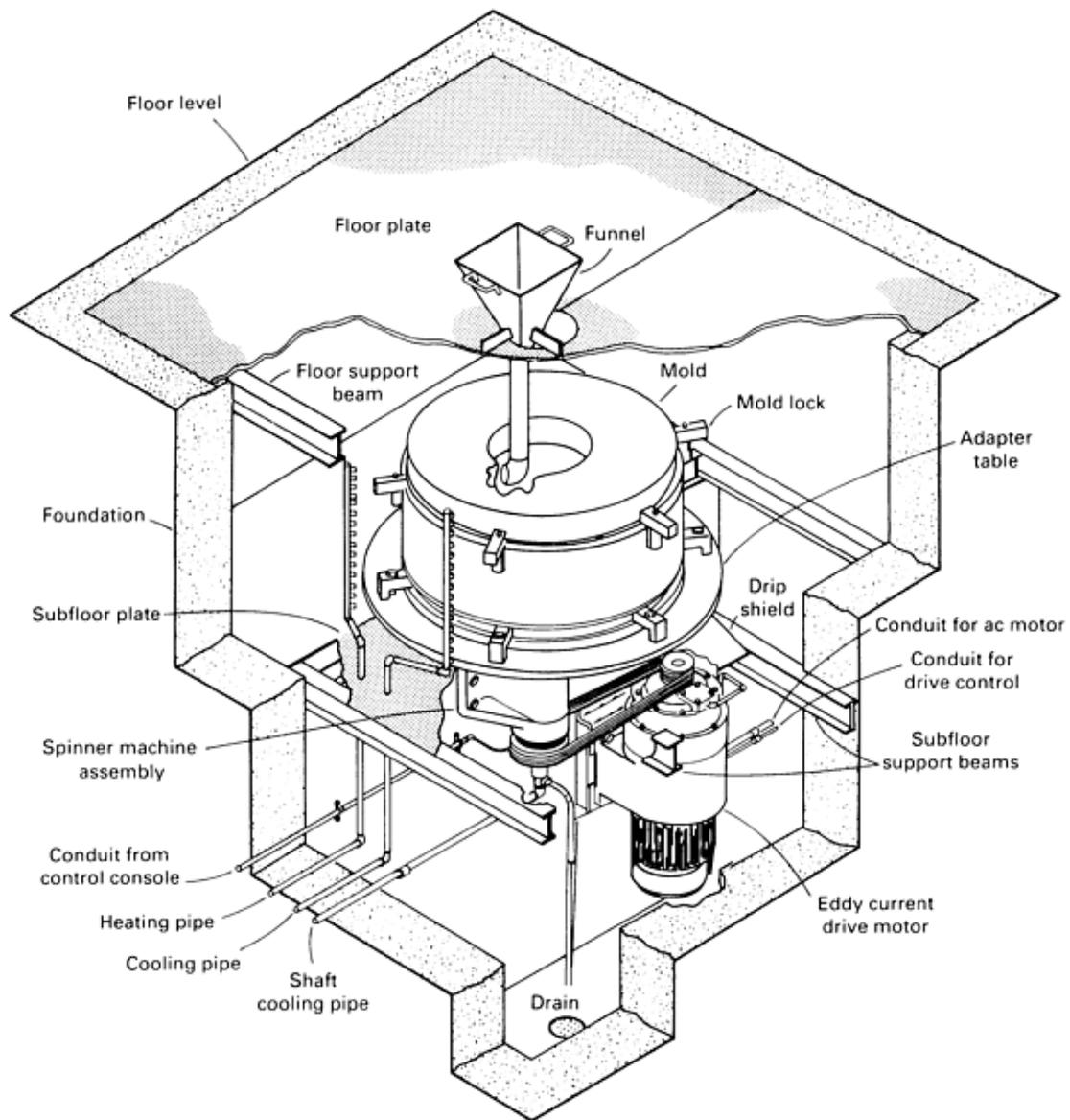


Fig. 15 Typical installation of a vertical centrifugal casting machine. The equipment is controlled from a remote console (not shown).

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## Continuous Casting

Robert D. Pehlke, University of Michigan

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## Introduction

THE ADVANTAGES OF CONTINUOUS CASTING in primary metals production have been recognized for more than a century. In recent decades, a dramatic growth of this processing technology has been realized in both ferrous and

nonferrous metal production. The principal advantages of continuous casting are a substantial increase in yield, a more uniform product, energy savings, and higher manpower productivity. These advantages and the ease of integration into metals production systems have led to the wide application of continuous casting processes.

## Acknowledgements

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Robert D. Pehlke, University of Michigan

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## Historical Aspects of Continuous Casting

One of the earliest references to continuous casting is a patent granted in 1840 to George Sellers, who had developed a machine for continuously casting lead pipe (Ref 1). There is some indication that this process had been underway before Sellers' patent, which was directed toward improvement of this continuous casting process. The first work on continuous casting of steel was by Sir Henry Bessemer, who patented a process for "manufacture of continuous sheets of iron and steel" in 1846 and made plant trials on continuous casting of steel in the 1890s (Ref 2).

Although continuous casting had its start before the beginning of the 20th century, it was not until the mid-1930s in Germany that commercial production of continuously cast brass billets was introduced. Sigfried Junghans, an active inventor of casting technology, provided many improvements in the process, in particular the introduction of the oscillating-mold system to prevent the casting from sticking to the mold. Further development of the process for the casting of nonferrous metals continued, including the installation of processing units in North America. Mold lubrication in the form of oil, or, more recently, low-melting slag powders, was introduced. Taper of the mold to compensate for metal shrinkage on solidification provided improved heat transfer and, more importantly, fewer cracks.

In 1935, a plant with casting rolls for continuous production of brass plates was operated at Scovill Manufacturing in the United States and the Vereinigte Leichtmetallwerke in 1936 started a semicontinuous casting machine for aluminum alloys. Immediately after World War II, commercial development of continuous casting of steel began in earnest, with pilot plants at Babcock and Wilcox Company (United States), Low Moor (Great Britain), Amagasaki (Japan), Eisenwerk Breitenfeld (Austria), BISRA (Great Britain), and Allegheny Ludlum Corporation (United States). These were followed by production plants for casting billets in the West and stainless slabs in the Soviet Union and Canada (the latter at Atlas Steels) (Ref 3).

The Schneckenburger and Kung patent on the curved strand was filed in Switzerland in 1956 and production was commercialized with a billet machine at Von Moosche Eisenwerke (Switzerland) in 1963. In 1961, at Dillingen Steelworks (West Germany), the first vertical-type large slab machine with bending of the strand to horizontal discharge was started up. In 1964, Shelton Iron and Steel (Great Britain) was the first new steelworks to turn out its entire production by continuous casting, consisting of four machines with 11 strands for medium to very large bloom sizes, and operating in connection with Kaldo converters. That same year, the first Concast S-type curved-mold machine for large slabs was started up at Dillingen Steelworks (West Germany). The height of this type of machine was less than 50% of the corresponding height of a vertical type of machine. In the same year, a bow-type slab caster was presented by Mannesmann (West Germany). In 1968, McLouth Steel (United States) started up four curved-strand slab casting machines immediately after the first four-strand low head caster for large slabs in the West was started up at the Weirton Steel Division of National Steel (United States). Subsequently, National pioneered the casting of slabs for tinplate applications (Ref 3).

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1. G. Sellers, U.S. Patent 1908, 1840

2. H. Bessemer, "On the Manufacture of Continuous Sheets of Malleable Iron and Steel Direct from Fluid Metal," Paper presented at the Iron and Steel Institute Meeting, Oct 1891; also, *J. Met.*, Vol 17, (No. 11), 1965, p 1189-1191

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## Continuous Casting

Robert D. Pehlke, University of Michigan

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## Continuous Casting of Steel

Continuous casting of steel is entering a new era of development, not only with respect to its increasing application in the production process, but also in its own evolution as a process and its interaction with other processes in steel manufacture. Continuous casting output has shown an accelerating growth curve. More than 50% of current world steel production is continuously cast, and continuous casting in Japan exceeds 80%. The advantages of the process, along with its developments and current challenges for improvement, are outlined in the following sections.

### *General Description of the Process*

The purpose of continuous casting is to bypass conventional ingot casting and to cast to a form that is directly rollable on finishing mills. The use of this process should result in improvement in yield, surface condition, and internal quality of product when compared to ingot-made material.

Continuous casting involves the following sequence of operations:

- Delivery of liquid metal to the casting strand
- Flow of metal through a distributor (tundish) into the casting mold
- Formation of the cast section in a water-cooled copper mold
- Continuous withdrawal of the casting from the mold
- Further heat removal to solidify the liquid core from the casting by water spraying beyond the mold
- Cutting to length and removing the cast sections

A diagram showing the main components of a continuous casting machine is presented in Fig. 1. Molten steel in a ladle is delivered to a reservoir above the continuous casting machine called a tundish. The flow of steel from the tundish into one or more open-ended, water-cooled copper molds is controlled by a stopper rod-nozzle or a slide gate valve arrangement.

To initiate a cast, a starter, or dummy bar, is inserted into the mold and sealed so that the initial flow of steel is contained in the mold and a solid skin is formed. After the mold has been filled to the desired height, the dummy bar is gradually withdrawn at the same rate that molten steel is added to the mold. The initial liquid steel freezes onto a suitable attachment of the dummy bar so that the cast strand can be withdrawn down through the machine. Solidification of a shell begins immediately at the surface of the copper mold. The length of the mold and the casting speed are such that the shell thickness is capable of withstanding the pressures of the molten metal core upon exiting from the copper mold. To prevent sticking of the frozen shell to the copper mold, the mold is normally oscillated during the casting operation and a lubricant is added to the mold. The steel strand is mechanically supported by rolls below the mold where secondary cooling is achieved by spraying cooling water onto the strand surface to complete the solidification process. After the strand has fully solidified, it is sectioned into desired lengths by a cutoff torch or shear. This final portion of the continuous casting machine also has provision for disengagement and storage of the dummy bar.

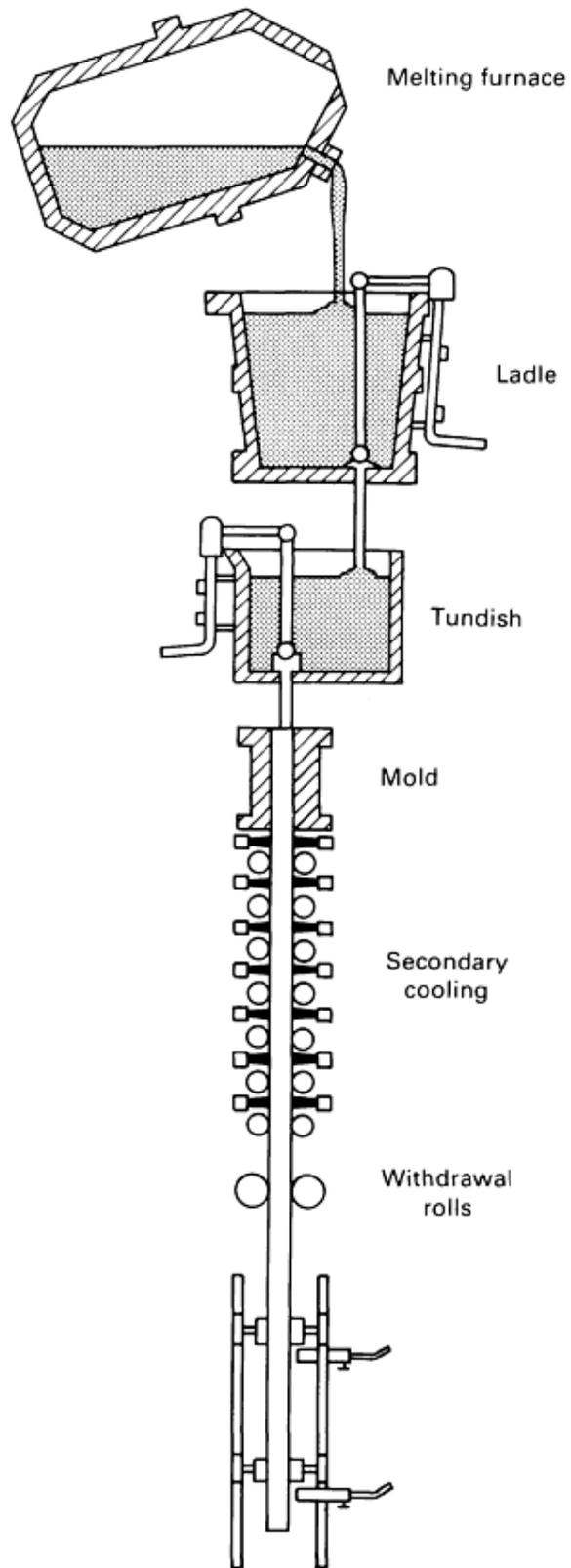


Fig. 1 Main components of a continuous casting strand. Source: Ref 4

Several arrangements are now in commercial use for the continuous casting of steel. The types of continuous casting machines in use include vertical, vertical with bending, curved or S-strand with either straight or curved mold, curved strand with continuous bending, and horizontal. Examples of the principal types of machines currently producing slabs are shown in Fig. 2.

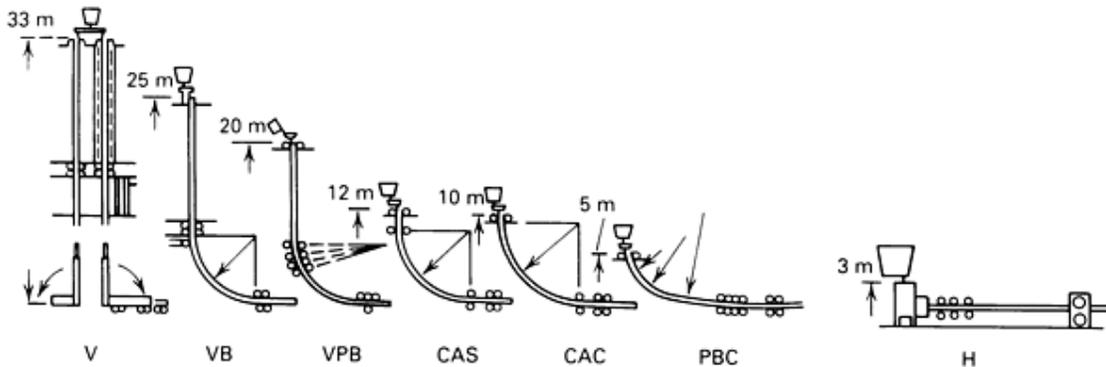


Fig. 2 Principal types of continuous casting. V, vertical; VB, vertical with bending; VPB, vertical with progressive bending; CAS, circular arc with straight mold; CAS, circular arc with curved mold; PBC, progressive bending with curved mold; H, horizontal. Source: Ref 5

Most of the original continuous casting machines for steel were vertical machines. Vertical machines with bending and curved strand machines, although more complicated in their construction, were developed to minimize the height of the machine and allow installation in existing plants without modification of crane height. Four basic caster designs for slabs are shown in Fig. 3, with an indication of the required installation height and the corresponding solidification distance or metallurgical length (ML).

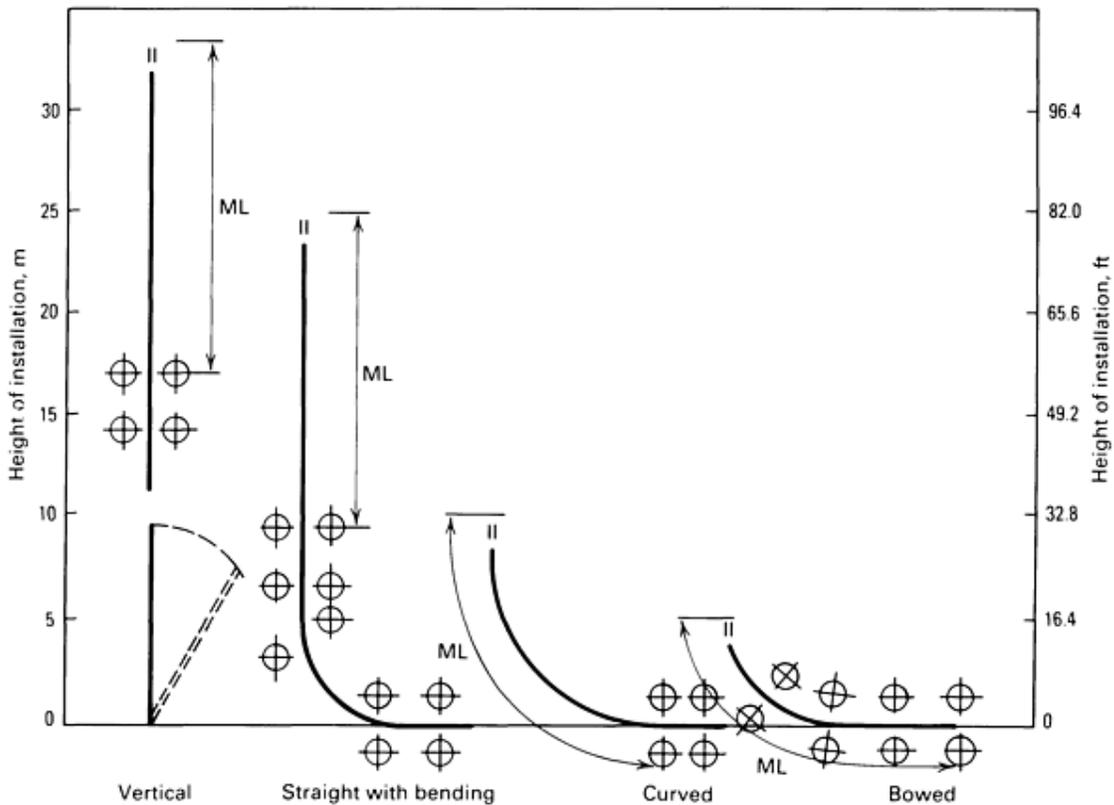


Fig. 3 Four basic designs for continuous casting machines. ML, metallurgical length. Source: Ref 6

### Plant Layout

The design and layout of a steelmaking facility often focus initially on continuous casting. The optimum plant layout varies markedly from one installation to another. One major factor in the configuration is whether or not the steelmaking complex is being constructed on a greenfield site or being added ("shoehorned") into an existing works. Many of the major integrated steel works in Japan were constructed as greenfield installations during the period from 1960 to 1975. Most of the minimills constructed throughout the world, and in particular in the United States, were also built on greenfield sites.

In building a greenfield site, the plant layout should incorporate two major features: a smooth and well-organized arrangement for material handling and flow, and the capacity for future expansion. Generally, these plants are designed for 100% continuous casting, and no ingot facilities are included (Ref 7). Nearly all of the recently built minimills incorporate one or more electric furnaces and provide for 100% continuous casting of billets. Chaparral Steel Company at Midlothian, TX is an excellent example (Ref 8). A profile of a proposed large-scale electric furnace billet casting plant is shown in Fig. 4.

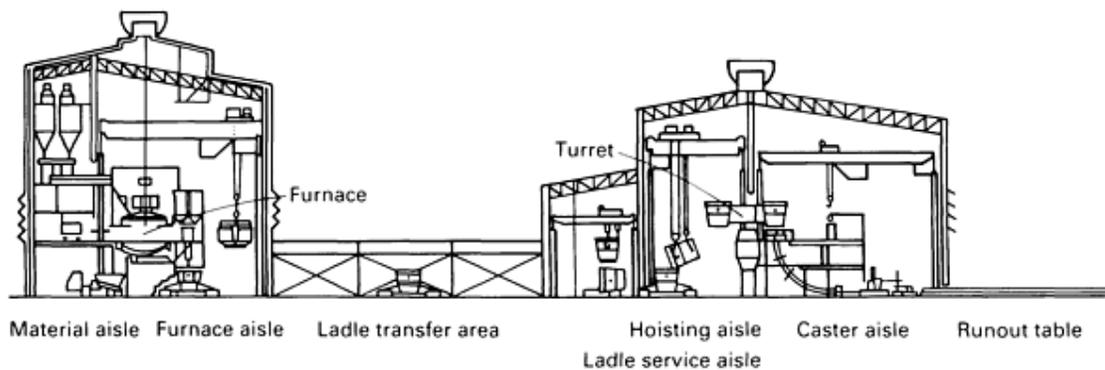


Fig. 4 Proposed melt shop capable of producing 1.2 million Mg (1.32 million tons) of billets annually. Source: Ref 9

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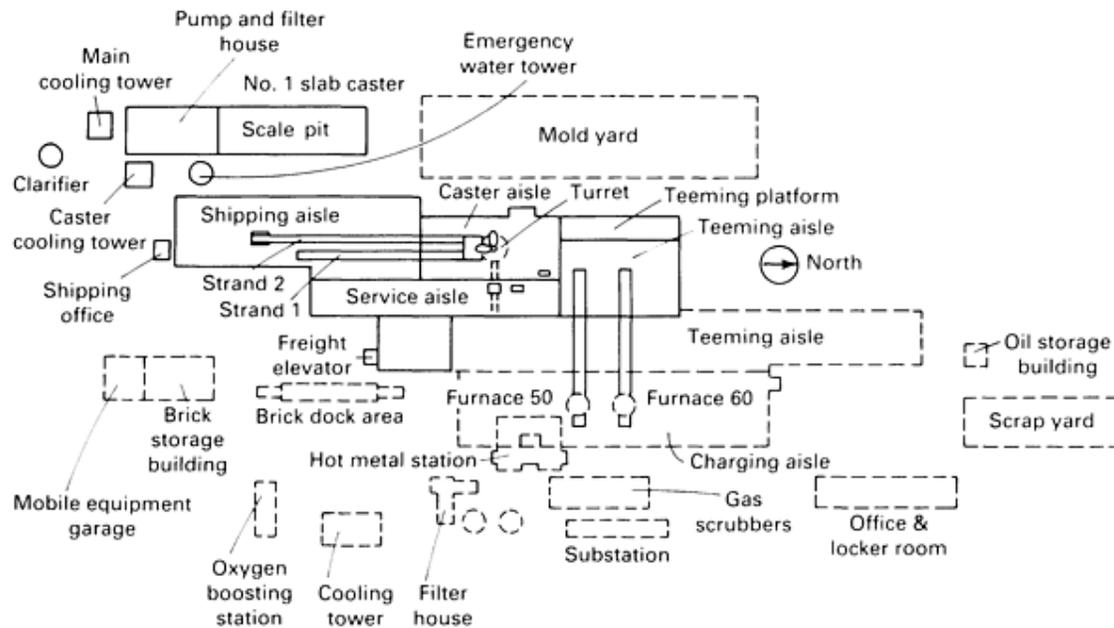


Fig. 5 Plant layout at the Inland Steel Company. Source: Ref 10

An important characteristic of the plant layout, and in particular of the material-handling facilities, is the concept that the continuous casting machine cannot wait. This design and operating concept has had a dramatic impact on steelmaking operations, which have now become a synergism to the continuous casting facilities. Because of this shift in priorities, marked improvements in productivity have been developed for continuous casting, as outlined below.

Dramatic increases in energy costs, as well as the desire for higher productivity, led to the development of the "hot connection". Substantial energy savings can be achieved by directly charging the hot continuously cast slab or billet to the reheating furnaces of the rolling mill. The latest installations have included direct in-line hot rolling of the cast product.

### *Process Development and Machine Design*

A number of methods for distributing liquid steel to the mold or to several molds of the casting machine have been investigated. Use of a tundish with appropriate flow control has been found to be a superior method for the production of quality steel. Considerable effort has been directed toward improvement of refractories and development of methods for preventing nozzle blockage. Geometric arrangements in tundishes, including the use of dams and weirs, have provided suitable fluid flow characteristics to maximize the separation of nonmetallic inclusions, resulting in improved quality. Another factor in separation of nonmetallic inclusions in the tundish is tundish size because of its effect on residence time. Figure 6 indicates the trend in tundish size for major slab casting installations over the past 20 years.

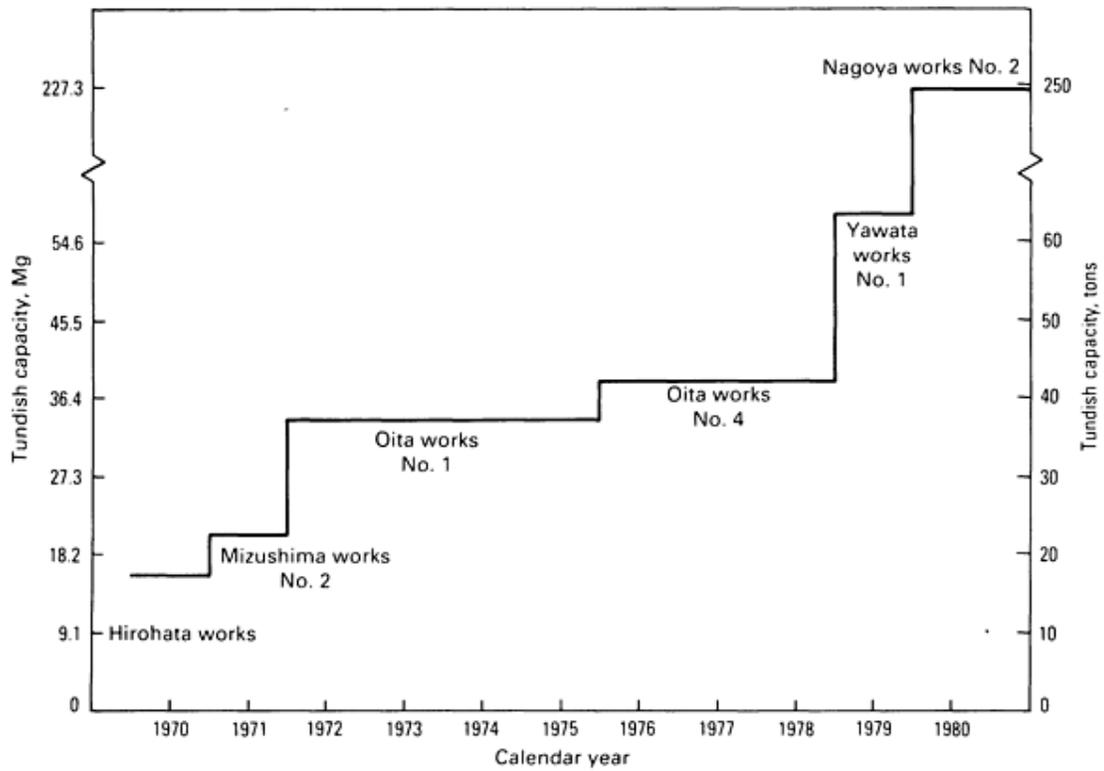


Fig. 6 Increases in capacity of tundishes for a two-strand slab caster. Source: Ref 11

Reoxidation of the molten steel is to be avoided. The use of refractory shrouds between the ladle and the tundish and the tundish and the mold have been adopted for slab casting (Fig. 7).

