Casting Engineering

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Chapter 1

Casting (Metalworking)

Casting iron in a sand mold

In metalworking, **casting** involves pouring a liquid metal into a mold, which contains a hollow cavity of the desired shape, and then is allowed to solidify. The solidified part is also known as a casting, which is ejected or broken out of the mold to complete the process. Casting is most often used for making complex shapes that would be difficult or uneconomical to make by other methods.

The casting process is subdivided into two main categories: expendable and non-expendable casting. It is further broken down by the mold material, such as sand or metal, and pouring method, such as gravity, vacuum, or low pressure.

Terminology

Metal casting processes uses the following terminology:

- Pattern: An approximate duplicate of the final casting used to form the mold cavity.
- Molding material: The material that is packed around the pattern and then the pattern is removed to leave the cavity where the casting material will be poured.
- Flask: The rigid wood or metal frame that holds the molding material.
    - Cope: The top half of the pattern, flask, mold, or core.
    - Drag: The bottom half of the pattern, flask, mold, or core.
- Core: An insert in the mold that produces internal features in the casting, such as holes.
    - Core print: The region added to the pattern, core, or mold used to locate and support the core.
- Mold cavity: The combined open area of the molding material and core, there the metal is poured to produce the casting.
- Riser: An extra void in the mold that fills with molten material to compensate for shrinkage during solidification.
- Gating system: The network of connected channels that deliver the molten material to the mold cavities.
    - Pouring cup or pouring basin: The part of the gating system that receives the molten material from the pouring vessel.
    - Sprue: The pouring cup attaches to the sprue, which is the vertical part of the gating system. The other end of the sprue attaches to the runners.
    - Runners: The horizontal portion of the gating system that connects the sprues to the gates.
    - Gates: The controlled entrances from the runners into the mold cavities.
- Vents: Additional channels that provide an escape for gases generated during the pour.
- Parting line or parting surface: The interface between the cope and drag halves of the mold, flask, or pattern.
- Draft: The taper on the casting or pattern that allow it to be withdrawn from the mold
- Core box: The mold or die used to produce the cores.

Some specialized processes, such as die casting, use additional terminology.

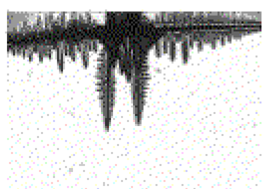
Theory

Casting is a solidification process, which means the solidification phenomenon controls most of the properties of the casting. Moreover, most of the casting defects occur during solidification, such as *gas porosity* and *solidification shrinkage*.

Solidification occurs in two steps: *nucleation* and *crystal growth*. In the nucleation stage solid particles form within the liquid. When these particles form their internal energy is lower than the surrounded liquid, which creates an energy interface between the two. The formation of the surface at this interface requires energy, so as nucleation occurs the material actually undercools, that is it cools below its freezing temperature, because of the extra energy required to form the interface surfaces. It then recalescences, or heats back up to its freezing temperature, for the crystal growth stage. Note that nucleation occurs on a pre-existing solid surface, because not as much energy is required for a partial interface surface, as is for a complete spherical interface surface. This can be advantageous because fine-grained castings possess better properties than coarse-grained castings. A fine grain structure can be induced by *grain refinement* or *inoculation*, which is the process of adding impurities to induce nucleation.