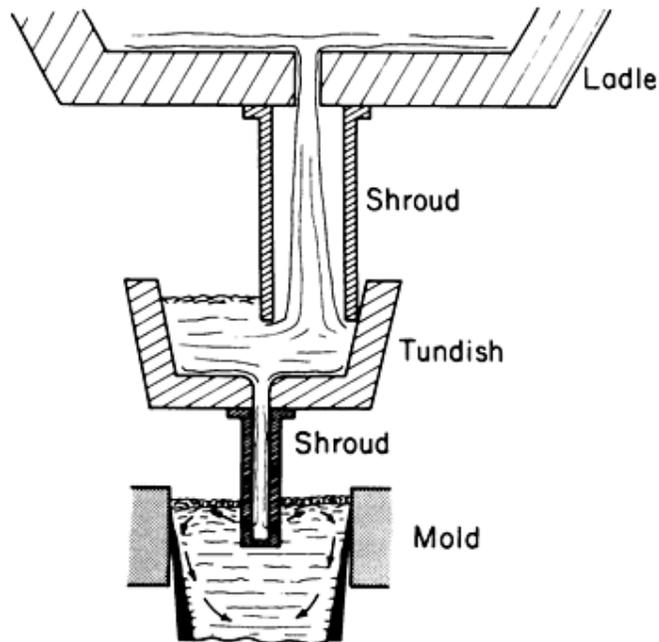


Fig. 7 Pouring shrouds from ladle to tundish to mold. Source: Ref 12

One of the difficulties encountered in continuous casting of small sections has been the protection of the pouring stream from tundish to mold because of the inapplicability of a pouring tube and the mechanical difficulty caused by the oscillation of the mold relative to the fixed tundish. In one instance, this has been overcome by the use of a flexible bellows (Fig. 8) and successfully applied to the continuous casting of special product quality steel bars. Recently, further development has been made in the use of ceramic shrouds to protect pouring streams on billet machines.

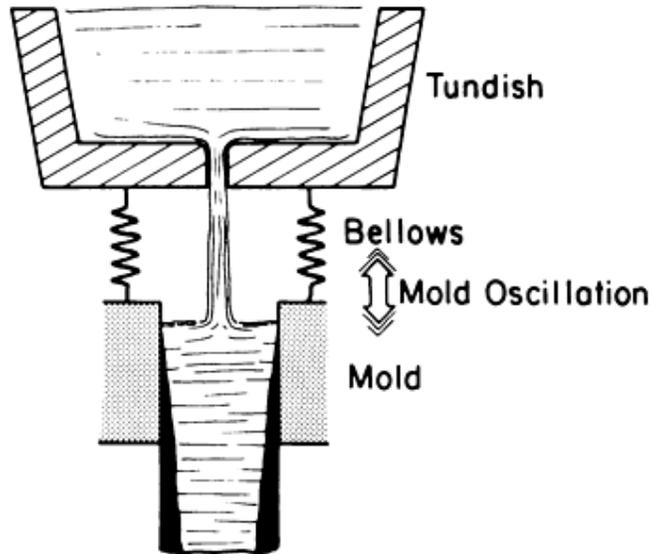


Fig. 8 Bellows between tundish and mold for casting billets. Source: Ref 12

Protection of the surface of the molten steel pool in the tundish has been achieved through the use of suitable synthetic oxide slags, inert-gas blanketing, and a refractory cover to seal the tundish. The metal level in the tundish, as well as the fluid flow pattern, is important in avoiding the ingestion of the slag layer into the metal stream flowing downward into the mold.

The tundish is supported with either two tundish cars or a two-position turret. Frequently, the double turret provides for changing of the tundish while continuing the casting process, which allows extended sequence casting. The changing of the tundish not only occurs at an appropriate time, but also allows a change in steel composition with a minimal length of transition in the cast product.

The flow-through water-cooled copper mold is the key element of the casting machine. Special attention has been given to problems associated with the design and material requirements for molds. A number of different designs have been used, including thin-wall tube-type molds, solid molds, and molds made from plate. Plate molds were found to provide excellent mold life and to avoid the necessity for manufacture of molds from solid copper blocks. Steel and brass, as well as copper, have been used for molds, but the most outstanding material is nearly pure copper with small additions of elements that promote precipitation hardening or raise the recrystallization temperature, because both effects apparently provide longer mold life. Mold coatings are applied to extend service life. A chromium coating is generally used, often with an intermediate layer of nickel for improved coherence.

The most suitable length for a continuous casting mold has been found to be 510 to 915 mm (20 to 36 in.), a range that seems to remain constant regardless of section size. This surprising result can be explained by the higher rates of heat removal achieved with smaller sections and higher casting rates. Also, a thinner skin can be permitted for smaller sections exiting from the mold than for larger sections because bulging of the solidifying shell will be less severe. At higher

casting rates, the use of an increased taper in the mold is necessary to maintain high heat removal rates, particularly for the narrow faces of slab molds.

Oscillating molds, as used by Junghans, have been adopted almost universally, although fixed molds can be successfully used with efficient lubricating systems. The oscillation is usually sinusoidal, a motion that can be achieved easily with simple mechanical arrangements. A fairly short stroke and a high frequency are used to provide a short period of "negative strip" during each oscillation, in which the mean downward velocity of the mold movement is greater than the speed of withdrawal of the casting strand in the casting direction. Oscillating frequencies are being increased from 50 to 60 cycles per minute (cpm) up to 250 to 300 cpm, with the benefits of shallower oscillation marks, less cracking, and reduced conditioning requirements.

Molten metal in the slab mold is normally covered with a layer of mold powder to protect the metal from reoxidation and absorb inclusions. The powder has a low melting point and flows over the liquid steel to provide mold lubrication and to help control heat transfer. Rapeseed oil, which has since been replaced by synthetic oils, has typically been used to prevent sticking to the mold in billet casting. Metal flow rates are matched with slab casting speeds using a stopper rod in the tundish, a slide gate, or a metering nozzle just above the shroud to control the delivery rate. Billets are normally cast with fixed metering nozzles, and the strand speed is adjusted to any changes in steel flow rate.

Support of the thin steel shell exiting the mold is required, particularly for slab casters. Several systems have been used (Fig. 9), all of which provide intensified direct water cooling.

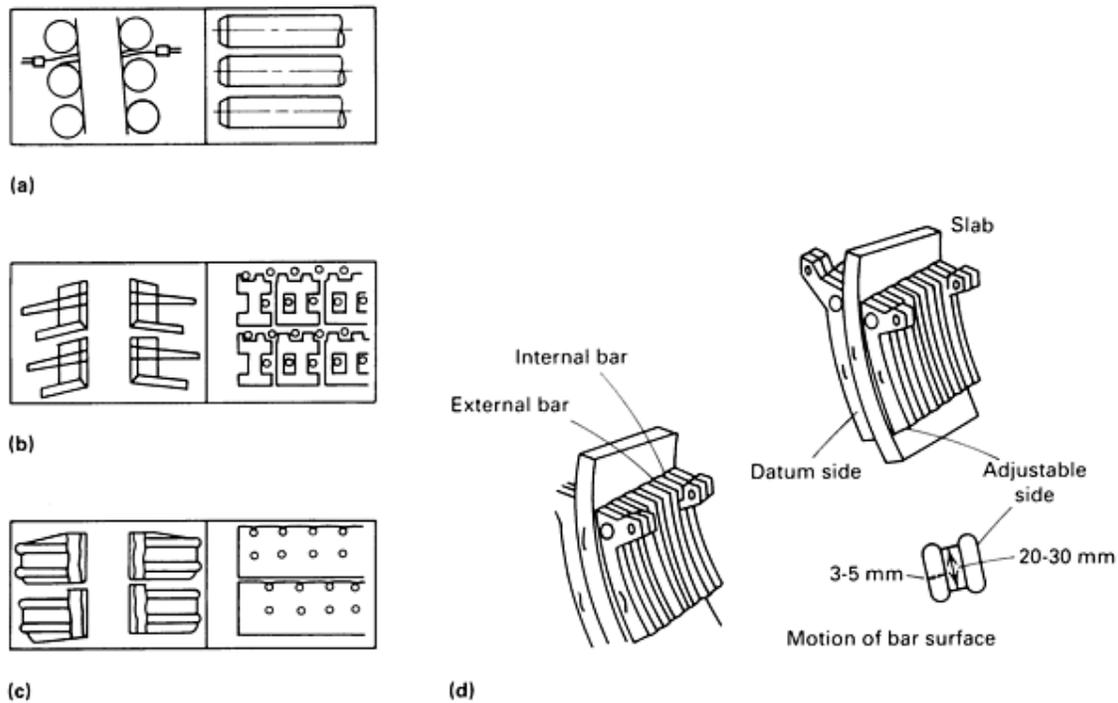


Fig. 9 Four types of shell supporting systems used in continuous casting. (a) Roll. (b) Cooling grid. (c) Cooling plate. (d) Walking bar. Source: Ref 13

Water spraying (secondary cooling) is critical to the process in that maximum cooling should be accomplished, but overcooling and large temperature increases must be avoided. The amount of heat removed by water sprays depends on the volume of the water, its temperature, and in particular the method of delivery, including spray pressure. Pressure is important in that the spray should be sufficiently intense to penetrate the blanket of steam on the surface of the solidifying strand. The thermal conductivity of steel is relatively low; consequently, as the surface temperature decreases and the shell thickness increases, cooling water has less influence on the solidification characteristics. The interrelationship between support rolls and the spray water and its delivery characteristics is quite important, particularly for the casting of wide slabs.

Mixed spraying of air and water develops a unique secondary cooling system with a uniform water droplet size. Air-mist cooling is illustrated in Fig. 10, along with the conventional water spray, as applied to slab casting. Although more costly, the air-mist spray system has a more uniform spray pattern and intensity that offers excellent spray cooling control. Decreases in transverse and longitudinal cracking with air-mist cooling have been reported (Ref 15, 16).

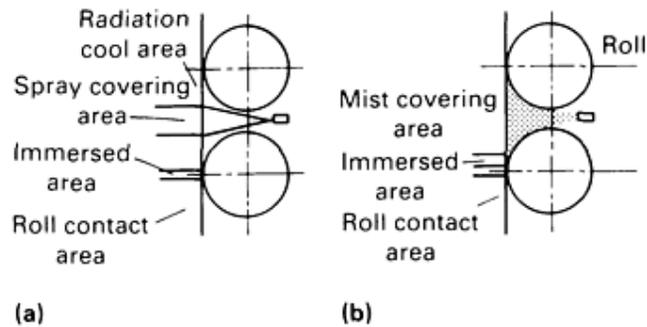


Fig. 10 Comparison of spray systems used in continuous casting. (a) Conventional spray. (b) Air-water mist spray. Source: Ref 14

The straightening operation on curved strand casters has required special design and operating control. In general, temperatures at or above 900 to 1050 °C (1650 to 1920 °F) have been recommended to avoid conditions under which certain grades of steel have limited ductility and are susceptible to cracking. Multipoint and four-point straighteners have reduced imposed strains, and compression casting systems have reduced tensile stresses. Uniform temperature of the strand, including corners, which tend to cool more quickly, is required.

The dummy bar, which is used to stopper the mold for the initiation of a cast, can be inserted from above or below, depending on the individual installation. Some arrangements are shown in Fig. 11. The top feeding arrangement, which "chases" the last metal cast through the machine, offers a productivity advantage.

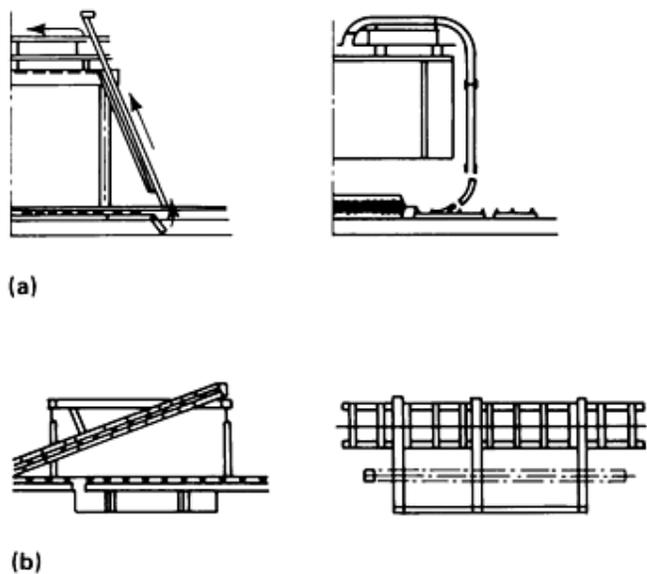


Fig. 11 Dummy bar arrangement. (a) Top feeding. (b) Bottom feeding. Source: Ref 17

While continual increases in casting speeds over the years have led to improvement in casting machine productivity, the most dramatic factor has been sequence casting, that is, continuous-continuous casting. Perfection of this development has required extraordinary achievement in the design of ladle and tundish handling systems, and in design and maintenance considerations for long-term operation with processing times that extend for several days. A summary of sequence casting records in Japan has been presented by T. Harabuchi (Ref 18) and is reported in Table 1. In comparison, the Jan 1983 casting record at Great Lakes Steel Corporation in the Detroit district involved a large slab caster (240 mm × 2.5 m, or  $9\frac{1}{2} \times 99$  in.), which cast 402 ladles and 83 160 Mg (91,480 tons) of steel continuously. In addition to the bulk steel handling requirements of sequence casting, the ability to change nozzles, shrouds, and tundishes at frequent intervals is also required. The string of casts at Great Lakes Steel Corporation involved 35 tundish changes and 177 shroud changes over a period of  $13\frac{2}{3}$  days. This record has been exceeded more recently at the Gary Works of United States Steel International, Inc.

**Table 1 Record of sequence casting in Japan**

Product	Company	Continuous casting plant	Heats per cast	Weight of steel per cast		Time of achievement
				Mg	tons	
Slab	Nippon Kokan	Keihin	270	22,523	24,775	<b>Sept 1974</b>
Slab	Nippon Kokan	Fukuyama	244	54,360	59,796	<b>Aug 1981</b>
Slab	Kawasaki Steel	Mizushima No. 5	204	51,000	56,100	<b>Nov 1980</b>
Slab	Nippon Steel	Yamata No. 2	186	30,199	33,219	<b>July 1974</b>
Bloom	Sumitomo Metals	Wakayama No. 3	1129	160,110	176,124	<b>July 1982</b>
Bloom	Daido Steel	Chita	320	19,091	21,000	<b>Feb 1984</b>
Bloom	Sumitomo Metals	Kokura	281	17,648	19,413	<b>April 1982</b>
Bloom	Nippon Steel	Kamishi	202	17,857	19,643	<b>Jan 1979</b>
Billet	Osaka Steel	Okajima	214	17,455	19,200	<b>July 1978</b>
Billet	Kokko Steel	Main Plant	174	5,063	5,569	<b>Aug 1978</b>
<b>Billet</b>	<b>Funabashi Steel</b>	<b>Main Plant</b>	<b>99</b>	<b>5,535</b>	<b>6,089</b>	<b>Oct 1975</b>

While it has been shown that sequence casting extending beyond five or six heats does not dramatically increase productivity, provided a reasonable turnaround time and interactive scheduling with the steelmaking facilities exist, the

capability for long-term sequence casting represents the opportunity for increased productivity with high quality at an essentially steady state operation of the caster.

An important characteristic of a casting operation with regard to productivity is the percentage of total clock time that steel is being processed in the machine. These percentages in high productivity casters can exceed 90% for frequently used casting operations. The turnaround time required for the dummy bar to restart a cast is one of the factors in producing steel-in-mold results, but under ideal conditions scheduled maintenance will be a major factor, and other items, such as problems in steelmaking or mechanical difficulty on the strand, will be minimized.

In the past and in many present installations, interruption of continuous casting production is required in order to make a width change. Several developments that avoid this requirement are now in operation. In one such arrangement, used at Great Lakes Steel Corporation, a very wide slab was cast and then slit into two or three optimum widths. Another approach is taken at Oita Works of Nippon Steel Corporation, where a sizing mill adjusts the slabs to various desired widths. Another, more versatile, system involves the use of a variable width mold in which the taper and width are adjusted continuously during the casting process. These techniques have permitted the adoption of sequence casting with a minimum mold inventory based on width.

Another barrier to increasing productivity of continuous casting has been the accommodation of ladle-to-ladle composition changes with adoption of sequence casting. Under ideal circumstances, as when a plant produces a narrow range of compositions, often with overlapping compositional requirements, compositional changes can be slowly stepped through each grade to accommodate the desired sequence of heats. However, when substantial variations in composition must be accommodated, physical barriers in the form of steel plates have been used to provide isolation of the grade changes in the strand. In this way, the transition zone can be minimized, and compositional changes can be accommodated without substantial losses in yield or quality.

### *Quality Improvements*

The operation of a continuous casting strand to produce good-quality steel uniformly and reliably on a routine basis can be the most valuable asset of the process. Development work continues in an effort to improve control and production reliability, particularly with regard to avoidance of inclusions and cracking for internal and surface quality.

Internal cracking is less important for those products (for example, sheet) that have large reduction ratios. Radial cracks, center looseness or centerline cracking, minor amounts of gas evolution, and other internal defects are not deleterious in heavily rolled products. In the manufacture of heavy plates, however, these conditions can represent serious product defects.

For aluminum-killed steel, subsurface inclusions are usually in the form of aluminum oxide. In some cases, surface scarfing can be effective in removing these inclusions, which could provide a surface defect in a final rolled product. Unfortunately, this surface conditioning results in substantial yield losses. It has been reported (Ref 4) that use of multiport shrouded nozzles can produce a fluid flow action in slab molds, which brings inclusions in contact with the molten mold powder covering to flux and dissolve oxide particles. This provides a clean subsurface zone that requires no scarfing. However, this method leads to the entrapment of complex nonmetallic inclusions containing mold powder. Clean steel practices in combination with nozzle configurations optimized for specific casting conditions are necessary to minimize nonmetallic inclusions. As noted above, the control of fluid flow and promotion of separation in ladle, tundish, and mold can provide a substantial reduction in large inclusions.

Depending on steel grade, cracking can result from intensive cooling or deformation in the casting strand. Surface cracking can be minimized by proper control of lubrication and cooling within the mold, and cooling and alignment in the upper spray zone. Other critical factors in cracking are control of spray cooling to avoid surface temperature rebound (resulting in midway cracks) or nonuniformity of cooling across or along the strand. Control of temperature distribution at the straightener and proper roll gap settings for slabs and blooms have also been noted as being very important.

### *Horizontal Continuous Casting*

Horizontal casting systems have been explored for many years, but only in the recent past have they been successfully applied to steels. Oldsmobile Division of General Motors Corporation started casting 95 mm (3.75 in.) steel bars in a horizontal mold in 1969 (Ref 19, 20), with uninterrupted casts of up to 24 h. This is believed to be the longest sustained continuous casting operation for steel up to that time.

Voest-Alpine is developing a horizontal continuous casting machine for steels, and the Nippon Kokan (NKK) Steel Company of Japan has been producing horizontally cast steel sections up to 210 mm (8 in.) square (Ref 21). These systems depend on a refractory nozzle or "break ring" at the entrance end of a stationary water-cooled metallic mold, and an intermittent motion for translating the bar, each forward stroke being followed by a discrete rest or dwell. A cross section of the tundish and mold arrangement of the NKK machine is shown in Fig. 12. Casting of larger sections is being explored throughout the world, as are continuous casting processes for high-speed casting of thin sections. As the technologies for cleaner steels evolve, these processes will come closer to commercial adoption.

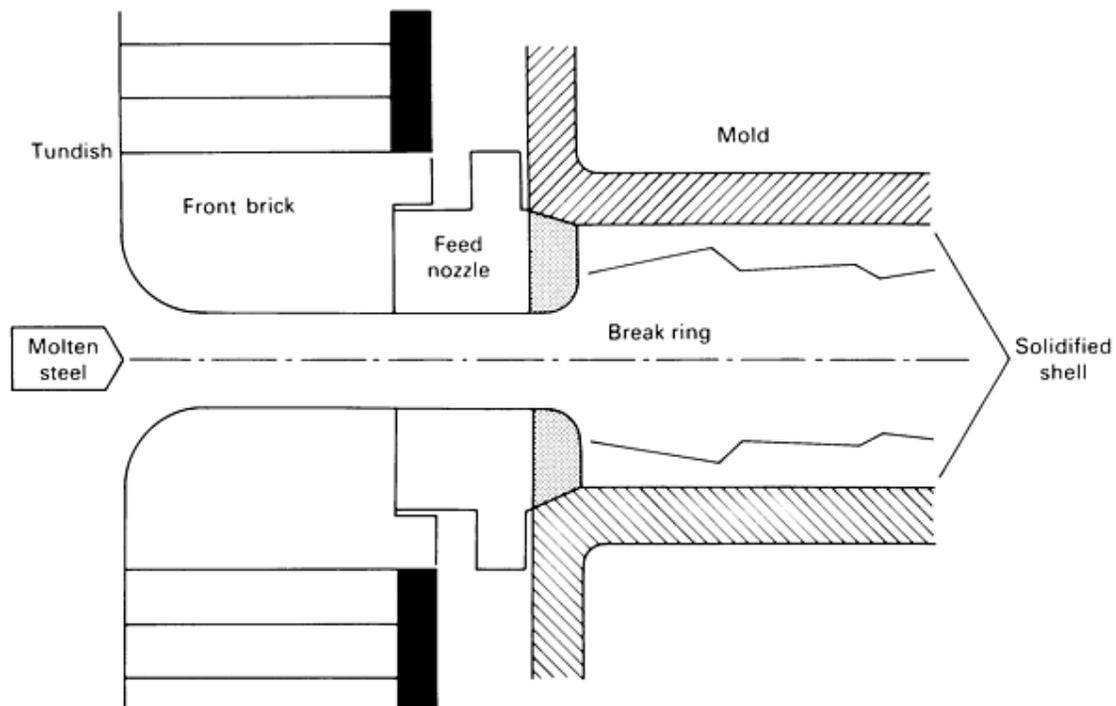


Fig. 12 Tundish and mold arrangement for horizontal caster. Source: Ref 22

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### Continuous Casting of Steel

Continuous casting of steel is entering a new era of development, not only with respect to its increasing application in the production process, but also in its own evolution as a process and its interaction with other processes in steel manufacture. Continuous casting output has shown an accelerating growth curve. More than 50% of current world steel production is continuously cast, and continuous casting in Japan exceeds 80%. The advantages of the process, along with its developments and current challenges for improvement, are outlined in the following sections.

#### *General Description of the Process*

The purpose of continuous casting is to bypass conventional ingot casting and to cast to a form that is directly rollable on finishing mills. The use of this process should result in improvement in yield, surface condition, and internal quality of product when compared to ingot-made material.

Continuous casting involves the following sequence of operations:

- Delivery of liquid metal to the casting strand
- Flow of metal through a distributor (tundish) into the casting mold
- Formation of the cast section in a water-cooled copper mold
- Continuous withdrawal of the casting from the mold
- Further heat removal to solidify the liquid core from the casting by water spraying beyond the mold
- Cutting to length and removing the cast sections

A diagram showing the main components of a continuous casting machine is presented in Fig. 1. Molten steel in a ladle is delivered to a reservoir above the continuous casting machine called a tundish. The flow of steel from the tundish into one or more open-ended, water-cooled copper molds is controlled by a stopper rod-nozzle or a slide gate valve arrangement. To initiate a cast, a starter, or dummy bar, is inserted into the mold and sealed so that the initial flow of steel is contained in the mold and a solid skin is formed. After the mold has been filled to the desired height, the dummy bar is gradually withdrawn at the same rate that molten steel is added to the mold. The initial liquid steel freezes onto a suitable attachment of the dummy bar so that the cast strand can be withdrawn down through the machine. Solidification of a shell begins immediately at the surface of the copper mold. The length of the mold and the casting speed are such that the shell thickness is capable of withstanding the pressures of the molten metal core upon exiting from the copper mold. To prevent sticking of the frozen shell to the copper mold, the mold is normally oscillated during the casting operation and a lubricant is added to the mold. The steel strand is mechanically supported by rolls below the mold where secondary cooling is achieved by spraying cooling water onto the strand surface to complete the solidification process. After the strand has fully solidified, it is sectioned into desired lengths by a cutoff torch or shear. This final portion of the continuous casting machine also has provision for disengagement and storage of the dummy bar.

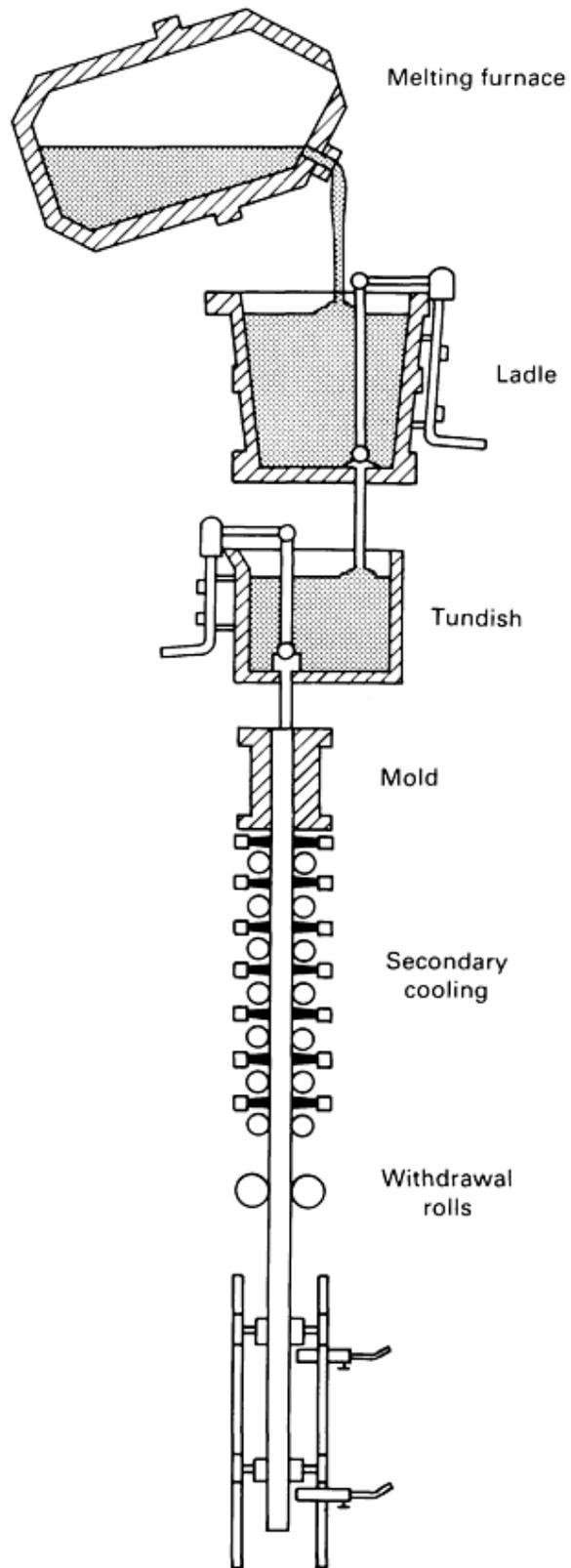


Fig. 1 Main components of a continuous casting strand. Source: Ref 4

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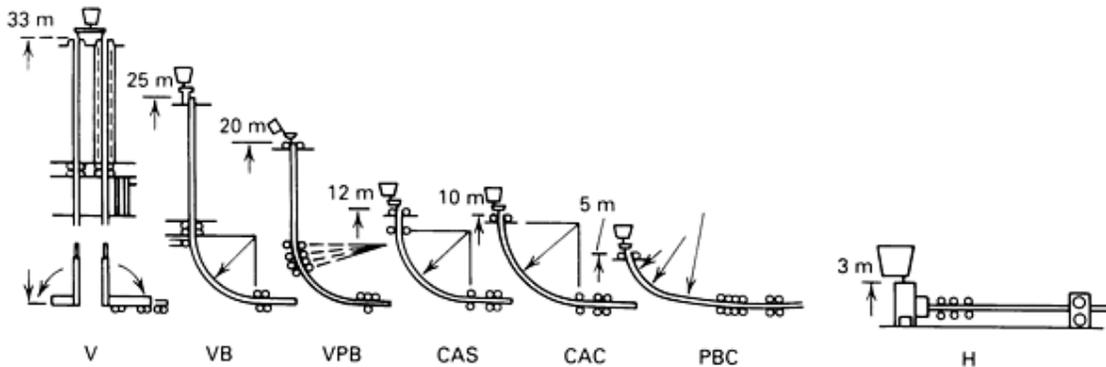


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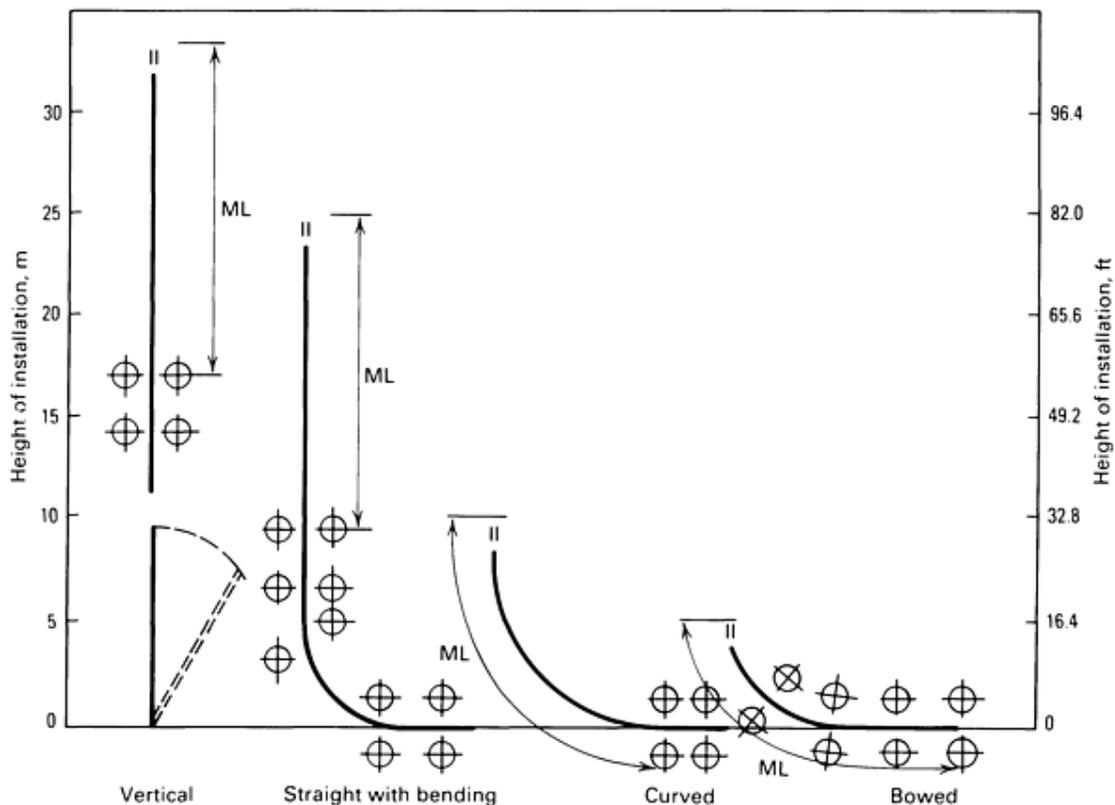


Fig. 3 Four basic designs for continuous casting machines. ML, metallurgical length. Source: Ref 6

### Plant Layout

The design and layout of a steelmaking facility often focus initially on continuous casting. The optimum plant layout varies markedly from one installation to another. One major factor in the configuration is whether or not the steelmaking complex is being constructed on a greenfield site or being added ("shoehorned") into an existing works. Many of the major integrated steel works in Japan were constructed as greenfield installations during the period from 1960 to 1975. Most of the minimills constructed throughout the world, and in particular in the United States, were also built on greenfield sites.

In building a greenfield site, the plant layout should incorporate two major features: a smooth and well-organized arrangement for material handling and flow, and the capacity for future expansion. Generally, these plants are designed for 100% continuous casting, and no ingot facilities are included (Ref 7). Nearly all of the recently built minimills incorporate one or more electric furnaces and provide for 100% continuous casting of billets. Chaparral Steel Company at Midlothian, TX is an excellent example (Ref 8). A profile of a proposed large-scale electric furnace billet casting plant is shown in Fig. 4.

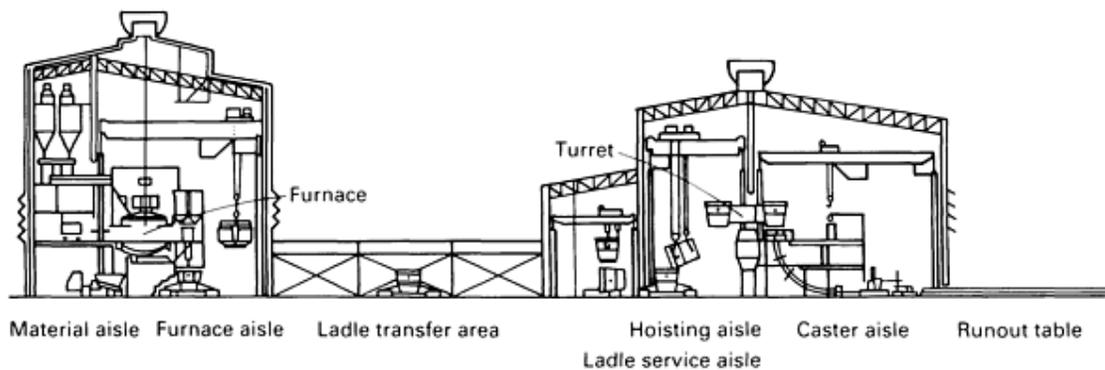


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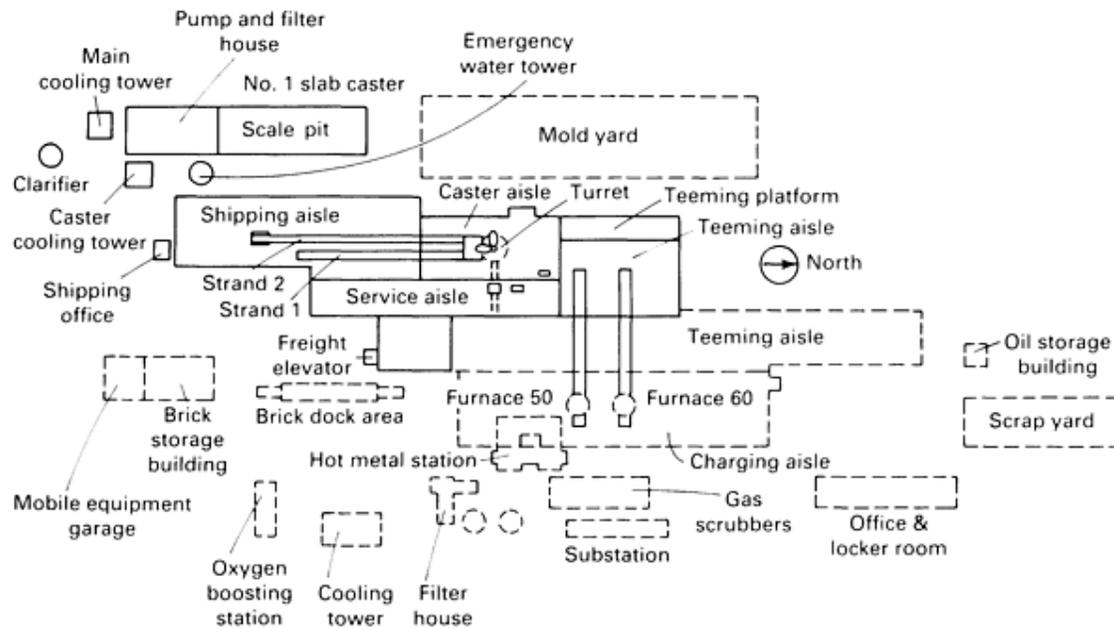


Fig. 5 Plant layout at the Inland Steel Company. Source: Ref 10

An important characteristic of the plant layout, and in particular of the material-handling facilities, is the concept that the continuous casting machine cannot wait. This design and operating concept has had a dramatic impact on steelmaking operations, which have now become a synergism to the continuous casting facilities. Because of this shift in priorities, marked improvements in productivity have been developed for continuous casting, as outlined below.

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A number of methods for distributing liquid steel to the mold or to several molds of the casting machine have been investigated. Use of a tundish with appropriate flow control has been found to be a superior method for the production of quality steel. Considerable effort has been directed toward improvement of refractories and development of methods for preventing nozzle blockage. Geometric arrangements in tundishes, including the use of dams and weirs, have provided suitable fluid flow characteristics to maximize the separation of nonmetallic inclusions, resulting in improved quality. Another factor in separation of nonmetallic inclusions in the tundish is tundish size because of its effect on residence time. Figure 6 indicates the trend in tundish size for major slab casting installations over the past 20 years.

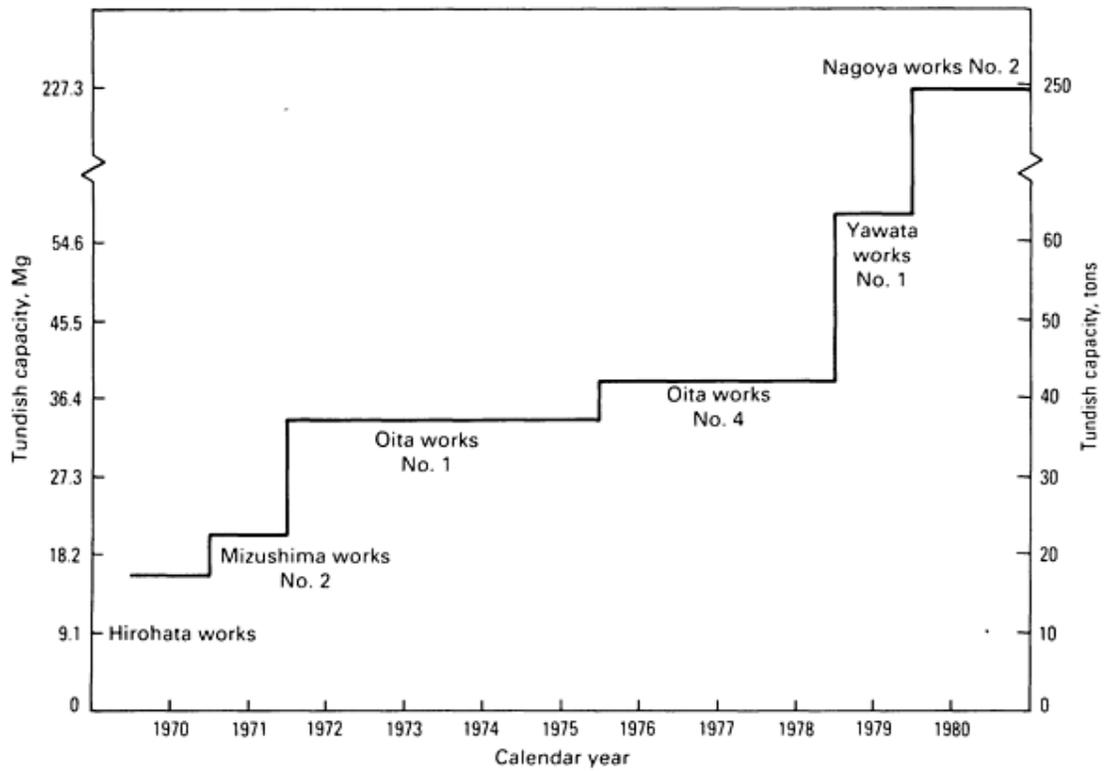


Fig. 6 Increases in capacity of tundishes for a two-strand slab caster. Source: Ref 11

Reoxidation of the molten steel is to be avoided. The use of refractory shrouds between the ladle and the tundish and the tundish and the mold have been adopted for slab casting (Fig. 7).

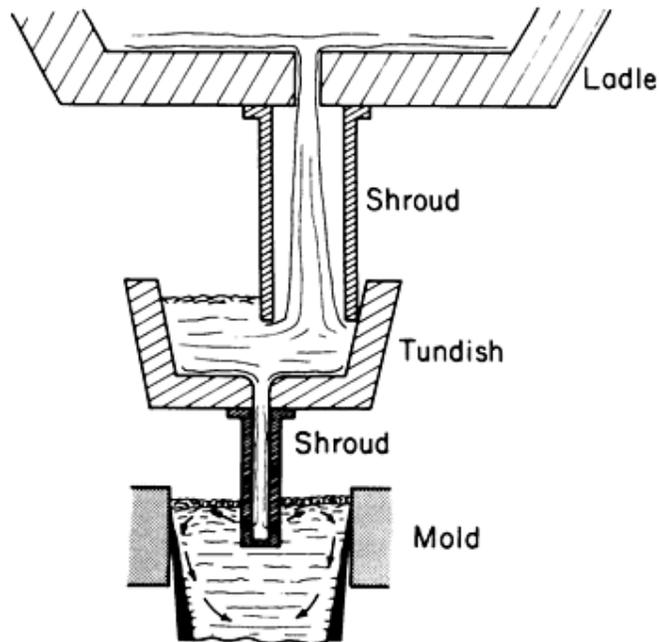


Fig. 7 Pouring shrouds from ladle to tundish to mold. Source: Ref 12

One of the difficulties encountered in continuous casting of small sections has been the protection of the pouring stream from tundish to mold because of the inapplicability of a pouring tube and the mechanical difficulty caused by the oscillation of the mold relative to the fixed tundish. In one instance, this has been overcome by the use of a flexible bellows (Fig. 8) and successfully applied to the continuous casting of special product quality steel bars. Recently, further development has been made in the use of ceramic shrouds to protect pouring streams on billet machines.

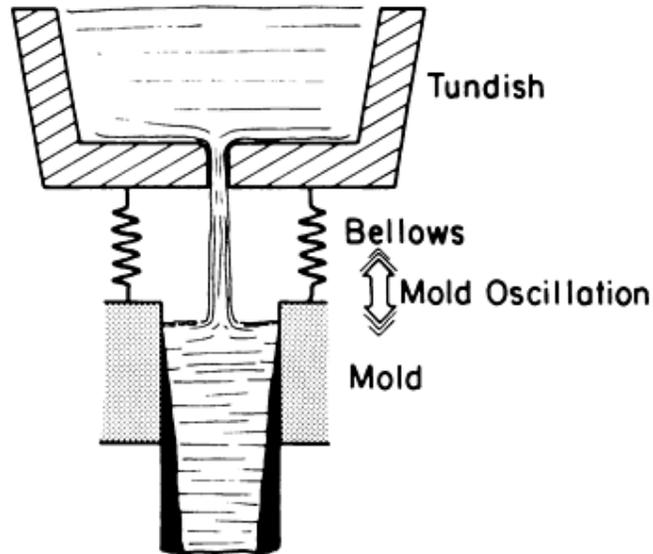


Fig. 8 Bellows between tundish and mold for casting billets. Source: Ref 12

Protection of the surface of the molten steel pool in the tundish has been achieved through the use of suitable synthetic oxide slags, inert-gas blanketing, and a refractory cover to seal the tundish. The metal level in the tundish, as well as the fluid flow pattern, is important in avoiding the ingestion of the slag layer into the metal stream flowing downward into the mold.

The tundish is supported with either two tundish cars or a two-position turret. Frequently, the double turret provides for changing of the tundish while continuing the casting process, which allows extended sequence casting. The changing of the tundish not only occurs at an appropriate time, but also allows a change in steel composition with a minimal length of transition in the cast product.

The flow-through water-cooled copper mold is the key element of the casting machine. Special attention has been given to problems associated with the design and material requirements for molds. A number of different designs have been used, including thin-wall tube-type molds, solid molds, and molds made from plate. Plate molds were found to provide excellent mold life and to avoid the necessity for manufacture of molds from solid copper blocks. Steel and brass, as well as copper, have been used for molds, but the most outstanding material is nearly pure copper with small additions of elements that promote precipitation hardening or raise the recrystallization temperature, because both effects apparently provide longer mold life. Mold coatings are applied to extend service life. A chromium coating is generally used, often with an intermediate layer of nickel for improved coherence.

The most suitable length for a continuous casting mold has been found to be 510 to 915 mm (20 to 36 in.), a range that seems to remain constant regardless of section size. This surprising result can be explained by the higher rates of heat removal achieved with smaller sections and higher casting rates. Also, a thinner skin can be permitted for smaller sections exiting from the mold than for larger sections because bulging of the solidifying shell will be less severe. At higher

casting rates, the use of an increased taper in the mold is necessary to maintain high heat removal rates, particularly for the narrow faces of slab molds.

Oscillating molds, as used by Junghans, have been adopted almost universally, although fixed molds can be successfully used with efficient lubricating systems. The oscillation is usually sinusoidal, a motion that can be achieved easily with simple mechanical arrangements. A fairly short stroke and a high frequency are used to provide a short period of "negative strip" during each oscillation, in which the mean downward velocity of the mold movement is greater than the speed of withdrawal of the casting strand in the casting direction. Oscillating frequencies are being increased from 50 to 60 cycles per minute (cpm) up to 250 to 300 cpm, with the benefits of shallower oscillation marks, less cracking, and reduced conditioning requirements.

Molten metal in the slab mold is normally covered with a layer of mold powder to protect the metal from reoxidation and absorb inclusions. The powder has a low melting point and flows over the liquid steel to provide mold lubrication and to help control heat transfer. Rapeseed oil, which has since been replaced by synthetic oils, has typically been used to prevent sticking to the mold in billet casting. Metal flow rates are matched with slab casting speeds using a stopper rod in the tundish, a slide gate, or a metering nozzle just above the shroud to control the delivery rate. Billets are normally cast with fixed metering nozzles, and the strand speed is adjusted to any changes in steel flow rate.

Support of the thin steel shell exiting the mold is required, particularly for slab casters. Several systems have been used (Fig. 9), all of which provide intensified direct water cooling.

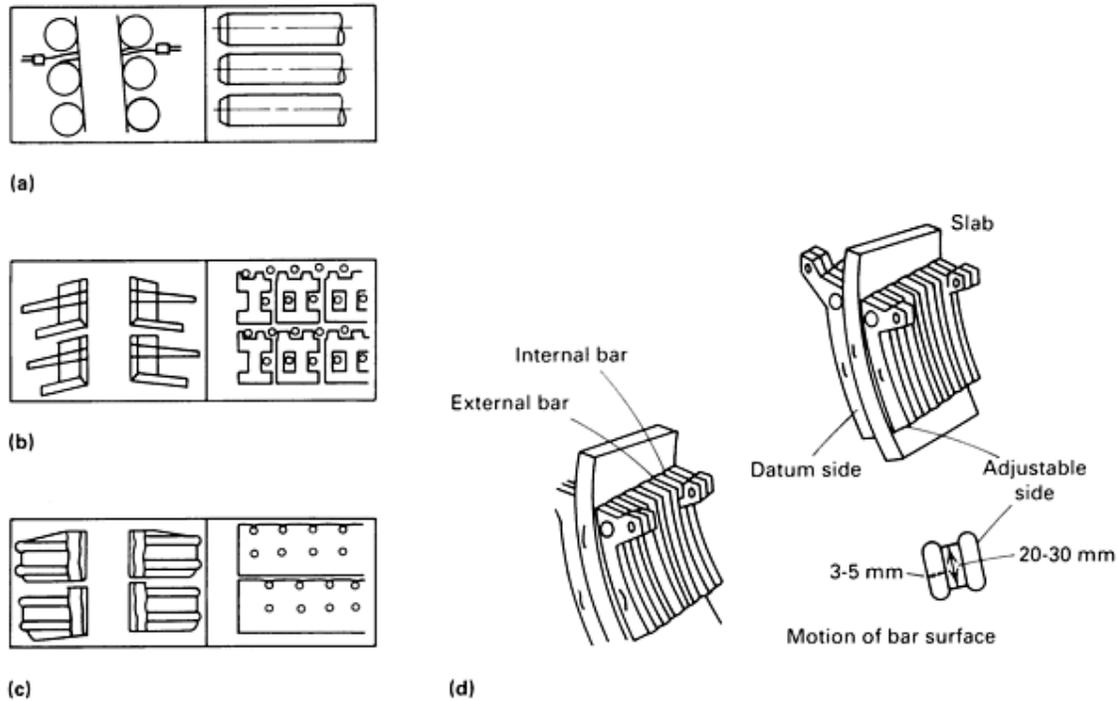


Fig. 9 Four types of shell supporting systems used in continuous casting. (a) Roll. (b) Cooling grid. (c) Cooling plate. (d) Walking bar. Source: Ref 13

Water spraying (secondary cooling) is critical to the process in that maximum cooling should be accomplished, but overcooling and large temperature increases must be avoided. The amount of heat removed by water sprays depends on the volume of the water, its temperature, and in particular the method of delivery, including spray pressure. Pressure is important in that the spray should be sufficiently intense to penetrate the blanket of steam on the surface of the solidifying strand. The thermal conductivity of steel is relatively low; consequently, as the surface temperature decreases and the shell thickness increases, cooling water has less influence on the solidification characteristics. The interrelationship between support rolls and the spray water and its delivery characteristics is quite important, particularly for the casting of wide slabs.

Mixed spraying of air and water develops a unique secondary cooling system with a uniform water droplet size. Air-mist cooling is illustrated in Fig. 10, along with the conventional water spray, as applied to slab casting. Although more costly, the air-mist spray system has a more uniform spray pattern and intensity that offers excellent spray cooling control. Decreases in transverse and longitudinal cracking with air-mist cooling have been reported (Ref 15, 16).

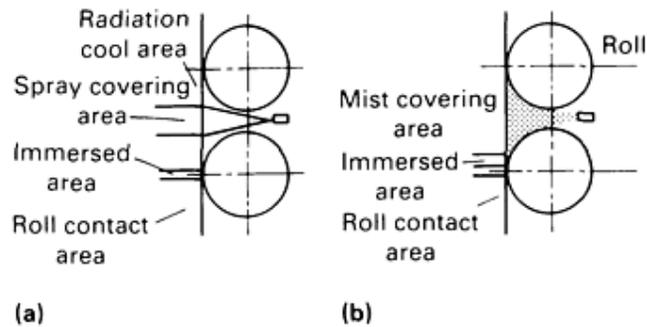


Fig. 10 Comparison of spray systems used in continuous casting. (a) Conventional spray. (b) Air-water mist spray. Source: Ref 14

The straightening operation on curved strand casters has required special design and operating control. In general, temperatures at or above 900 to 1050 °C (1650 to 1920 °F) have been recommended to avoid conditions under which certain grades of steel have limited ductility and are susceptible to cracking. Multipoint and four-point straighteners have reduced imposed strains, and compression casting systems have reduced tensile stresses. Uniform temperature of the strand, including corners, which tend to cool more quickly, is required.

The dummy bar, which is used to stopper the mold for the initiation of a cast, can be inserted from above or below, depending on the individual installation. Some arrangements are shown in Fig. 11. The top feeding arrangement, which "chases" the last metal cast through the machine, offers a productivity advantage.

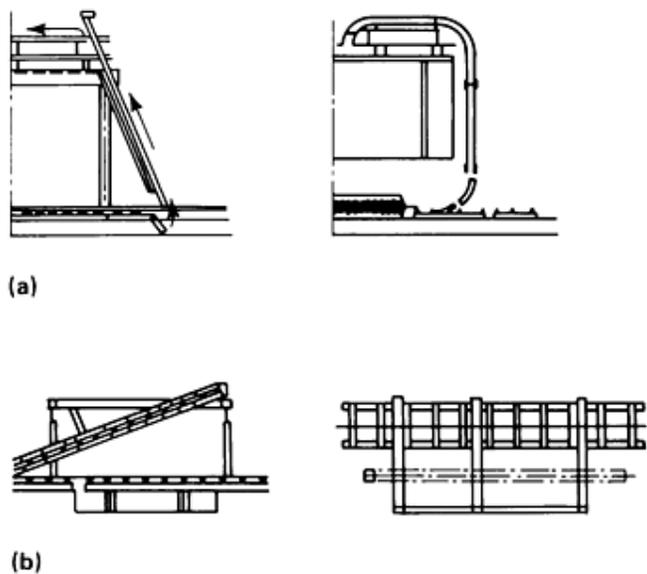


Fig. 11 Dummy bar arrangement. (a) Top feeding. (b) Bottom feeding. Source: Ref 17

*Productivity Improvements*

While continual increases in casting speeds over the years have led to improvement in casting machine productivity, the most dramatic factor has been sequence casting, that is, continuous-continuous casting. Perfection of this development has required extraordinary achievement in the design of ladle and tundish handling systems, and in design and maintenance considerations for long-term operation with processing times that extend for several days. A summary of sequence casting records in Japan has been presented by T. Harabuchi (Ref 18) and is reported in Table 1. In comparison, the Jan 1983 casting record at Great Lakes Steel Corporation in the Detroit district involved a large slab caster (240 mm × 2.5 m, or 9 × 99 in.), which cast 402 ladles and 83 160 Mg (91,480 tons) of steel continuously. In addition to the bulk steel handling requirements of sequence casting, the ability to change nozzles, shrouds, and tundishes at frequent intervals is also required. The string of casts at Great Lakes Steel Corporation involved 35 tundish changes and 177 shroud changes over a period of 13 days. This record has been exceeded more recently at the Gary Works of United States Steel International, Inc.

**Table 1 Record of sequence casting in Japan**

Product	Company	Continuous casting plant	Heats per cast	Weight of steel per cast		Time of achievement
				Mg	tons	
Slab	Nippon Kokan	Keihin	270	22,523	24,775	Sept 1974
Slab	Nippon Kokan	Fukuyama	244	54,360	59,796	Aug 1981
Slab	Kawasaki Steel	Mizushima No. 5	204	51,000	56,100	Nov 1980
Slab	Nippon Steel	Yamata No. 2	186	30,199	33,219	July 1974
Bloom	Sumitomo Metals	Wakayama No. 3	1129	160,110	176,124	July 1982
Bloom	Daido Steel	Chita	320	19,091	21,000	Feb 1984
Bloom	Sumitomo Metals	Kokura	281	17,648	19,413	April 1982
Bloom	Nippon Steel	Kamishi	202	17,857	19,643	Jan 1979
Billet	Osaka Steel	Okajima	214	17,455	19,200	July 1978
Billet	Kokko Steel	Main Plant	174	5,063	5,569	Aug 1978
Billet	Funabashi Steel	Main Plant	99	5,535	6,089	Oct 1975

While it has been shown that sequence casting extending beyond five or six heats does not dramatically increase productivity, provided a reasonable turnaround time and interactive scheduling with the steelmaking facilities exist, the capability for long-term sequence casting represents the opportunity for increased productivity with high quality at an essentially steady state operation of the caster.

An important characteristic of a casting operation with regard to productivity is the percentage of total clock time that steel is being processed in the machine. These percentages in high productivity casters can exceed 90% for frequently used casting operations. The turnaround time required for the dummy bar to restart a cast is one of the factors in producing steel-in-mold results, but under ideal conditions scheduled maintenance will be a major factor, and other items, such as problems in steelmaking or mechanical difficulty on the strand, will be minimized.

In the past and in many present installations, interruption of continuous casting production is required in order to make a width change. Several developments that avoid this requirement are now in operation. In one such arrangement, used at Great Lakes Steel Corporation, a very wide slab was cast and then slit into two or three optimum widths. Another approach is taken at Oita Works of Nippon Steel Corporation, where a sizing mill adjusts the slabs to various desired widths. Another, more versatile, system involves the use of a variable width mold in which the taper and width are adjusted continuously during the casting process. These techniques have permitted the adoption of sequence casting with a minimum mold inventory based on width.

Another barrier to increasing productivity of continuous casting has been the accommodation of ladle-to-ladle composition changes with adoption of sequence casting. Under ideal circumstances, as when a plant produces a narrow range of compositions, often with overlapping compositional requirements, compositional changes can be slowly stepped through each grade to accommodate the desired sequence of heats. However, when substantial variations in composition must be accommodated, physical barriers in the form of steel plates have been used to provide isolation of the grade changes in the strand. In this way, the transition zone can be minimized, and compositional changes can be accommodated without substantial losses in yield or quality.

### *Quality Improvements*

The operation of a continuous casting strand to produce good-quality steel uniformly and reliably on a routine basis can be the most valuable asset of the process. Development work continues in an effort to improve control and production reliability, particularly with regard to avoidance of inclusions and cracking for internal and surface quality.

Internal cracking is less important for those products (for example, sheet) that have large reduction ratios. Radial cracks, center looseness or centerline cracking, minor amounts of gas evolution, and other internal defects are not deleterious in heavily rolled products. In the manufacture of heavy plates, however, these conditions can represent serious product defects.

For aluminum-killed steel, subsurface inclusions are usually in the form of aluminum oxide. In some cases, surface scarfing can be effective in removing these inclusions, which could provide a surface defect in a final rolled product. Unfortunately, this surface conditioning results in substantial yield losses. It has been reported (Ref 4) that use of multiport shrouded nozzles can produce a fluid flow action in slab molds, which brings inclusions in contact with the molten mold powder covering to flux and dissolve oxide particles. This provides a clean subsurface zone that requires no scarfing. However, this method leads to the entrapment of complex nonmetallic inclusions containing mold powder. Clean steel practices in combination with nozzle configurations optimized for specific casting conditions are necessary to minimize nonmetallic inclusions. As noted above, the control of fluid flow and promotion of separation in ladle, tundish, and mold can provide a substantial reduction in large inclusions.

Depending on steel grade, cracking can result from intensive cooling or deformation in the casting strand. Surface cracking can be minimized by proper control of lubrication and cooling within the mold, and cooling and alignment in the upper spray zone. Other critical factors in cracking are control of spray cooling to avoid surface temperature rebound (resulting in midway cracks) or nonuniformity of cooling across or along the strand. Control of temperature distribution at the straightener and proper roll gap settings for slabs and blooms have also been noted as being very important.

### *Horizontal Continuous Casting*

Horizontal casting systems have been explored for many years, but only in the recent past have they been successfully applied to steels. Oldsmobile Division of General Motors Corporation started casting 95 mm (3.75 in.) steel bars in a horizontal mold in 1969 (Ref 19, 20), with uninterrupted casts of up to 24 h. This is believed to be the longest sustained continuous casting operation for steel up to that time.

Voest-Alpine is developing a horizontal continuous casting machine for steels, and the Nippon Kokan (NKK) Steel Company of Japan has been producing horizontally cast steel sections up to 210 mm (8 in.) square (Ref 21). These

systems depend on a refractory nozzle or "break ring" at the entrance end of a stationary water-cooled metallic mold, and an intermittent motion for translating the bar, each forward stroke being followed by a discrete rest or dwell. A cross section of the tundish and mold arrangement of the NKK machine is shown in Fig. 12. Casting of larger sections is being explored throughout the world, as are continuous casting processes for high-speed casting of thin sections. As the technologies for cleaner steels evolve, these processes will come closer to commercial adoption.

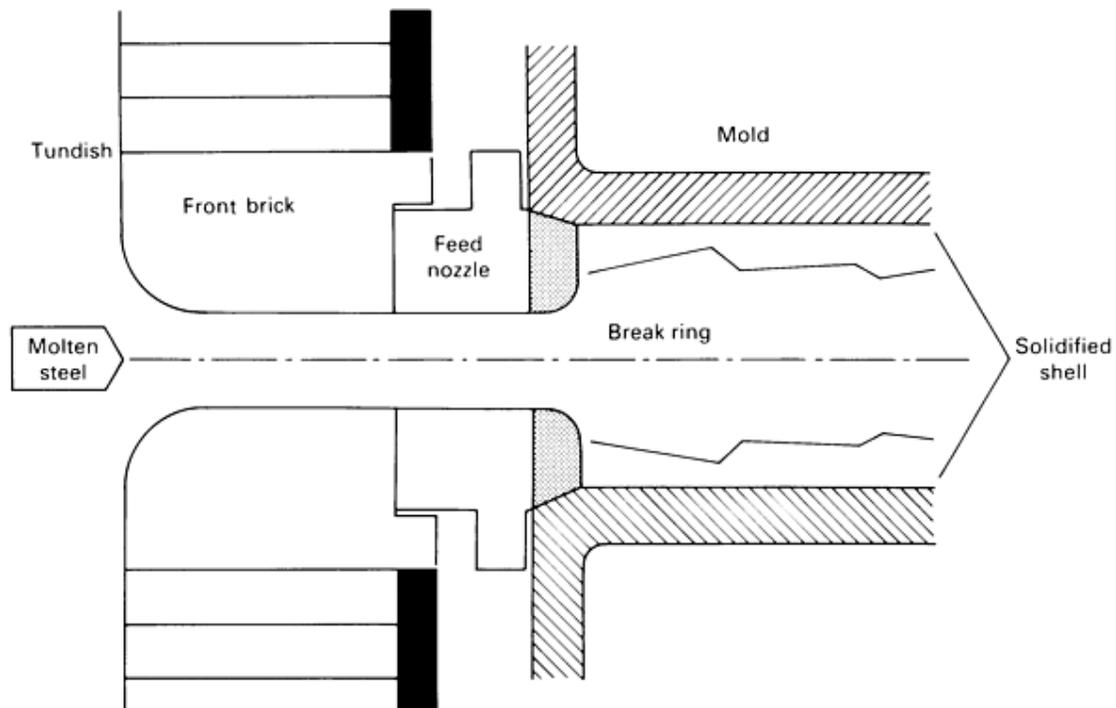


Fig. 12 Tundish and mold arrangement for horizontal caster. Source: Ref 22

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Robert D. Pehlke, University of Michigan

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### Nonferrous Continuous Casting

The early development of continuous casting processes occurred to a large extent at production installations for nonferrous alloys.

#### *Direct-Chill Casting*

The principal casting process for light metals is the direct-chill process (Ref 22, 23, 24, 25). The vertical direct-chill casting process was patented by Alcoa in 1942 (Ref 26), and is shown schematically in its present form in Fig. 13. The process can directly prepare billets for extrusion, blocks for rolling, and sheet for fabrication, thus eliminating intermediate mechanical working processes by casting near-net shapes.

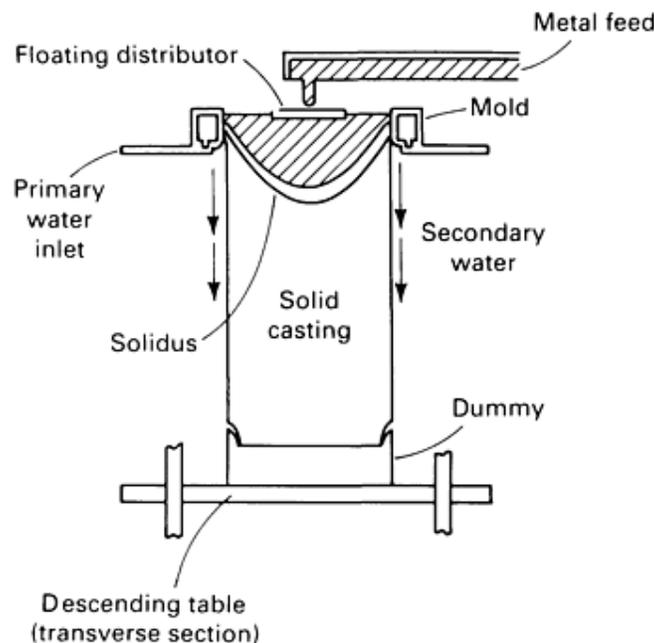


Fig. 13 Conventional vertical direct-chill casting arrangement. Source: Ref 22

Most direct-chill casting capacity is of the vertical type for semicontinuous casting, but more importance is being assumed by the continuous horizontal direct-chill casting process (Fig. 14). The section sizes in which aluminum alloys are cast range from  $1.5 \times 0.5$  m ( $5 \times 1.6$  ft) blocks for rolling to 5 to 30 mm (0.2 to 1.2 in.) thick by 2 m (6.6 ft) wide for plate and strip. There is considerable economic advantage in wide strip casting. This processing, which is far ahead of steel continuous casting of wide strip, could portend the future for steel.

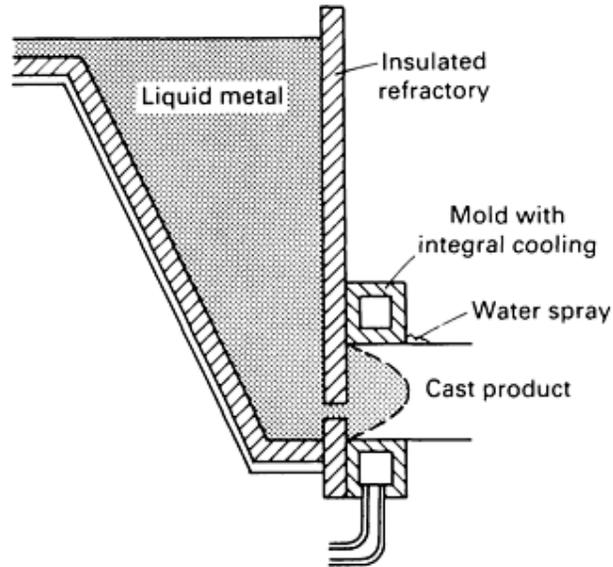


Fig. 14 Horizontal direct-chill casting system. Source: Ref 22

The key operating requirement in direct-chill casting is that a sufficiently strong shell be developed in the limited time of contact with the mold to retain the interior molten pool. Withdrawal rates of up to 0.2 m/min (0.66 ft/min) can be achieved in conventional casters. Withdrawal speeds of 2.5 m/min (8.2 ft/min) for a 10 mm (0.4 in.) thick section have been reported for horizontal casters producing pure aluminum strip (Ref 27). Pure aluminum or dilute alloys are easier to cast than higher alloys with wide freezing ranges. Higher casting speeds have led to problems in maintaining casting shape and have also caused higher internal stresses in the solidified ingot. Control of heat extraction rates is required to limit the extent of these difficulties.

Vertical direct-chill casting is used extensively to produce rectangular slabs and cylindrical billets of copper alloys, and, to a lesser extent, of pure copper. A diagram of an entire vertical direct-chill unit for casting copper slabs is shown in Fig. 15. For copper and copper-base alloys, the liquid metal is poured through a water-cooled, oscillating, graphite-lined collar or mold. The graphite produces a smooth surface on the casting and minimizes oxidation.

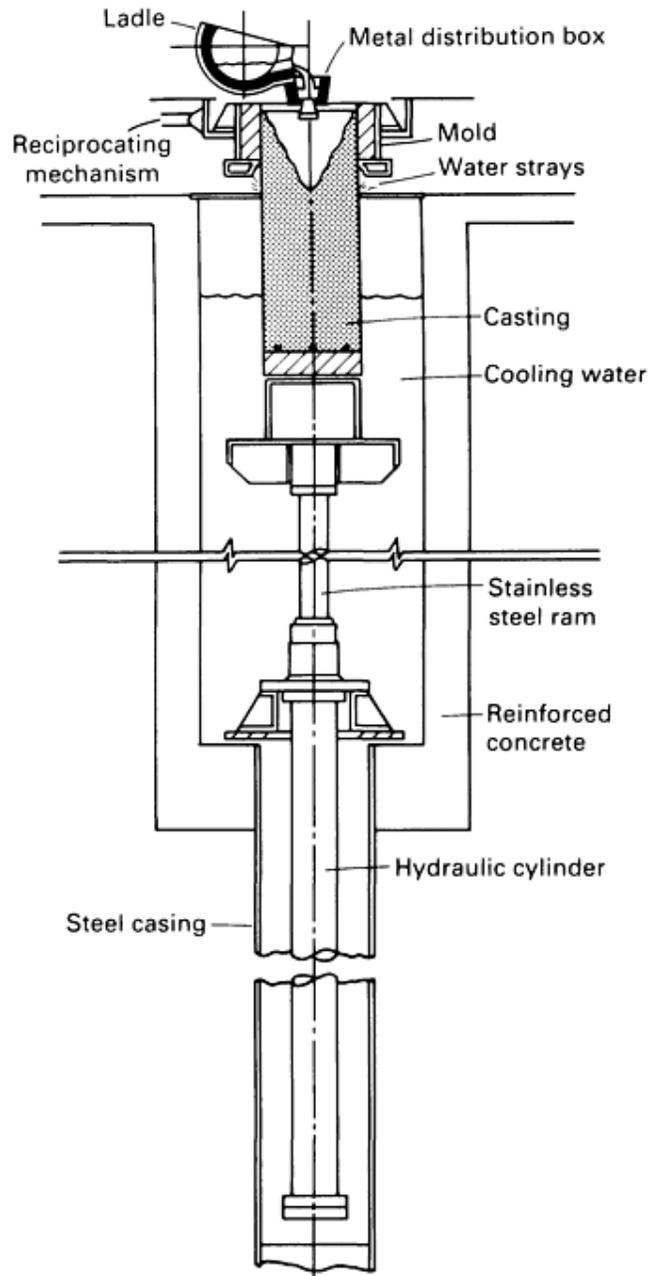


Fig. 15 A direct-chill unit for casting copper alloy slabs. The slabs produced by this unit are approximately 9 m (29.5 ft) long. Source: Ref 28

### *Other Processes*

There are numerous types of continuous casting processes that commercially produce nonferrous metals, principally aluminum and copper alloys (Ref 29). These processes can be characterized by their products. The more common processes are discussed below.

**Wheel-and-Band Machines.** Rod and bar are continuously cast on wheel-and-band machines, such as the Properzi process (Fig. 16), or the more recent Southwire casting system, which is illustrated in Fig. 17. These processes involve casting between the circumference of a large copper-rimmed wheel containing the mold configuration and a steel band (Fig. 18). The metal solidifies in the gap as the wheel and band rotate through a portion of a circular path, which includes

water sprays. Casting rates of 32 Mg/h (35 tons/h) for a 450 × 450 mm (18 × 18 in.) copper billet have been reported (Ref 31). The Southwire process has recently been applied to the production of steel billets.

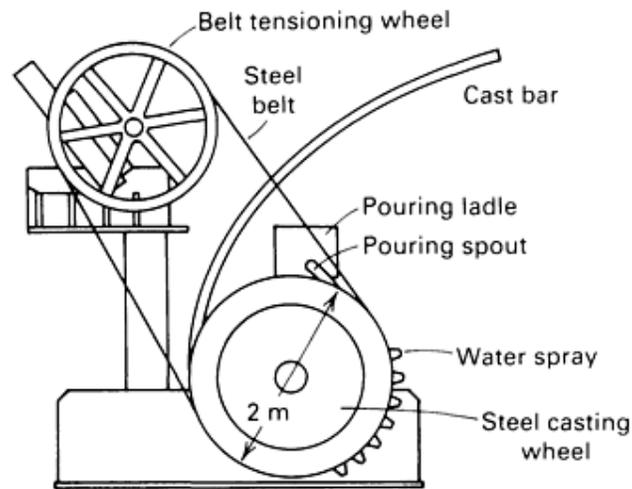


Fig. 16 The Properzi casting machine. Source: Ref 30

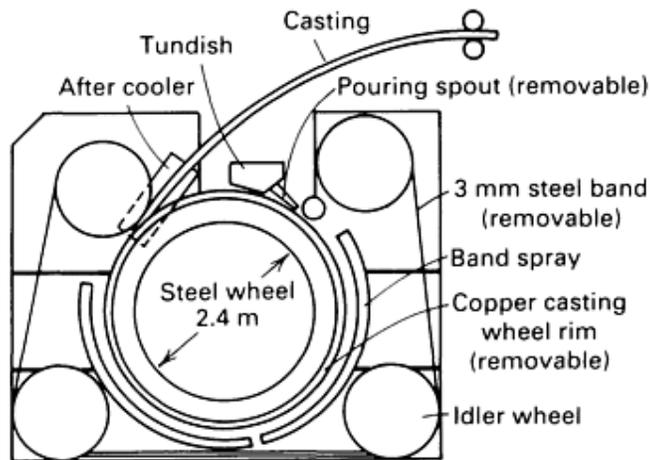
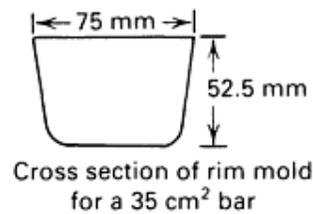


Fig. 17 The Southwire wheel-and-band continuous casting machine. Source: Ref 31

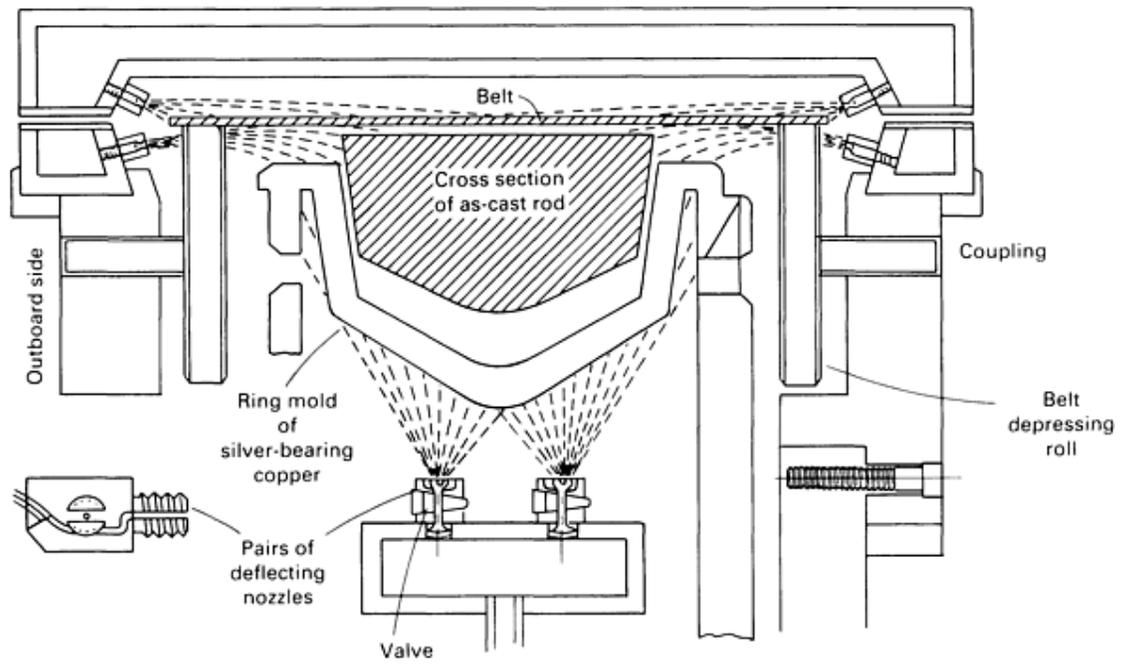
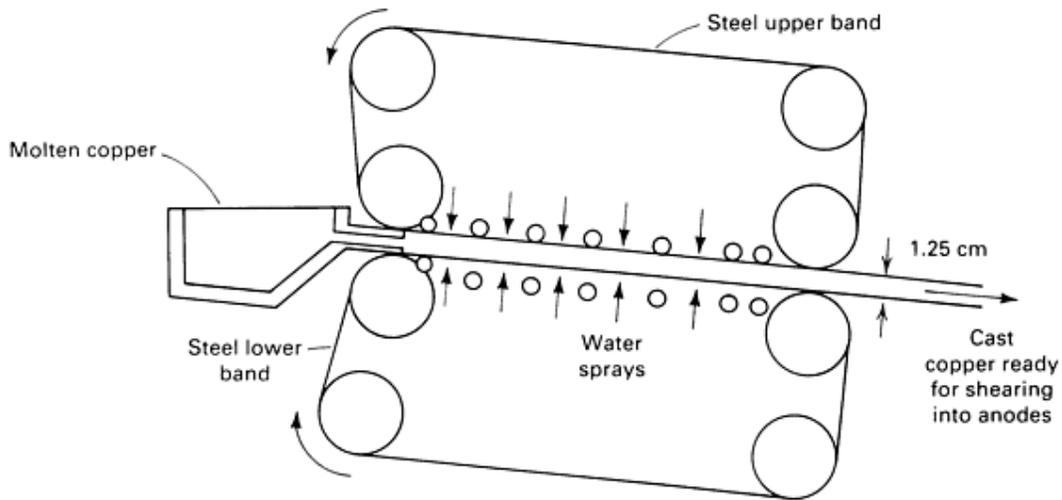
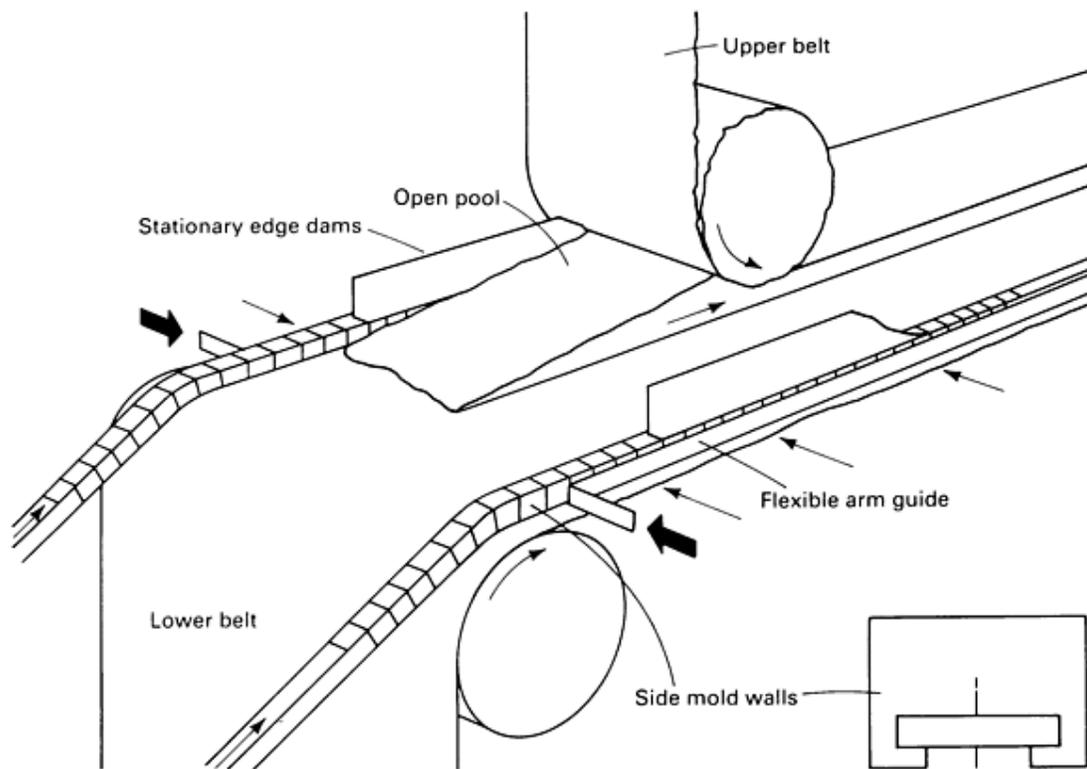


Fig. 18 The Properzi ring mold, belt, and as-cast rod. Source: Ref 32

Wide, thick strip is normally produced on a twin band machine, such as the Hazelett caster (Fig. 19).



(a)



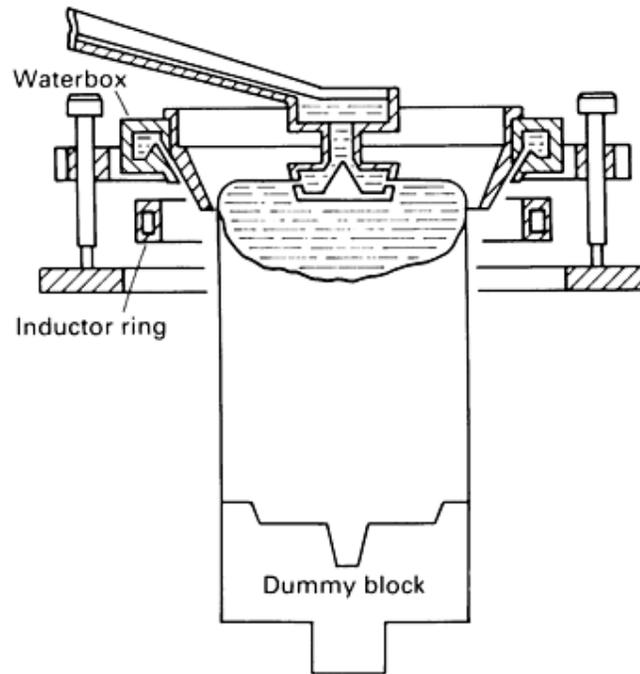
(b)

Fig. 19 The Hazelett machine for continuous casting of copper anode strip. Source: Ref 33

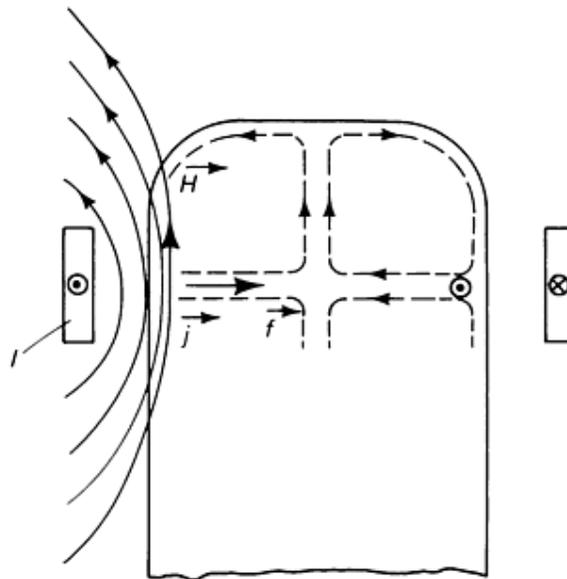
The bands are separated by edge dams on each side of the castings; these dams can be moved to set the width of the strip.

Twin roll casting has been used for the production of wide, thin aluminum strips. Several twin roll processes are used to cast 6 to 12 mm (0.24 to 0.48 in.) thick by 1500 to 2000 mm (59 to 79 in.) wide strip.

Many product quality problems relate to mold and air gap formation, as well as interaction of the ingot shell and liquid core. These could be eliminated by moldless casting, wherein an electromagnetic field supports the liquid metal until it enters the direct-quench zone. Such a process was developed in the Soviet Union (Ref 34). Electromagnetic casting is currently being used in the aluminum industry (Ref 35) and has been developed for copper-base alloys (Ref 36). The process is shown in Fig. 20.



(a)



(b)

Fig. 20 The electromagnetic casting process. (a) Equipment. (b) Physical principles involved.  $H$ , magnetic field strength;  $I$ , inductor current;  $j$ , eddy and current density;  $f$ , volume force

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Robert D. Pehlke, University of Michigan

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## Future Developments

The emphasis on the further development of continuous casting will focus on control systems and automation, with the objective of maintaining high quality and high productivity. Accomplishing this will include monitoring metal quality and ensuring that all aspects of the process are under proper control. Various operating parameters, such as mold, slag, or flux levels in ladle, and tundish, also will be monitored directly. Sensors will be developed to control automatically the process for proper cooling in the mold, first zone, and secondary cooling systems. Hot inspection techniques will be developed that will provide a direct measure of product quality as it leaves the casting machine and moves to hot-rolling processing.

Also, current worldwide efforts on steel processing are in the area of the belt casting of thin slabs, the roll casting of thin strip, and the electromagnetic casting of steel.

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Robert D. Pehlke, University of Michigan

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## Continuous Casting

Robert D. Pehlke, University of Michigan

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## Counter-Gravity Low-Pressure Casting

Dixon Chandley, Metal Casting Technology, Inc.

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## Introduction

ENGINEERS have made various attempts, since early in this century, at drawing metal up into molds against the flow of gravity to produce castings. Molds were typically put into a vacuum box with a fill pipe extending from the mold out of the box. The fill pipe was submerged in molten metal, and a vacuum was generated around the mold, causing the metal to rise into the mold. Metal molds were generally used, and by World War II, many premium-quality aluminum castings were made in such molds by counter-gravity filling. Metal molds were vented to permit the vacuum to exhaust the mold cavities properly and to draw in the metal. In the early 1970s, new methods were developed for counter-gravity casting into nonmetal permeable molds, first using ceramic investment molds and later using low-temperature bonded sand molds. The processes described in this article are covered by U.S. and other patents and are in high-volume production in nine countries and fourteen companies worldwide. Counter-gravity low-pressure casting processes are widely known by acronyms; therefore, these acronyms will be used here for convenience. Counter-gravity low-pressure casting processes include:

- Counter-gravity low-pressure casting of air-melted alloys (CLA)
- Counter-gravity low-pressure casting of vacuum-melted alloys (CLV)
- Check-valve casting (CV)
- Counter-gravity low-pressure air-melted sand casting (CLAS)

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## Counter-Gravity Low-Pressure Casting

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## The CLA Process

The CLA process (Fig. 1) is used to cast metals that are normally melted in air. The economies of the process are based on casting more parts per mold, high gating efficiencies (because most of the gating metal flows back into the furnace), and fewer casting defects (especially melt inclusions, which are reduced because the fill pipe is always submerged into clean metal). Thin-wall parts (wall thickness as small as 0.75 mm, or 0.03 in.) are easily made at high volume and low cost.

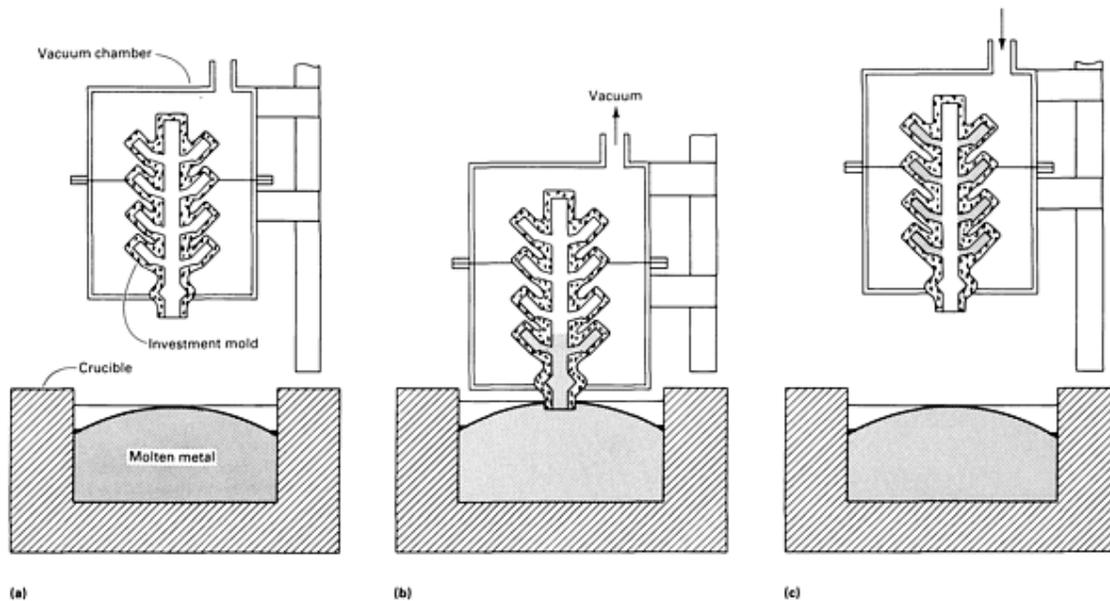


Fig. 1 Schematic of the operations in the CLA process. (a) Investment shell mold in the casting chamber. (b) Mold lowered to filling position. (c) Mold containing solidified castings; most of the gating has flowed back into the melt.

Applications. The CLA process is used to make parts from all types of alloys for many industries. For the automotive industry, steering system components, transmission parts, diesel precombustion chambers, rocker arms, mounts, and hinges are made. Among the components produced for the aircraft and aerospace industries are temperature probes, fuel pump impellers, missile wings, brake parts, pump housings, and structural parts. Other applications include golf club heads, innumerable machine parts, wood router tool bits, tin snip blades, small wrenches, lock parts, gun parts, valves and fittings, and power tools.

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#### Counter-Gravity Low-Pressure Casting

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### The CLV Process

The CLV process (Fig. 2) is used for alloys containing reactive metals, especially the superalloys which may contain aluminum, titanium, zirconium, and hafnium. It can be seen that the advantages of the CLA process also apply to the CLV process. The outstanding features of this process include the ability to fill thin sections and to make castings that are free of the small oxides that plague gravity pouring methods. It is possible to make castings of large area in wall thicknesses down to 0.5 mm (0.02 in.) and without the small oxides that would render such parts defective.

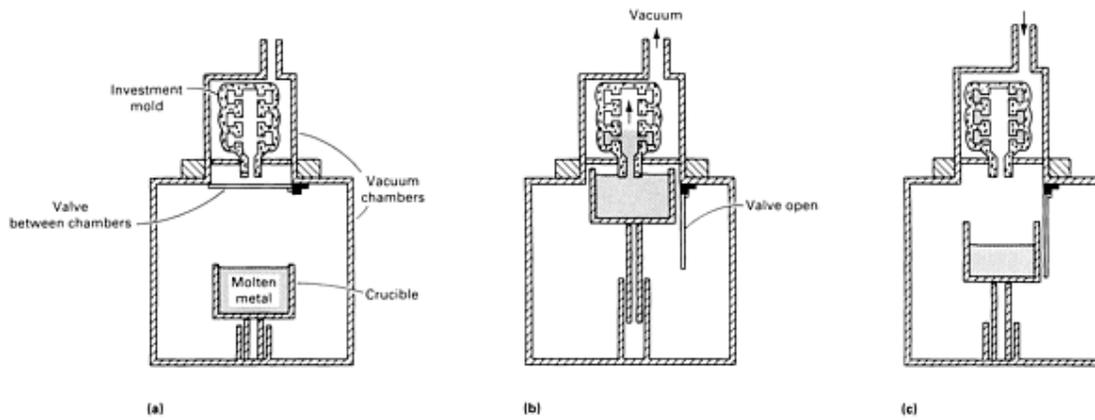


Fig. 2 Schematic showing steps in the CLV process. (a) Metal is melted in vacuum, and the hot mold is introduced into a separate upper chamber. A vacuum is then created in the second chamber. (b) Both chambers are partially flooded with argon, the valve between the chambers is opened, and the fill pipe enters the molten metal. Additional vacuum is then applied to the upper chamber to draw metal upward. (c) The vacuum is released after the parts are solidified, and the remaining molten metal in the gating system returns to the crucible.

Applications. For gas turbine engines, the CLV process provides parts with the lowest level of melt oxide inclusions for alloys such as MAR-M 509 and René 125, which are noted for hafnium and zirconium inclusions when gravity poured. The process enables a new approach to the design of jet engine burner cans, in which the rolled and welded sheet metal design has been replaced with an assembly of thin-wall (0.5 mm, or 0.02 in.) castings shaped for maximum heat transfer and mechanically assembled to reduce thermal fatigue. Such burner cans provide a much higher temperature capability. Important cost and quality improvements have been achieved in cast airfoils, turbine seals, conduits, clamps, and turbocharger wheels.

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### Counter-Gravity Low-Pressure Casting

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### The CV Process

The CV process (Fig. 3) is used for castings that are too thick to solidify in the manner required by the CLA or CLV process. As shown in Fig. 3, this process uses a flexible fill pipe, which is crimped shut by a check valve when the mold is filled. The CV process provides a good fill of thin castings, along with the improved metal cleanliness of the other processes, and it applies to all molding methods.

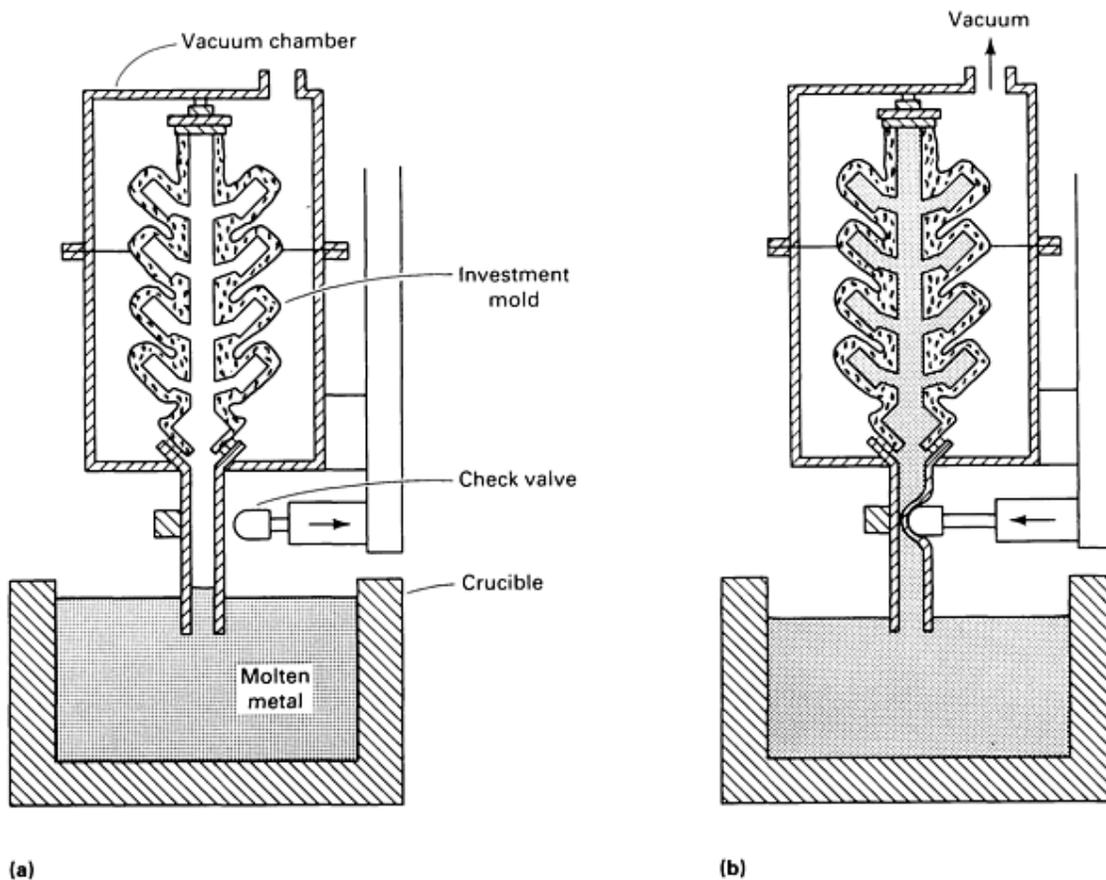


Fig. 3 Schematic of the CV process. (a) Fill pipe is submerged and vacuum is used to fill the mold as in the CLA process. (b) When the mold is filled, a check valve crimps the fill pipe shut. Metal is trapped in the mold, which is then moved away and allowed to solidify as in gravity-filled molds.

Applications of the process include large missile wings, valve bodies, hinges, and other large parts with varying section thickness.

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#### Counter-Gravity Low-Pressure Casting

Dixon Chandley, Metal Casting Technology, Inc.

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#### The CLAS Process

The CLAS process (Fig. 4) is used for sand casting and is quite different from the other processes discussed above. It has a unique ability to make thin castings at low vacuum levels. Because the metal is taken from the clean portion of the melt and because castings are made at low metal temperatures, melt inclusions are very low in volume as compared to those found in gravity casting.

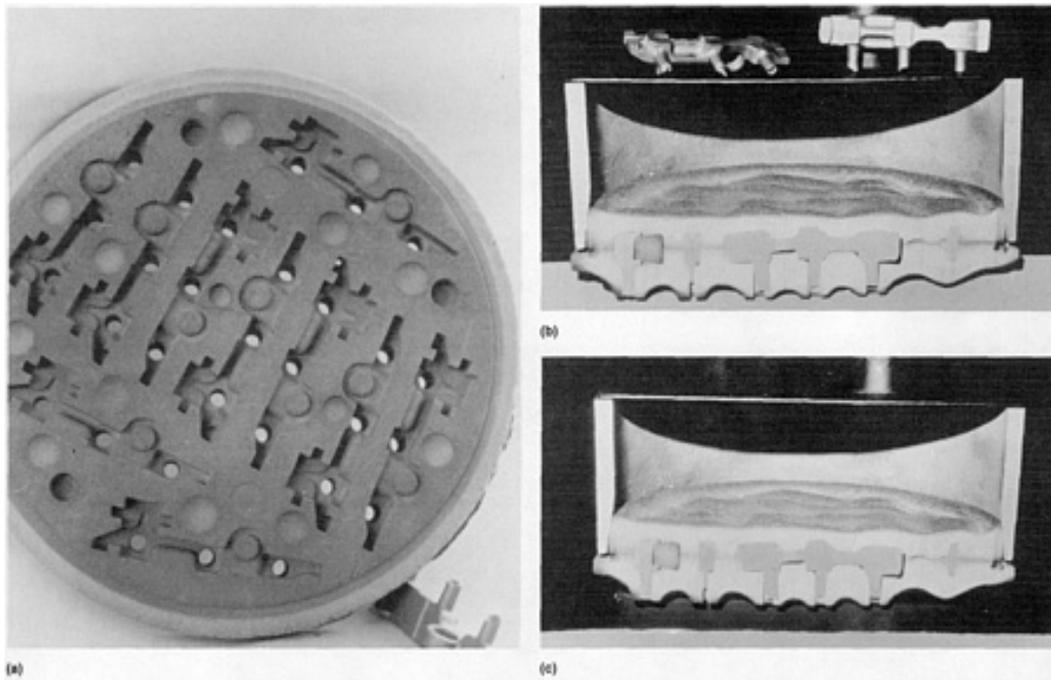


Fig. 4 Essential features of the CLAS process. (a) View of CLAS mold showing high pattern density and open bottom gates. The mold shown uses direct gating into parts. (b) Cross section of mold and casting head during mold filling. (c) Cross section of mold and casting head after solidification. Blind risers can be used for thick-wall castings.

Applications. Connecting rods and thin, hollow cam shafts for automotive use can be made with wall thicknesses of only 1.5 mm (0.06 in.) in steels and cast irons. Stainless steel truck wheel centers that are lighter than aluminum wheels can be made, owing to the thin walls that are possible with this process.

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#### Directional and Monocrystal Solidification

Thomas S. Piwonka, Metal Casting Technology Center, University of Alabama

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## Introduction

Most castings are employed in applications in which stress fields are isotropic, but there are a few important uses in which the stresses are primarily unidirectional along a single axis. In such cases, casting practices that enhance the properties along that axis have been developed. Two of the most widely used methods are directional solidification and monocrystal (single-crystal) casting.

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#### Directional and Monocrystal Solidification

Thomas S. Piwonka, Metal Casting Technology Center, University of Alabama

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## Directional Solidification

The process used to manufacture directionally solidified castings with a columnar structure requires careful control to ensure that castings which are of acceptable quality are produced. Specialized furnaces are used, and mold design is quite different from that used for conventional investment castings.

### *Metallurgical Effects of Columnar Structures*

An important application of directional solidification is in the manufacture of blades (rotating parts) for gas turbine engines (Fig. 1). These components are subjected to high stresses along their major axes, as well as high temperatures. Because grain boundaries are weaker than grains at high temperatures, it is logical to align them parallel to the axis of principal stress to minimize their effect on properties.

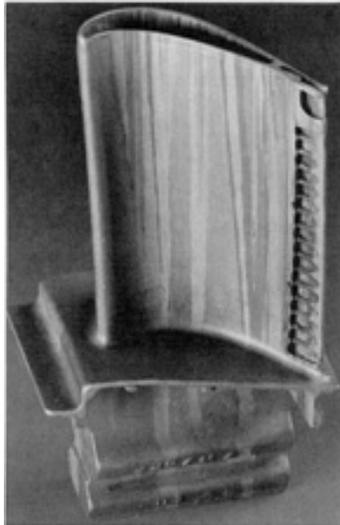
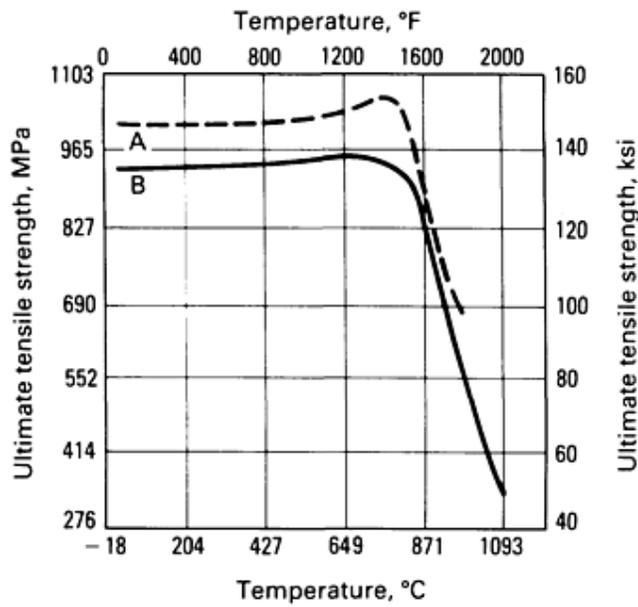
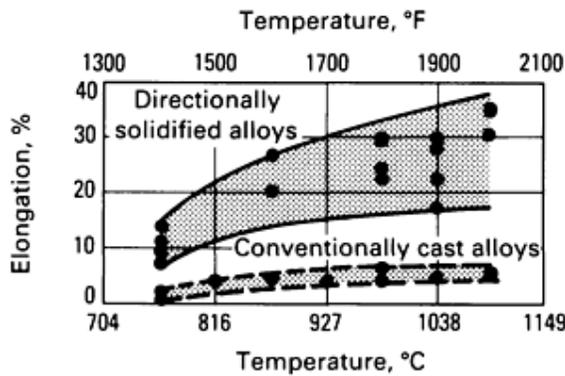


Fig. 1 Directionally solidified thin-wall turbine blade cast from Alloy CM 247 LC (modified MAR M-247 composition)

**Materials.** The alloy that was originally used in directionally solidified turbine components was MAR M-200, a nickel-base alloy containing 12.5% W (Ref 1). The solidified structure consisted of tungsten-rich dendrites with high strength and creep resistance that grew to the length of the casting. The grain-boundary material, which was parallel to the dendrites, was strong enough to withstand the transverse stresses on the components. The properties of the directionally solidified alloy were far superior to those of the equiaxed alloy, as shown in Fig. 2. Other alloys have since been designed to make use of the process.



(a)



(b)

Fig. 2 Comparison of properties of directionally solidified and conventionally cast alloys. (a) Ultimate tensile strength of MAR M-200 alloy. Curve A, directionally solidified; curve B, conventionally cast. Source: Ref 1. (b) Average rupture elongation of various alloys

In columnar structures, the primary dendrites are aligned, as are the grain boundaries. The primary dendrites form around spines of the highest-melting constituent to freeze. As freezing continues, the solid rejects solute into the residual liquid (segregation occurs) until the final low-melting eutectic has frozen at the grain boundaries. Because segregation products collect in the grain boundaries, it is important to consider the composition of these grain boundaries in directional structures.

An ideal composition for directional solidification is one in which the primary dendrites form around a strong spine, while the grain boundaries also retain their strength. A poor alloy is one in which the segregation products form embrittling phases, especially adjacent to secondary dendrite arms, which are normal to the primary stress axis.

### Heat Flow Control

To obtain a directionally solidified structure, it is necessary to cause the dendrites to grow from one end of the casting to the other. This is accomplished by removing the bulk of the heat from one end of the casting. To this end, a strong thermal gradient is established in the temperature zone between the liquidus and solidus temperatures of the alloy and is passed from one end of the casting to the other at a rate that maintains the steady growth of the dendrite, as shown in Fig. 3. If the thermal gradient is moved through the casting too rapidly, nucleation of grains ahead of the solid/liquid interface

will result; if the gradient is passed too slowly, excessive macrosegregation will result, along with the formation of freckles (equiaxed grains of interdendritic composition) (Ref 3). Therefore, the production of directionally solidified castings requires that both the thermal gradient and its rate of travel be controlled. For the case of nickel-base alloys, thermal gradients of 36 to 72 °C/cm (165 to 330 °F/in.) have been found to be effective (Ref 4), and rates of travel of 30 cm/h (12 in./h) can be used. There is, however, no upper limit on the allowable gradient, and higher gradients usually produce better castings than lower gradients. The lower limit on the thermal gradient is a function of alloy composition and casting geometry.

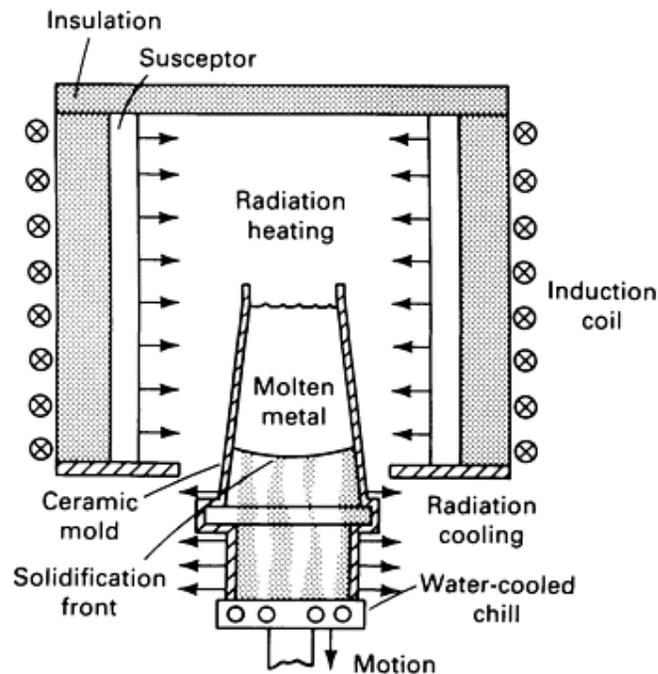


Fig. 3 Schematic showing the directional solidification process. Source: Ref 2

The most effective way to control heat flow is to use a thin-wall mold, such as an investment casting mold, that is open at the bottom. The mold is placed on a chill (which is usually water cooled) and heated above the liquidus temperature of the alloy. Molten metal is poured into the mold, and the mold is cooled from the chilled end by withdrawing the mold from the mold-heating device.

The chill is used to ensure that there is good nucleation of grains to start the process. Because of the low thermal conductivity of nickel-base alloys, the thermal effect of the chill extends only about 50 to 60 mm (2 to 2.4 in.) (Ref 5, 6). Although the grains originally nucleate with random orientations, those with the preferred growth direction normal to the chill surface grow and crowd out the other grains. Therefore, those grains that grow through the casting are all aligned in the direction of easiest growth. For nickel-base alloys, the preferred growth direction is  $\langle 001 \rangle$ ; therefore, in castings made of these alloys, the grains are aligned in the  $\langle 001 \rangle$  direction. Passing the thermal gradient through the casting at a uniform rate ensures that the secondary dendrite arm spacing is uniform throughout the casting (Ref 5).

### *Processing of Directionally Solidified Castings*

In the most common directional solidification process, an investment casting mold, open at the bottom as well as the top, is placed on a water-cooled copper chill and raised into the hot zone of the furnace (Fig. 4). The mold is heated to a temperature above the liquidus temperature of the alloy to be poured. Meanwhile, the alloy is melted (usually under vacuum) in an upper chamber of the furnace. When the mold is at the proper temperature and the charge is molten, the alloy is poured into the mold. After a pause of a few minutes to allow the grains to nucleate and begin to grow on the chill, during which the most favorably oriented grains are established, the mold is withdrawn from the hot zone to the cold zone.

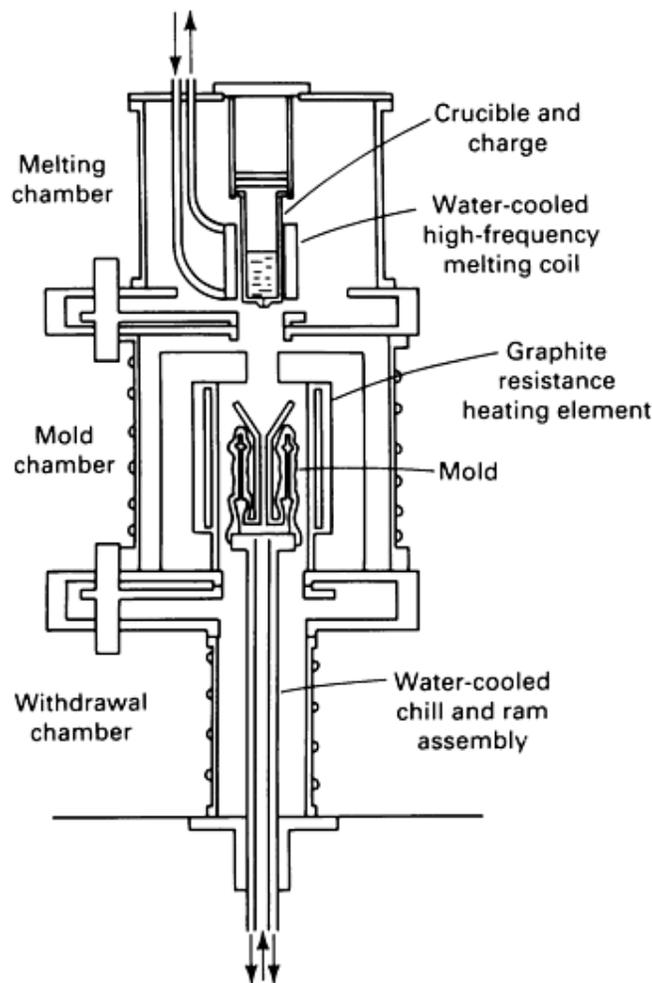


Fig. 4 Configuration of one type of directional solidification furnace. Source: Ref 7

Furnaces. The furnace shown in Fig. 4 has a relatively small chill diameter (140 mm, or 5.5 in.) to enhance the thermal gradient, a resistance-heated hot zone, and an unconventional melting method in which the charge melts through a plate in a bottom-pour crucible instead of being poured. However, other furnace designs use larger chill plates (up to 500 mm, or 20 in.), induction-heated graphite susceptors in their hot zones, and conventional pouring to produce these castings. Additional information on furnaces and other equipment for directional solidification is available in the section "Vacuum Induction Remelting and Shape Casting" in the article "Vacuum Melting and Remelting Processes" in this Volume.

Gating. Castings can be gated either into the top of the mold cavity or the bottom. Bottom gating heats the mold just above the chill and sets up a very high gradient that encourages well-aligned dendrites. Particular care is taken to keep the transition between the hot and cold zones as sharp as possible through the use of radiation baffles made of refractory materials; these baffles are placed at the chill level between the hot and cold zones.

Mold Design. In designing molds for the process, consideration must be given to the orientation of the part on the cluster. Because heat transfer is by radiation, parts must be placed to minimize shadowing. Internal radiation baffles are sometimes added to the mold, particularly around the center downsprue, to distribute radiation energy to those parts of the mold that would otherwise be shadowed, and some furnace designs use a heating source or a cooling baffle around the center downpole (the chill is designed with a circular cutout at its center) to increase the gradient. Because castings solidify directionally, it is possible to stack them on top of each other to increase the number of castings that can be made in each heat.

Process Control. A very high degree of control must be exercised over the process; therefore, the furnaces are highly automated. Completely automated furnaces (which charge, melt, heat the mold, pour, hold, and withdraw according to a programmed cycle) are commonly used, and even in those furnaces in which melting is done manually the solidification (withdrawal) cycle is automated. Thermocouples are placed within the mold cavity on large clusters to ensure that the molds are at the proper temperature before pouring.

Withdrawal rates during solidification are not necessarily constant. Large differences in section size in specific castings change the solidification rate, and the withdrawal rate can be changed to compensate for this. In selecting a solidification cycle for a hollow part, the effect of the core must be included. Cores lengthen the time required to preheat the mold and slow the withdrawal rate because the heat they contain must also be removed in the process.

### *Defects Unique to Directional Solidification*

Directionally solidified castings are routinely inspected by etching their surfaces and examining the surface visually for defects. The most obvious defect is the presence of an equiaxed or misoriented grain. Equiaxed grains are most often freckles, which are caused by segregation of eutectic liquid that is less dense than the bulk liquid in many alloys. This liquid forms jets within the mushy zone, and as these jets freeze they form equiaxed grains. Freckles are usually cured by increasing the thermal gradient and solidification rate in the casting.

Misoriented grains occur when the temperature ahead of the interface falls below the liquidus temperature and new grains nucleate. These grains will have a random orientation, but because they are growing in gradient, they will be columnar. They can be eliminated by increasing the gradient.

Shrinkage is sometimes encountered on the upper surfaces of directionally solidified castings. There is no way to feed these surfaces; the addition of risers to these surfaces usually interferes with radiation heat transfer from another part of the casting. The most common solution is to invert the casting in order to minimize the surface area that is susceptible to shrinkage.

Microporosity may occur in directionally solidified castings if the length of the mushy zone (length of the casting that is between the liquidus and solidus temperatures during solidification) becomes too great for feed metal to reach into the areas where solidification is taking place. Increasing the thermal gradient (which shortens the length of the mushy zone) usually solves this problem.

Mold or Core Distortion. A frequent cause of scrap in directionally solidified castings results from mold or core distortion. Because the mold and core are held at high temperatures for long times while the casting solidifies, it is possible for the mold or core to sag or to undergo local allotropic transformations of the refractory materials from which they are made. The resulting changes in mold or core dimensions are reflected in the casting dimensions. Careful control of the core and mold composition, their uniformity, and the firing conditions under which they are made is required in order to avoid these dimensional problems.

### *Other Directional Solidification Methods*

The process described above is the most widely used method of producing directionally solidified castings. However, other methods can be used as well. For example, instead of using electrical means to heat the mold before pouring, the mold can be invested with an exothermic material (Ref 8). When ignited, the material burns in the classic thermit reaction, heating the mold to a temperature above the liquidus of the alloy. The mold and hot exothermic material are placed on a water-cooled copper chill, and the alloy is poured. Both the exothermic material and the metal are cooled by the chill, thus causing solidification to proceed directionally. This process is limited by the properties of the exothermic mixture, and it is most useful for small solid parts. It can also be used in sand molds, for which the grain size and alignment specifications are not as stringent as they are for aerospace castings.

A variation on the mold withdrawal method described above, which is used when very high thermal gradients are desired (as in the production of directionally solidified eutectic alloys), is the liquid metal cooling process (Ref 9). In this method, the mold is immersed in a bath of a liquid metal, such as tin. Heat is removed from the mold by conduction; in addition, the liquid metal bath is an extremely efficient baffle for the radiation in the hot zone.

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## Directional and Monocrystal Solidification

Thomas S. Piwonka, Metal Casting Technology Center, University of Alabama

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### Monocrystal Casting

It was early recognized that if columnar-grain castings could be produced, the production of castings that contained only a single crystal (more accurately, a single grain or primary dendrite) could be produced by suppressing all but one of the columnar grains (Ref 10). Such a casting is compared with equiaxed and directionally solidified castings in Fig. 5. The fact that the castings consisted of a single crystal removed the limitations on transverse strength imposed by the grain boundaries, but overall properties were only slightly improved.

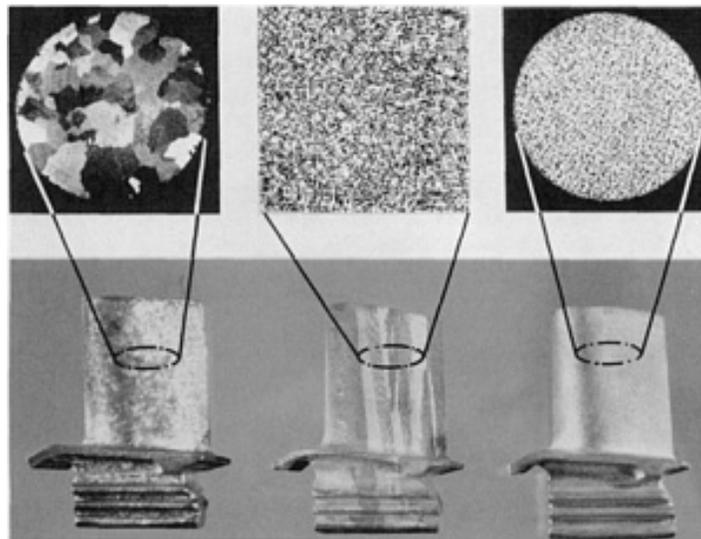


Fig. 5 Comparison of microstructures in (from left) equiaxed, directionally solidified, and single-crystal blades. Courtesy of P.R. Sahm, Giesserei-Institut der RWTH (West Germany)

### *Metallurgy of Monocrystal Casting*

Many alloys contain elements added as grain-boundary strengtheners. These elements lower the incipient melting temperature and therefore limit the temperature at which the alloys can be solutionized.

After it was recognized that alloys having no grain boundaries need no grain-boundary strengtheners, and therefore can be solutionized at higher temperatures, development of high-temperature nickel-base monocrystal alloys began in earnest (Ref 2, 11, 12). These alloys have better high-temperature properties than conventionally cast or directionally solidified alloys because they can precipitate a higher percentage of the  $\gamma'$  strengthening phase (Fig. 6). In addition, because they have no grain boundaries, monocrystal alloys have improved corrosion resistance (Fig. 7).

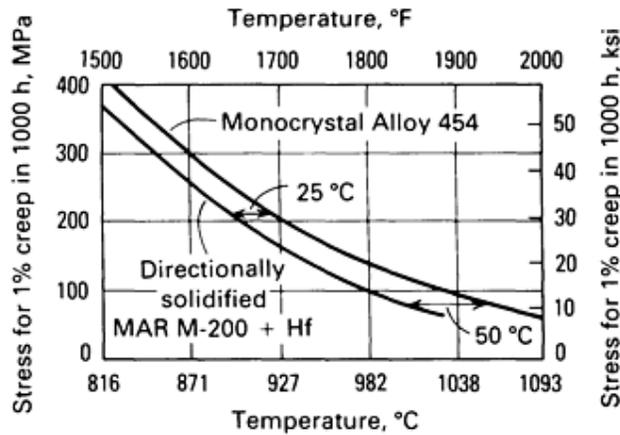


Fig. 6 Creep strength of monocrystal Alloy 454 compared with that of directionally solidified MAR M-200 + Hf. Source: Ref 2

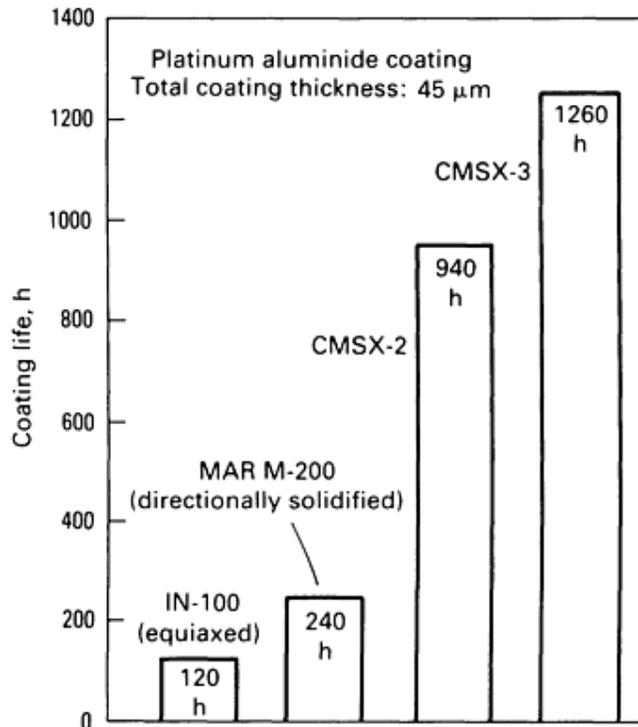


Fig. 7 Effect of grain structure on coating life in hot corrosion testing. Test consisted of exposure to hot salt at 850 °C (1562 °F) and oxidizing atmosphere at 1000 °C (1832 °F). Source: Ref 11

Applications of monocrystal castings must take into consideration the fact that many alloy systems are anisotropic; that is, their properties vary with crystallographic orientation, as shown in Fig. 8. This means that designers must design with this

in mind and that castings must be produced with specific orientations (a tolerance of  $\pm 5^\circ$  of the required orientation is often specified). Further, orientation control may be required in more than one crystallographic direction.

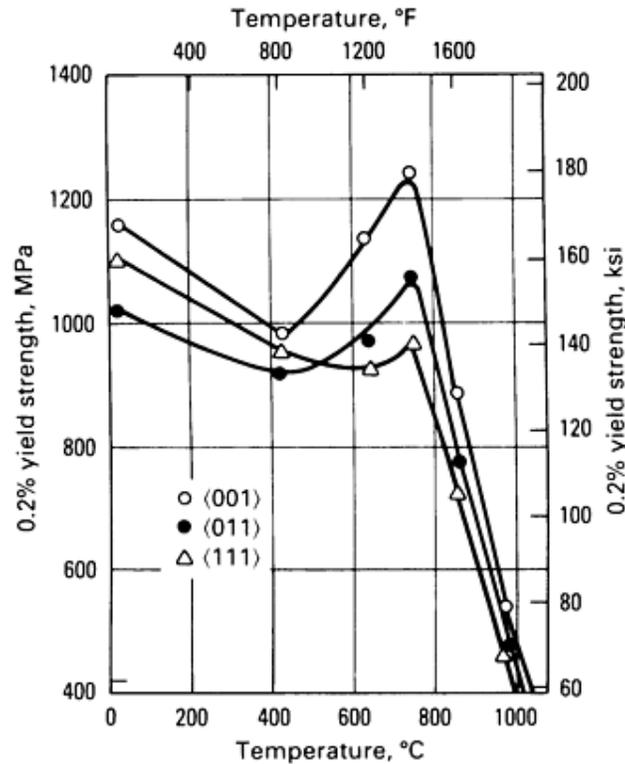


Fig. 8 Yield strength of monocrystal PWA 1480 alloy as a function of temperature and orientation. Source: Ref 13

### Monocrystal Casting Processing

Monocrystal castings are produced using techniques similar to those used for directionally solidified castings, with one important difference: A method of selecting a single, properly oriented grain is required. Three methods are most commonly used, as shown in Fig. 9.

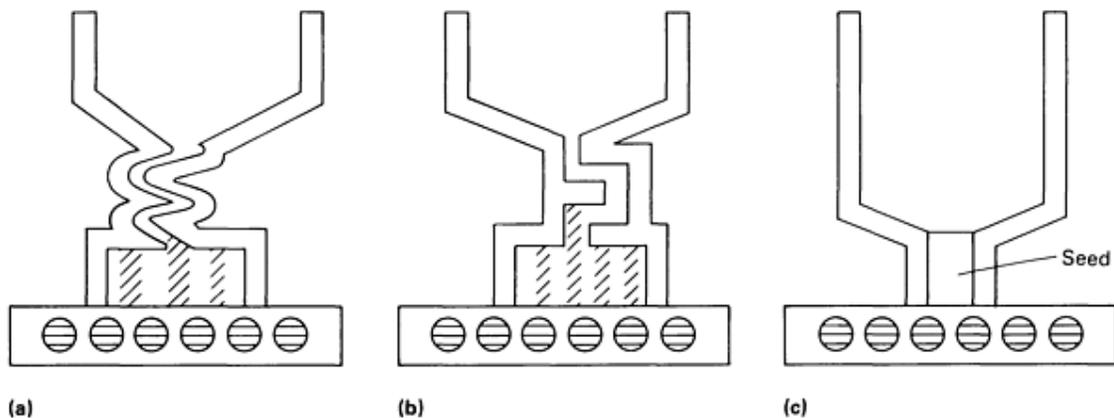


Fig. 9 Three methods of producing monocrystal castings. (a) Use of a helical mold section. (b) Use of a right-angle mold section. (c) Seeding. Source: Ref 14

Helical Mold Sections. In the first method, a helical section of mold is placed between the chill and the casting. Only the most favorably oriented grains are able to grow through this helix because all others are intercepted by the helix wall. Eventually, only one grain is left to emerge from the helix to form the casting. In this method, only the primary orientation of growth can be controlled, and it will be the preferred growth direction ( $\langle 001 \rangle$ ) for nickel-base alloys.

Right-Angle Mold Sections. The second method uses a series of right-angle bends in the helix. Because growth takes place along the preferred growth direction in each of the arms of the selector, the grain that emerges tends to be doubly oriented. If an orientation other than the preferred growth direction is desired, the casting can be tilted on the selector.

Seeding, the third method, is particularly useful for an orientation other than the preferred growth direction. Use of seeding requires that the seeds be prepared and placed in the mold before the casting is poured.

Molds. Because monocrystal alloys have higher incipient melting temperatures than conventional alloys, mold preheat temperatures will normally be higher for their manufacture than for columnar-grain castings. Therefore, mold composition control is of particular importance in the production of these castings.

Testing and Inspection. In addition to surface etching, monocrystal castings are inspected by using back reflection Laue techniques to determine crystallographic orientation. Defects in monocrystal castings are usually the same as those found in columnar castings, and remedial actions are also generally the same. Some monocrystal alloys are susceptible to local recrystallization from rough handling or solidification-induced strains and must be given a stress-relief heat treatment before solution heat treatment.

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#### Directional and Monocrystal Solidification

Thomas S. Piwonka, Metal Casting Technology Center, University of Alabama

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## Squeeze Casting

J.L. Dorcic and S.K. Verma, IIT Research Institute

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## Introduction

Squeeze casting, also known as liquid-metal forging, is a process by which molten metal solidifies under pressure within closed dies positioned between the plates of a hydraulic press. The applied pressure and the instant contact of the molten metal with the die surface produce a rapid heat transfer condition that yields a pore-free fine-grain casting with mechanical properties approaching those of a wrought product.

The squeeze casting process is easily automated to produce near-net to net shape high-quality components. The process was introduced in the United States in 1960 and has since gained widespread acceptance within the nonferrous casting industry. Aluminum, magnesium, and copper alloy components are readily manufactured using this process. Several ferrous components with relatively simple geometry--for example, nickel hard-crusher wheel inserts--have also been manufactured by the squeeze casting process. Despite the shorter die life for complex ferrous castings requiring sharp corners within the die or punch (tooling), the process can be adopted for products where better properties and/or savings in labor or material costs are desired.

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## Advantages of Squeeze Casting (Ref 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11)

With the current emphasis on reducing materials consumption through virtually net shape processing and the demand for higher-strength parts for weight savings, the emergence of squeeze casting as a production process has given materials and process engineers a new alternative to the traditional approaches of casting and forging. By pressurizing liquid metals while they solidify, near-net shapes can be achieved in sound, fully dense castings.

The near-net and net shape capabilities of this manufacturing process are key advantages. Tolerances of  $\pm 0.05$  mm ( $\pm 0.002$  in.) are not uncommon for nonferrous castings, with yields of 100% in a number of applications. Improved mechanical properties are additional advantages of squeeze cast parts.

Squeeze casting has been successfully applied to a variety of ferrous and nonferrous alloys in traditionally cast and wrought compositions. Applications include aluminum alloy pistons for engines and disk brakes; automotive wheels, truck hubs, barrel heads, and hubbed flanges; brass and bronze bushings and gears; steel missile components and differential pinion gears; and a number of parts in cast iron, including ductile iron mortar shells.

Squeeze casting is simple and economical, efficient in its use of raw material, and has excellent potential for automated operation at high rates of production. The process generates the highest mechanical properties attainable in a cast product. The microstructural refinement and integrity of squeeze cast products are desirable for many critical applications.

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J.L. Dorcic and S.K. Verma, IIT Research Institute

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## Process Description (Ref 1, 2, 3)

As shown in Fig. 1, squeeze casting consists of metering liquid metal into a preheated, lubricated die and forging the metal while it solidifies. The load is applied shortly after the metal begins to freeze and is maintained until the entire casting has solidified. Casting ejection and handling are done in much the same way as in closed die forging.

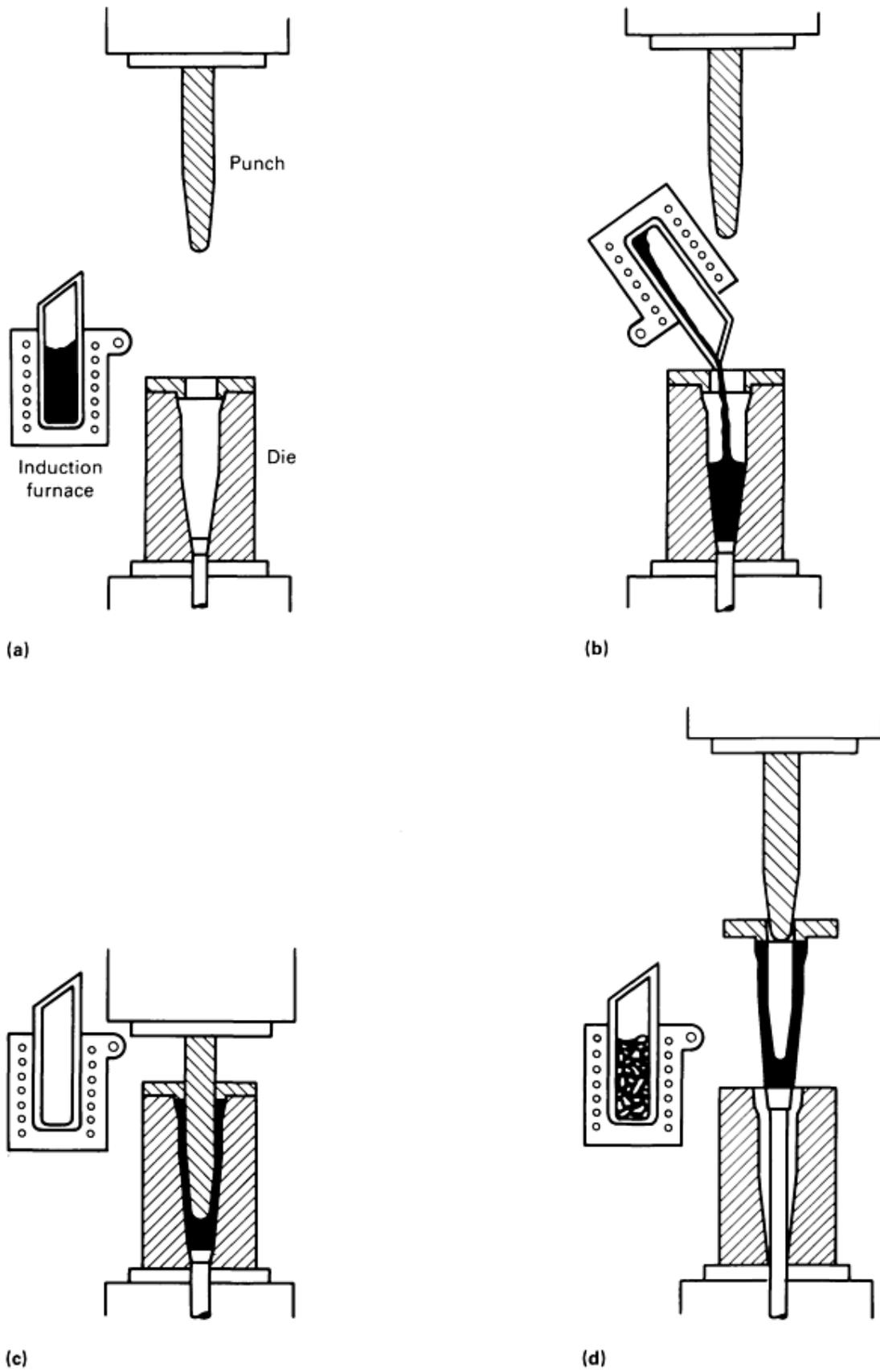


Fig. 1 Schematic illustrating squeeze casting process operations. (a) Melt charge, preheat, and lubricate

tooling. (b) Transfer melt into die cavity. (c) Close tooling, solidify melt under pressure. (d) Eject casting, clean dies, charge melt stock

The high pressure applied (typically 55 to 100 MPa, or 8 to 15 ksi) is enough to suppress gas porosity except in extreme cases, for which standard degassing treatments are used. The tendency toward shrinkage porosity is limited by using a bare minimum of superheat in the melt during pouring. This is possible in squeeze casting because melt fluidity, which requires high pouring temperatures, is not necessary for die fill, the latter being readily achieved by the high pressure applied. In heavy sections of the casting, which are particularly prone to the incidence of shrinkage porosity, the applied pressure squirts liquid or semiliquid metal from hot spots into incipient shrinkage pores to prevent pores from forming. Alloys with wide freezing ranges accommodate this form of melt movement very well, resulting in sound castings with a minimum of applied pressure.

The squeeze casting cycle starts with the transfer of a metered quantity of molten metal into the bottom half of a preheated die set mounted in a hydraulic press (Fig. 1). The dies are then closed, and this fills the die cavity with molten metal and applies pressures of up to 140 MPa (20 ksi) on the solidifying casting.

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## Process Variables

There are a number of variables that are generally controlled for the soundness and quality of the castings. The variable ranges discussed in the following sections vary with the alloy system and part geometry being squeeze cast.

**Melt Volume.** Precision control of the metal volume is required when filling the die cavity. This ensures dimensional control.

Casting temperatures depend on the alloy and the part geometry. The starting point is normally 6 to 55 °C (10 to 100 °F) above the liquidus temperature.

Tooling temperatures ranging from 190 to 315 °C (375 to 600 °F) are normally used. The lower range is more suitable for thick-section casting. The punch temperature is kept 15 to 30 °C (25 to 50 °F) below the lower die temperature to maintain sufficient clearance between them for adequate venting. Excess punch-to-die clearance allows molten metal to be extruded between them, eroding the surface.

Time delay is the duration between the actual pouring of the metal and the instant the punch contacts the molten pool and starts the pressurization of thin webs that are incorporated into the die cavity. Because increased pouring temperatures may be required to fill these sections adequately upon pouring, a time delay will allow for cooling of the molten pool before closing of the dies to avoid shrink porosity.

Pressure levels of 50 to 140 MPa (7.5 to 20 ksi) are normally used; 70 MPa (10 ksi) is generally applied, depending on part geometry and the required mechanical properties. There is an optimum pressure for each of the systems after which no added advantages in mechanical properties are obtained.

Pressure duration varying from 30 to 120 s has been found to be satisfactory for castings weighing 9 kg (20 lb). However, the pressure duration is again dependent on part geometry. Applied pressure after composite solidification and temperature equalization will not contribute any property enhancements and will only increase cycle times.

Lubrication. For aluminum, magnesium, and copper alloys, a good grade of colloidal graphite spray lubricant has proved satisfactory when sprayed on the warm dies prior to casting. Care should be taken to avoid excess buildup on narrow webs and fin areas where vent holes or slots are used. Care must also be taken to prevent plugging of these vents. For ferrous castings, ceramic-type coatings are required to prevent welding between the casting and the metal die surfaces.

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J.L. Dorcic and S.K. Verma, IIT Research Institute

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## Quality Control

In general, the process parameters are optimized for each component geometry to be squeeze cast. Maintaining established optimized parameters is critical to the quality and reproducibility of the squeeze cast components. Failure to do so can result in one or more of the following defects.

- Oxide inclusions
- Porosity
- Extrusion segregation
- Centerline segregation
- Blistering
- Cold laps
- Hot tearing
- Sticking
- Case debonding
- Extrusion debonding

The root causes of these defects, as well as methods for their control, are described below.

Oxide inclusions result from the failure to maintain clean melt-handling and melt-transfer systems. To minimize the likelihood of introducing metallic inclusions, filters should be included within the melt-transfer system, or molten metal turbulence should be minimized when filling the die cavity. Preventing foreign objects from entering open dies is also helpful.

Porosity and voids can occur when insufficient pressure is applied during squeeze casting operations. A general rule of thumb is to apply a pressure of 70 MPa (10 ksi), although sound castings have been produced with pressures as low as 50 MPa (7.5 ksi). Porosity and/or voids are usually eliminated by increasing the casting pressure when the other variables are optimized.

Extrusion Segregation. The relative microsegregation that occurs in squeeze cast components is much less than that in other cast components. However, the regions filled by back extrusion are rich in solute; these areas are the last to solidify within a casting. The extrusion segregation can lead to local variations in mechanical and corrosion properties. Such defects can be avoided by designing dies properly, by using a multiple gate system, by increasing die temperature, or by decreasing delay time before die closure.

Centerline segregation is a defect that is normally encountered with high-alloy wrought aluminum alloys at lower solute temperatures. As solidification begins on the die walls, the liquid phase becomes more concentrated with the lower-melting solute, which is trapped within the center areas of the extruded projections or more massive areas of the casting.

Such defects are avoided by increasing die temperature, by minimizing die closure time, or by selecting an alternative alloy.

**Blistering.** Air or gas from the melt that is trapped below the surface during turbulent die filling forms blisters on the cast surface upon the release of pressure or during subsequent solution heat treatments. Methods of avoiding such defects include degassing the melt and preheating the handling transfer equipment, using a slower die closing speed, increasing the die and punch venting, and reducing the pouring temperature.

**Cold laps** are caused by molten metal overlapping previously solidified layers, with incomplete bonding between the two. To alleviate cold laps, it is necessary to increase the pouring temperature or the die temperature. Reducing the die closure time has also been found to be beneficial.

**Hot tearing** takes place in alloys that have an extended freezing range (for example, off eutectic composition). When solid and liquid coexist over a wide range of temperatures, contraction of the solid around the rigid mold surface can initiate rupture in partially solidified regions. The methods used to avoid hot tearing in squeeze cast products include reducing the pouring temperature, reducing the die temperature, increasing the pressurization time, and increasing the draft angles on the casting.

**Sticking.** A thin layer of casting skin adheres to the die surface because of rapid cycling of the process without sufficient die/punch cooling and lubrication. To avoid sticking, it is recommended to decrease die temperature or pouring temperature.

**Case debonding** is found only in high-silicon alloys when an extremely fine-grain case 0.51 to 2.0 mm (0.020 to 0.080 in.) thick is formed on the surface and peels off during subsequent machining or cleaning operations. It is caused by extreme chilling of the outer skin of the casting against a cold punch or die. This problem can be overcome by increasing the tooling temperature or the pouring temperature. Decreasing the die closure time may also help eliminate case bonding.

**Extrusion debonding** takes place when the casting has deeply extruded details and the metal remains in the open die for a long period of time before it is extruded to fill the die cavity. The oxide present on the partially solidified crust in the die remains there after the melt has been extruded around it, resulting in the absence of a metal-to-metal bond at oxide stringer locations. Extrusion debonding can be prevented by increasing the tooling temperature or the pouring temperature. Decreasing the die closure time can reduce the oxide formation on the semi-liquid metal present in the die.

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## Microstructure (Ref 1, 2, 3, 4, 5, 6)

In addition to the densification achieved, there are several reasons why squeeze casting produces castings with superior properties. Even moderately applied pressure causes intimate contact between the solidifying casting and the die for a tenfold increase in heat transfer rate over permanent mold casting. This results in relatively fine grains in the casting. Fine grain size is also promoted by the large number of nuclei formed because of the low casting temperature and the elevated pressure. Furthermore, because die filling in squeeze casting does not require high melt fluidity, a number of wrought alloys can be squeeze cast. Again, pressurized solidification with rapid heat transfer tends to minimize the segregation that wrought alloys are usually prone to. As indicated in Table 1, the tensile properties of ferrous and nonferrous materials produced by squeeze casting are generally comparable to those of forgings.

**Table 1 Comparative properties of commercial wrought and cast alloys**

Alloy	Process	Tensile strength		Yield strength		Elongation, %
		MPa	ksi	MPa	ksi	

356-T6 aluminum	Squeeze casting	309	44.8	265	38.5	<b>3</b>
	Permanent mold	262	38.0	186	27.0	<b>5</b>
	Sand casting	172	25.0	138	20.0	<b>2</b>
535 aluminum (quenched)	Squeeze casting	312	45.2	152	22.1	<b>34.2</b>
	Permanent mold	194	28.2	128	18.6	<b>7</b>
6061-T6 aluminum	Squeeze casting	292	42.3	268	38.8	<b>10</b>
	Forging	262	38.0	241	35.0	<b>10</b>
A356 T4 aluminum <sup>(a)</sup>	Squeeze casting	265	38.4	179	25.9	<b>20</b>
A206 T4 aluminum <sup>(a)</sup>	Squeeze casting	390	56.5	236	34.2	<b>24</b>
CDA 377 forging brass	Squeeze casting	379	55.0	193	28.0	<b>32.0</b>
	Extrusion	379	55.0	145	21.0	<b>48.0</b>
CDA 624 aluminum bronze	Squeeze casting	783	113.5	365	53.0	<b>13.5</b>
	Forging	703	102.0	345	50.0	<b>15.0</b>
CDA 925 leaded tin bronze	Squeeze casting	382	55.4	245	35.6	<b>19.2</b>
	Sand casting	306	44.4	182	26.4	<b>16.5</b>
Type 357 (annealed)	Squeeze casting	614	89.0	303	44.0	<b>46</b>
	Sand casting	400	58.0	241	35.0	<b>20</b>
	Extrusion	621	90.0	241	35.0	<b>50</b>
Type 321 (heat treated)	Squeeze casting	1063	154.2	889	129.0	<b>15</b>
	<b>Forging</b>	<b>1077</b>	<b>156.2</b>	<b>783</b>	<b>113.6</b>	<b>7</b>

Source: Ref 3, 7, 10

(a) Added as additional reference information only.

In a recent investigation, a side-by-side comparison was made between squeeze casting and permanent mold casting for E-132 aluminum components. As seen in Fig. 2, the squeeze casting is sounder and has a pore-free, fine-grain, nearly equiaxed microstructure as compared to that of the permanent mold casting. In particular, a thin case, which is characterized by an unusually fine cast structure, forms to 2.0 mm (0.080 in.) below the punch. This is caused by a combination of high pressure (resulting in undercooling and a greater number of nucleation sites) and rapid heat extraction into the punch. In practice, squeeze castings made with a  $\pm 0.76$  mm ( $\pm 0.030$  in.) tolerance on the as-cast head location can be machined to the finished tolerances and still retain more than 0.51 mm (0.020 in.) of the ultrafine-grain case.

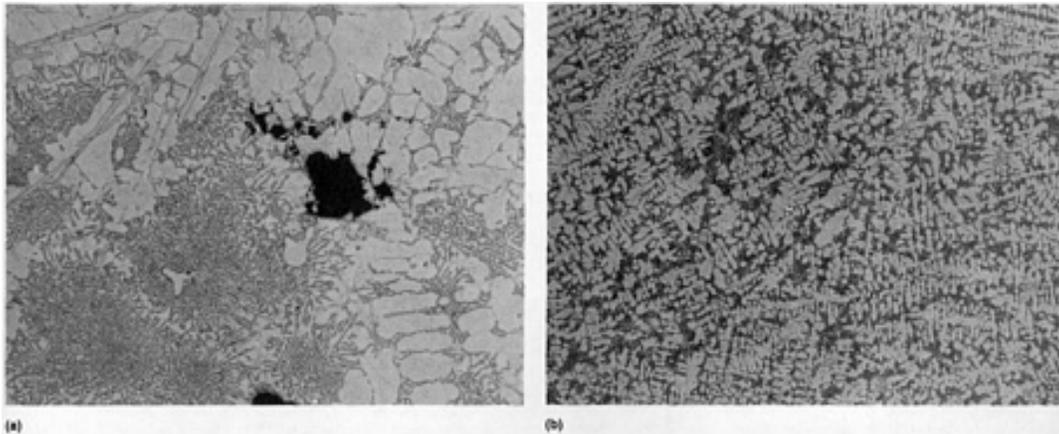


Fig. 2 Comparison of permanent mold cast (a) and squeeze cast (b) E-132 aluminum near the edge in contact with the punch. The microstructure shown in (a) is coarse dendritic; that in (b) is preferred ultrafine dendritic. Both 80 $\times$

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#### Squeeze Casting

J.L. Dorcic and S.K. Verma, IIT Research Institute

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## Product Applications

The squeeze casting process has been explored for a number of applications using various metals and alloys. The parts shown in Fig. 3 include an aluminum dome, a ductile iron mortar shell, and a steel bevel gear. Other parts that have been squeeze cast include stainless steel blades, superalloy disks, aluminum automotive wheels and pistons, and gear blanks made of brass and bronze. Recently, this process has also been adopted to make composite materials at an affordable cost (see the article "Cast Metal-Matrix Composites" in this Volume). A porous ceramic preform is placed in the preheated die, which is later filled with the liquid metal; pressure is then applied. The pressure, in this case, helps the liquid metal infiltrate the porous ceramic preform, giving a sound metal ceramic composite. The technological breakthrough of manufacturing metal-ceramic composites, along with the ability to make complex parts by a near-net shape squeeze casting process, suggests that this process will find application where cost considerations and physical properties of alloys are key factors.



Fig. 3 Typical ferrous and nonferrous parts produced by squeeze casting. Dome in center measures 423 mm (16.5 in.) in outside diameter and weighs 29.5 kg (65 lb). Courtesy of IIT Research Institute

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### Squeeze Casting

J.L. Dorcic and S.K. Verma, IIT Research Institute

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## Semisolid Metal Casting and Forging

Malachi P. Kenney, James A. Courtois, Robert D. Evans, Gilbert M. Farrior, Curtis P. Kyonka, and Alan A. Koch, ALUMAX Engineered Metal Processes, Inc.; Kenneth P. Young, AMAX Research & Development Center

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## Introduction

Semisolid metalworking, also known as semisolid forming, is a hybrid manufacturing method that incorporates elements of both casting and forging. It was based on a discovery made at the Massachusetts Institute of Technology (MIT) in the early 1970s. Processes based on the discovery were identified by MIT as rheocasting, thixocasting, or stir casting (Ref 1). Today it is a two-step process for the near-net shape forming of metal parts using a semisolid raw material that incorporates a unique nondendritic microstructure (Fig. 1).

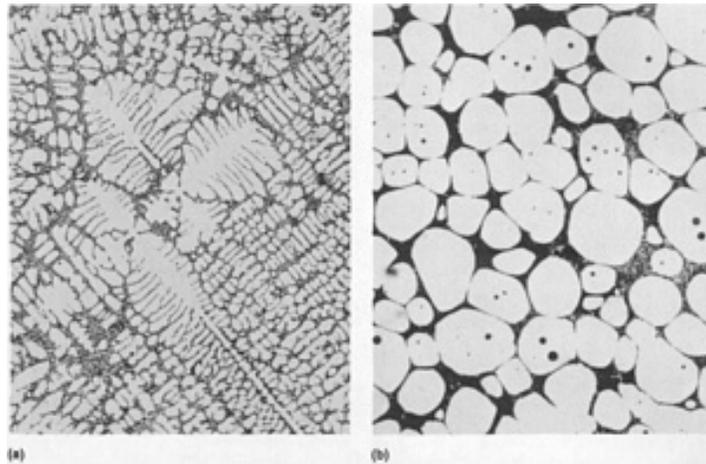


Fig. 1 Comparison of dendritic conventionally cast (a) and nondendritic semisolid formed (b) microstructures of aluminum alloy 357 (Al-7Si-0.5Mg). Both 200 $\times$

The key to the process is shown in Fig. 2, in which the semisolid slug has been cut with a spatula while free standing (that is, without containers), thus demonstrating the thixotropic nature of the material. The thixotropic properties permit the material to be handled by robotic devices in the semisolid condition, allowing process automation and precision controls while increasing productivity.



Fig. 2 Semisolid aluminum billet being cut by a spatula

The major commercial semisolid metalworking activity is in the semisolid forging of a variety of aluminum alloy parts for military, aerospace, and automotive applications. In addition, there is moderate copper alloy production for electrical and fluid-handling use. Further, semisolid metalworking technology has been demonstrated to be applicable to most engineering alloy families, including zinc (Ref 2), magnesium (Ref 3), copper (Ref 4), ferrous (Ref 5), titanium (Ref 6), and superalloys (Ref 7).

The unique nondendritic microstructure and the initial processes are protected by a series of patents that began with awards to M.C. Flemings and associates at MIT in the 1970s and has continued with awards to a number of individuals and organizations. A number of corporations have investigated and tested the MIT processes. Universities in Great Britain, Europe, and the United States have also conducted studies in the technology. Along with MIT, these include Delaware and Virginia (USA), Sheffield (Great Britain), and Aachen (West Germany), which have been studying the applications to high-temperature alloys for a number of years. The patent list continues to grow as the technology broadens its application in the emerging field of metal-matrix composites, in which semisolid metalworking has been a key process since the early 1970s (see the article "Cast Metal-Matrix Composites" in this Volume).

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## Background

**Basic Discovery.** Semisolid metal forming is based on a discovery made during research on hot tearing undertaken at MIT in the early 1970s. Seeking to understand the magnitude of the forces involved in deforming and fragmenting dendritic growth structures, MIT researchers constructed a high-temperature viscometer. They poured model lead-tin alloys into the annular space created by two concentric cylinders and measured the forces transmitted through the freezing alloy when the outer cylinder was rotated. During the course of these experiments, it was discovered that when the outer cylinder was continuously rotated the semisolid alloy exhibited remarkably low shear strength even at relatively high fractions solidified. This unique property was attributed to a novel nondendritic (that is, spheroidal) microstructure.

The research expanded, and the MIT engineers coined the term rheocasting to describe the process of producing this unique microstructure (a schematic of the rheocast process is shown in Fig. 5 of the article "Classification of Processes and Flow Chart of Foundry Operations" in this Volume) (Ref 5). They showed that sheared and partially solidified alloys could be assigned an apparent viscosity and that they possess many of the characteristics of thixotropy (Fig. 3). Most notably, the semisolid alloys displayed viscosities that depended on shear rate and that rose to several hundred, even thousands, of poise (approaching the consistency of table butter) when at rest and yet decreased to less than 5.0 Pa s or 50 P (poise) (the range of machine oils) upon vigorous agitation or shearing. For the first time, therefore, these results afforded an opportunity to control the viscosity of alloy melts from that of fully liquid to any desired upper limit.

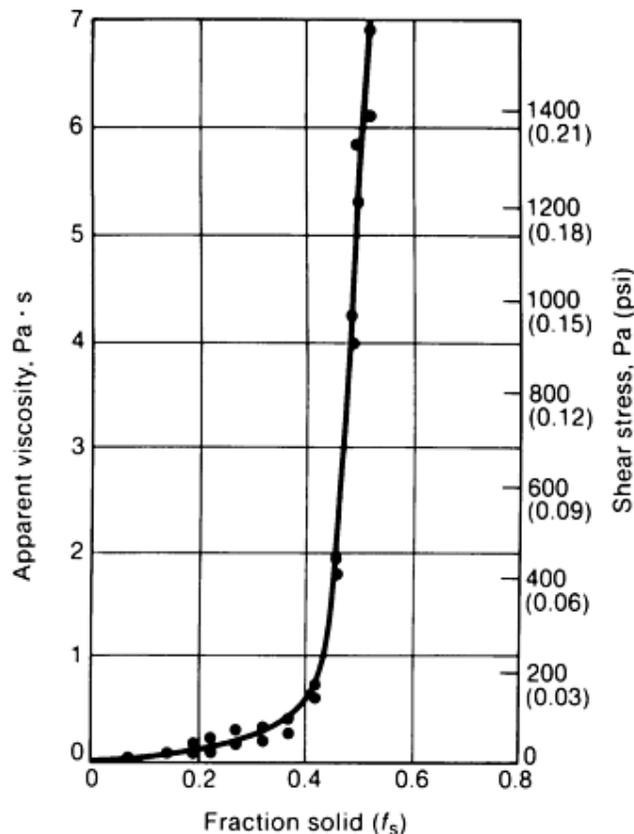


Fig. 3 Apparent viscosity and shear stress of model Sn-15Pb semisolid melts as a function of fraction solid at constant shear rate. Source: Ref 13

Potential Benefits. The MIT researchers were quick to identify several potential benefits that could result from forming processes utilizing semisolid metal and that would differentiate these processes from conventional casting (Ref 8). First, and particularly significant for higher-melting alloys, semisolid metalworking afforded lower operating temperatures and reduced metal heat content (reduced enthalpy of fusion). Second, the viscous flow behavior could provide for a more laminar cavity fill than could generally be achieved with liquid alloys. This could lead to reduced gas entrapment. Third, solidification shrinkage would be reduced in direct proportion to the fraction solidified within the semisolid metalworking alloy, which should reduce both shrinkage porosity and the tendency toward hot tearing.

In addition, the MIT team showed that the viscous nature of semisolid alloys provided a natural environment for the incorporation of third-phase particles in the preparation of particulate-reinforced metal-matrix composites (Ref 9). Here the enhanced viscosity of semisolid metalworking alloys would serve to entrap the reinforcement material physically, allowing time to develop good bonding between the reinforcement and the matrix alloy.

As these ideas unfolded, research into the nature of semisolid alloys progressed, and it became apparent that bars could be cast from semisolid fluids possessing the rheocast nondendritic microstructure. The final freezing of these bars captures this microstructure. The bars then represented a raw material that could be heated at a later time or a remote location to the semisolid temperature range to reclaim the special rheological characteristics.

This process, using semisolid alloys heated from specially cast bars, was termed thixocasting by the MIT inventors (Ref 10). This distinguished it from rheocasting, which has come to be known as the process used for producing semisolid structures and/or forming parts from slurry without an intermediate freezing step.

The efforts at MIT to continue the development of semisolid metalworking were supported by the U.S. government under the Advanced Research Projects Agency and the Defense Advanced Research Projects Agency. This work was directed to a machine casting process for ferrous alloys. Thousands of ferrous components were successfully formed using semisolid metalworking ingots as part of these programs.

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## Semisolid Metal Casting and Forging

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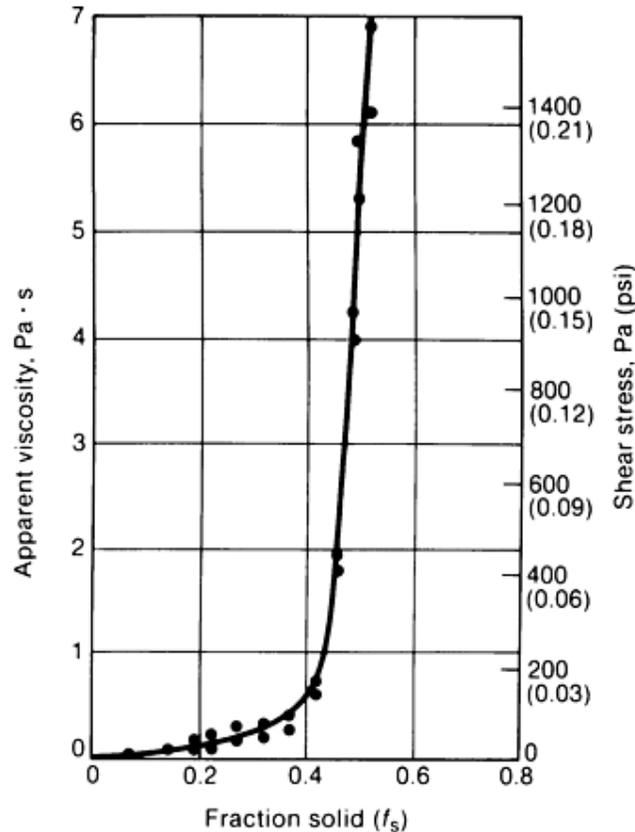


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### Semisolid Forging Applications

The advantages of semisolid forging have enabled it to compete effectively with a variety of conventional processes in a number of different applications. In this section, a number of automotive, aerospace, and industrial applications of semisolid forged parts are outlined with data on alloys, yield, production rates, mechanical properties, and performance requirements. Figure 10 shows a complex high-pressure hydraulic brake valve typical of applications for semisolid forged components.



Fig. 10 Semisolid forged hydraulic brake valve

Semisolid forged parts have replaced conventional forgings, permanent mold and investment castings, impact extrusions, machined extrusion profiles, parts produced on screw machines, and, in unusual circumstances, die castings and stampings. Applications include automobile wheels, master brake cylinders, antilock brake valves, disk brake calipers, power steering pump housings, power steering pinion valve housings, engine pistons, compressor housings, steering

column mechanical components, airbag containment housings, power brake proportioning valves, electrical connectors, and various covers and housings that require leak-tight integrity. Table 1 lists mechanical properties of selected aluminum alloys used in these components.

**Table 1 Mechanical properties of typical semisolid forged aluminum parts**

Aluminum alloy	Mechanical properties						
	Temper	Ultimate tensile strength		Tensile yield strength		Elongation, %	Hardness, HB
		MPa	ksi	MPa	ksi		
206	T7	386	56.0	317	46.0	6.0	<b>103</b>
2017	T4	386	56.0	276	40.0	8.8	<b>89</b>
2219	T8	352	51.0	310	45.0	5.0	<b>89</b>
6061	T6	330	47.8	290	42.1	8.2	<b>104</b>
6262	T6	365	52.9	330	47.9	10.0	<b>82</b>
7075	T6	496	72.0	421	61.0	7.0	<b>135</b>
356	T5	234	34.0	172	25.0	11.0	<b>89</b>
356	T6	296	43.0	193	28.0	12.0	<b>90</b>
357	T5	296	43.0	207	30.0	11.0	<b>90</b>

Reproducible high integrity is a key in this diversity, but this could be offset by the higher cost of the raw material--MHD billets. The near-net shape ability of the process reduces both the weight required and the machining time. When the higher production rate is added to these other advantages, the process becomes cost-effective for many applications.

#### Example 1: Aluminum Automobile Wheels.

Aluminum automobile wheels (Fig. 11) have been produced by permanent mold casting (gravity and low pressure), squeeze casting, and fabrications of castings or stampings welded to rolled rims. Semisolid forging is a more recent process. Table 2 compares the characteristics of aluminum automobile wheels produced by semisolid forging and permanent mold casting. In addition to an economic advantage, semisolid forging offers other advantages that will be discussed below.

**Table 2 Comparison of semisolid forging and permanent mold casting for the production of aluminum automobile wheels**

See Example 1.

Process	Characteristic											
	Weight direct from die or mold		Finished part weight		Production rate per die or mold, pieces per hour	Aluminum alloy	Heat treatment	Ultimate tensile strength		Yield strength		Elongation, %
	kg	lb	kg	lb				MPa	ksi	MPa	ksi	
Semisolid forging	7.5	16.5	6.1	13.5	90	357	T5	290	42	214	31	<b>10</b>
<b>Permanent mold</b>	<b>11.1</b>	<b>24.5</b>	<b>8.6</b>	<b>19.0</b>	<b>12</b>	<b>356</b>	<b>T6</b>	<b>221</b>	<b>32</b>	<b>152</b>	<b>22</b>	<b>8</b>



Fig. 11 Semisolid forged aluminum alloy 357 automobile wheels

*Lighter Weight.* The ability to form thinner sections without heavy ribs to aid in filling the cavity allows a wheel to be semisolid formed nearer to net size with light ribs on the brake side. This results in a finished wheel that is up to 30% lighter than a cast wheel of the same style.

*Consistent Quality.* The forging process employs a high-quality, specially prepared (MHD) billet with an engineered metallurgical structure, closely controlled chemistry, and consistent casting variables, supplying an extremely consistent raw material with complete traceability. The wheel-forming process is computer controlled and automated with precise control of the heating and forging process variables, making the entire process adaptable to statistical process control.

*Structure and Properties.* The semisolid forged wheel is fine grained, dense structured, and formed to close tolerances in precision tooling in which the temperature is controlled to provide consistent forging conditions. This provides consistency in part dimensions and metallurgical properties. Forging in the semisolid state avoids the entrapment

of air or mold gas, and the high fraction of solid material, together with the high pressure after forming, reduces the microporosity due to liquid/solid shrinkage. Unlike conventional forgings, the wheel properties are isotropic, reflecting the nondendritic structure of the high-performance aluminum alloy 357 used in the billet.

*Design Versatility.* The ability to form thin sections (roughly one-quarter to one-half the thickness of casting) permits not only a reduction in the weight of the wheel, but also allows the designer to style the wheel with thinner ribs/spokes and finer detail. Forming in the semisolid state under very high final pressure provides part surfaces and details that reflect the die surfaces. Therefore, the designer has a selection of surface conditions to enhance the style and can obtain exact replication of the fine detail designed in the die.

## Example 2: Electrical Connector Multi-conductor.

Military/aerospace electrical connectors (Fig. 12) are highly stressed in service. As a result, the qualification of these parts involves extensive and severe functional testing under various environmental conditions. Production quality control procedures are equally stringent to ensure conformance to specifications and performance under load.

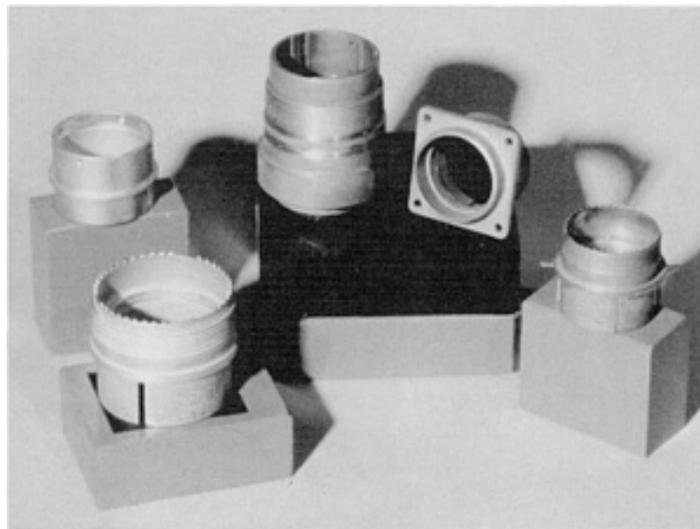


Fig. 12 Aluminum alloy (SIMA 6262) electrical connectors produced by semisolid forging

Before semisolid forging, these parts were machined (on screw machines) from extruded aluminum alloy 6262-T9 bar. Today, a large number of these parts are semisolid forged from SIMA 6262 bar and finish machined after the T6 heat treatment. The characteristics of semisolid forged and machined parts are compared in Table 3.

**Table 3 Comparison of the characteristics of semisolid forged and machined electrical parts**

See Example 2.

Process	Characteristic														
	Aluminum alloy	Raw material diameter		Raw material weight		Finished part weight		Material yield, %	Production rate (primary operation), pieces per hour	Heat treatment	Ultimate tensile strength		Yield Strength	Elongation, %	
		mm	in.	g	oz	g	oz				MPa	ksi	MPa	ksi	
Semisolid forging	SIMA 6262	19	0.75	25	0.88	23	0.81	92	300	T6	345	50	276	40	10

The semisolid forged component possessed all major keyways and locating devices with tolerances at least equivalent to machined parts. The savings in material, plus the higher production rate, makes the semisolid forged part a very economical selection.

After full T6 heat treatment, the parts are finish machined and anodized. The parts are tested per MIL-C-38999 and meet all specified performance criteria. These tests include bending, vibration, durability, thermal shock, and impact.

### Example 3: Aluminum Brake Master Cylinder.

Some permanent mold cast brake master cylinders (Fig. 13) are cast essentially solid in order to place solidification shrinkage defects in the center bore, where they are subsequently machined away. The energy crisis motivated the move to lighter automobiles to improve fuel economy. This has caused the conversion of many ferrous automobile components into aluminum. Brake master cylinders have been difficult and expensive to convert, and until the application of semisolid forging, the only acceptable production methods were low-pressure or gravity permanent mold casting. Table 4 compares a permanent mold cast aluminum part, cored as indicated above, with a semisolid forged replacement.

**Table 4 Comparison of a permanent mold cast aluminum part with a semisolid forged replacement**

See Example 3.

Process	Characteristic											
	Weight (as forged or cast)		Weight (finish machined)		Production rate, pieces per hour	Aluminum alloy	Heat treatment	Ultimate tensile strength		Yield strength		Elongation, %
	kg	lb	kg	lb				MPa	ksi	MPa	ksi	
Semisolid forging	0.45	1.0	0.39	0.85	150	357	T5	303	44	228	33	8
<b>Permanent mold</b>	<b>0.76</b>	<b>1.67</b>	<b>0.45</b>	<b>1.0</b>	<b>24</b>	<b>356</b>	<b>T6</b>	<b>290</b>	<b>42</b>	<b>214</b>	<b>31</b>	<b>8</b>

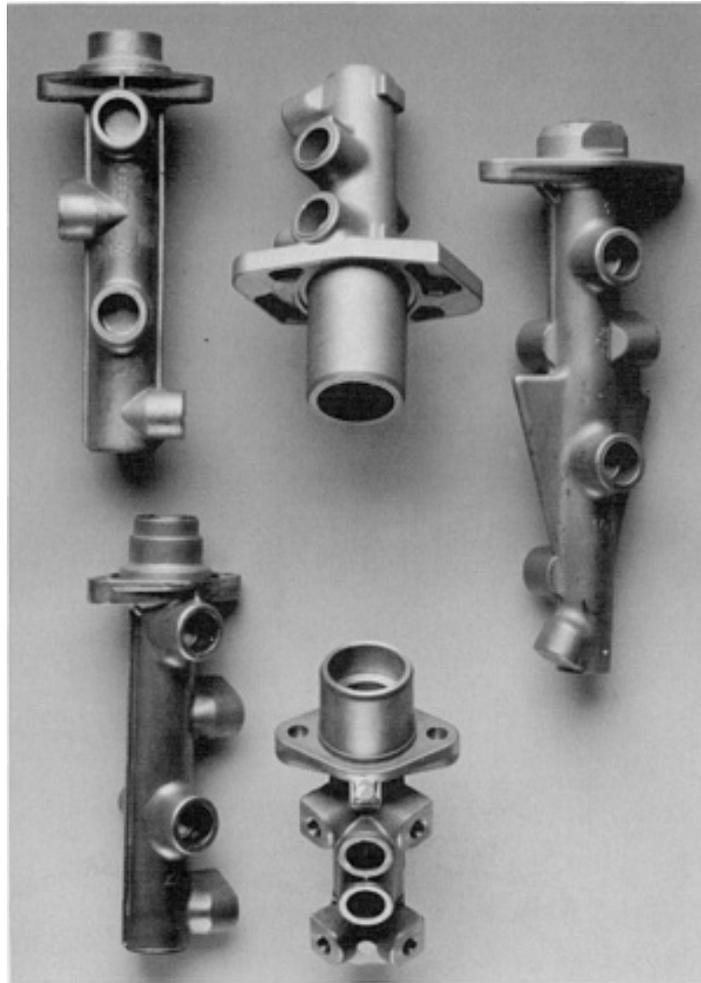


Fig. 13 Aluminum alloy 357 automotive brake master cylinders produced by semisolid forging

Semisolid forging utilizes a two-cavity indirect forming approach and MHD cast alloy 357 slugs cut from 76 mm (3 in.) diameter bar. All major holes are sufficiently cored for tapping or other finishing operations. After semisolid forging, T5 heat treatment, and final machining, parts are subjected to a 9.7 MPa (1400 psi) nitrogen leak test and extensive endurance testing, which includes 300,000 to 1 million hydraulic cycles that must be endured without a sign of wear.

#### Example 4: Valve Bodies.

Automotive, aerospace, refrigeration, and industrial valves are frequently manufactured by machining, drilling, and tapping the hydraulic passages and valve seats in a section cut from an extruded aluminum profile. Valves typical of such production are shown in Fig. 14.

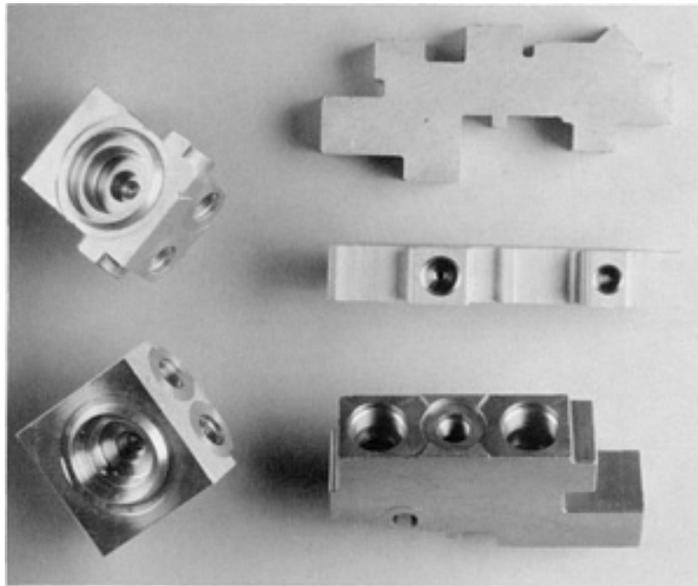


Fig. 14 Aluminum alloy valve bodies machined from extruded profiles

Semisolid forging production can be competitive with this efficient manufacturing method by the substitution of semisolid forging for extrusion, cutoff, milling, and drilling. The semisolid forged valve body is cored and sculpted to minimize metal weight. Finishing requires tapping and drilling the smallest holes, requiring less than one-half the time needed to machine the extruded valve. A typical comparison of weights is given in Table 5.

**Table 5 Comparison of weights for semisolid forged and extruded parts**

See Example 4.

Process	Weight (as forged or cut off, including kerf)		Relative raw material cost per pound (foundry ingot = 1)	Weight of finished valve	
	kg	lb		kg	lb
Semisolid forging	0.32	0.7	1.2	0.27	<b>0.6</b>

#### Example 5: Brass Plumbing Parts.

Brass plumbing components (Fig. 15) were semisolid forged using a closed die to produce a net shape part complete with threads. Strain-induced melt-activated processed Alloy C36000 (free-cutting brass) is heated to the semisolid condition before direct forging. After forging, the part is unscrewed and tumbled to remove minor flash and the die lubricant. Die life of 40,000 pieces is typical for this type of application. Total weight reduction of 50% is frequent when replacing conventional forgings, and 60% weight reduction is common when replacing castings. This weight reduction is an important part of the cost improvement.

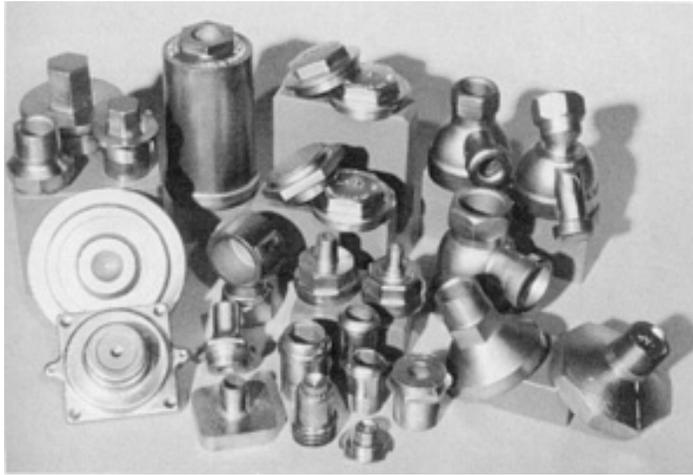


Fig. 15 Copper alloy C36000 (free-cutting brass) plumbing fittings produced by semisolid forging

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## Quality Factors

As with all processes, it is possible to form parts when all variables are not controlled within specified limits and when discontinuities result. Some discontinuities that may be observed in semisolid forging are outlined below and are shown in Fig. 16.

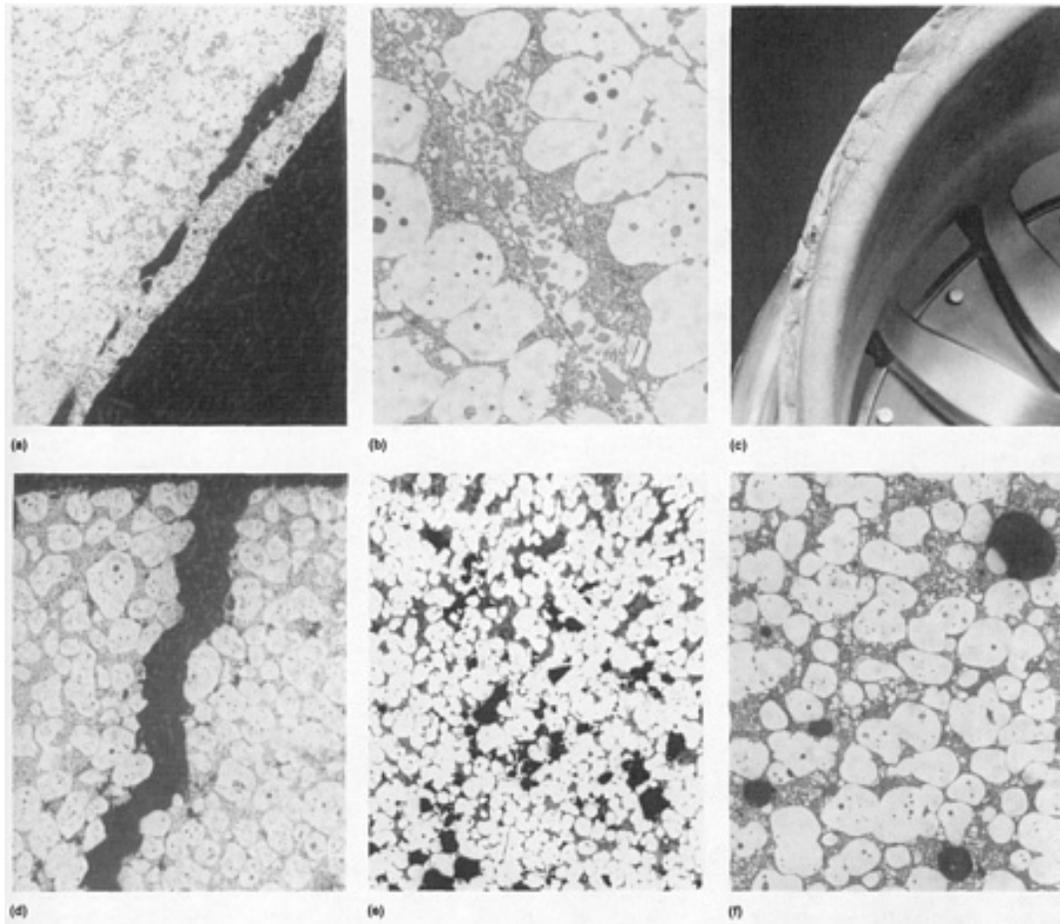


Fig. 16 Defects that may be encountered in semisolid forging. (a) Surface blisters. 75 $\times$ . (b) Cold shuts. 225 $\times$ . (c) Non-fill. 0.5 $\times$ . (d) Hot tears. 75 $\times$ . (e) Shrinkage porosity. 40 $\times$ . (f) Gas porosity. 100 $\times$

Blisters (Fig. 16a) are occasionally observed on the surfaces of aluminum parts that are subjected to the 540 °C (1000 °F) solution heat treatment. They may result from one of several causes, the most frequent of which is an excessively high metal flow rate where metal is sprayed ahead of the main mass flow. It coats die surfaces, and the following mass entraps minute amounts of mold gas between the skin and the bulk of the mass.

Another cause may be the contamination of die surfaces by substances that are contained in various lubricants and hydraulic fluids. These become contained in the part surface. Later, when the temperature rises, the yield strength drops, and the pressure of the contained gas deforms the surface. The blister usually originates in a zone that is 0.5 to 2.0 mm (0.020 to 0.080 in.) below the surface. Blisters can be avoided by ensuring that all die surfaces are free of contamination and by slowing metal velocities, increasing gate areas, and reducing ram velocities.

Cold shuts, folds, and laps (Fig. 16b) are infrequent. These defects occur when two metal surfaces meet but fusion is incomplete. This may be caused when an oxide film is entrapped or when the flow of metal in two approaching surfaces is slowed by entrapped air, allowing solidification to proceed before the surfaces have fully fused. Such problems can be avoided by changing the metal flow pattern and/or increasing localized venting.

Non-fill (Fig. 16c) occurs infrequently when cold semisolid metal, premature freezing, low pressure or metal velocity, or entrapped mold atmosphere prevents the complete filling of the die cavity. It can be corrected by increasing the liquid fraction in slug, raising die temperatures, increasing venting, and adjusting hydraulics for higher pressure or velocity.

Surface blow occurs occasionally when moisture (lubricant, hydraulic fluid) trapped on the die surface by the semisolid metal generates gas pressure, forcing the semisolid metal surface away from the die. Surface blow is identified by a shiny surface area or an indentation in the part. It can be corrected by ensuring that all die surfaces are clean and dry.

Hot tears (Fig. 16d) are infrequent in casting alloys, but are more frequent in wrought alloys. They occur when the solidified part is constrained by the die while solid-state shrinkage induces strains that exceed the hot ductility. Hot tears may be internal or external. They can be avoided by part/die redesign, higher metal pressure in the die, reduced dwell time, or changing alloys.

Shrinkage porosity (Fig. 16e) can occur when heavy and/or thicker sections solidify after their feeding sections. It can be prevented by adjusting die temperatures and feeding sections and by higher time and pressure during dwell after forging.

Gas porosity (Fig. 16f) is very infrequent. It can be caused by excessively high gate velocities, resulting in excessive turbulence in the metal flow and entrapping mold atmosphere. Gas porosity can be avoided by reducing velocity or opening the gates.

Flow lines occur occasionally where metal flows through a heavy section or past a filled region. They can be observed visually unaided on polished sections of a part, but are difficult to resolve at higher magnifications. The zone between a stationary surface and the moving material evidences slightly higher eutectic concentration.

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## Metal-Matrix Composites (MMC)

As discussed earlier in this section, the viscous behavior of semisolid alloys allows for substantial benefits in particle incorporation processes. This was recognized by the early MIT inventors, who coined the term compocast to describe the application of rheocasting techniques to the inclusion of fibers and particulate in metal alloy matrices (Ref 9).

In 1981, one company began a program in which tons of MMCs were mixed and formed into housings for lighting fixtures. These composites, mixtures of about 20% by volume of SiO<sub>2</sub> (silica sand) and aluminum, were produced with a continuous process in an effort to substitute an inexpensive filler (that is, foundry sand) for the increasingly expensive aluminum (Ref 23). The process was successful and, the product met all expectations, including cost. However, the price of aluminum decreased and so did the need for this early MMC.

A number of organizations are currently engaged in developing methods for the creation of MMCs, but regardless of the preparation techniques, semisolid forging offers a unique advantage for forming near-net shape parts from MMCs. Therefore, semisolid forging represents a viable process for shaping these difficult-to-cast MMC materials and can achieve a high degree of accuracy. This is particularly beneficial when the MMC material presents difficulties in machining. A number of prototype applications of semisolid formed MMCs are currently under evaluation. Detailed information on other foundry production methods for MMCs is available in the article "Cast Metal-Matrix Composites" in this Volume.

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## Safety

The potential hazards of semisolid forging are similar to those encountered in other high-speed forging operations. These include mechanical and electrical hazards.

**Mechanical Hazards.** Semisolid forming equipment typically operates at high speed and is capable of exerting high forces. Therefore, pinch points and personnel access should be shielded, and the equipment is quite capable of automatic operation.

**Electrical Hazards.** Induction heating coils typically operate at high voltage (>1000 V) and frequency. Coils and leads should be well protected and shielded from personnel contact. Induction coils should also be shielded from inadvertent contact with the workpiece, particularly in the last stages of heating when the possibility exists for workpiece slumping or collapse in extreme circumstances. This could cause coil arcing.

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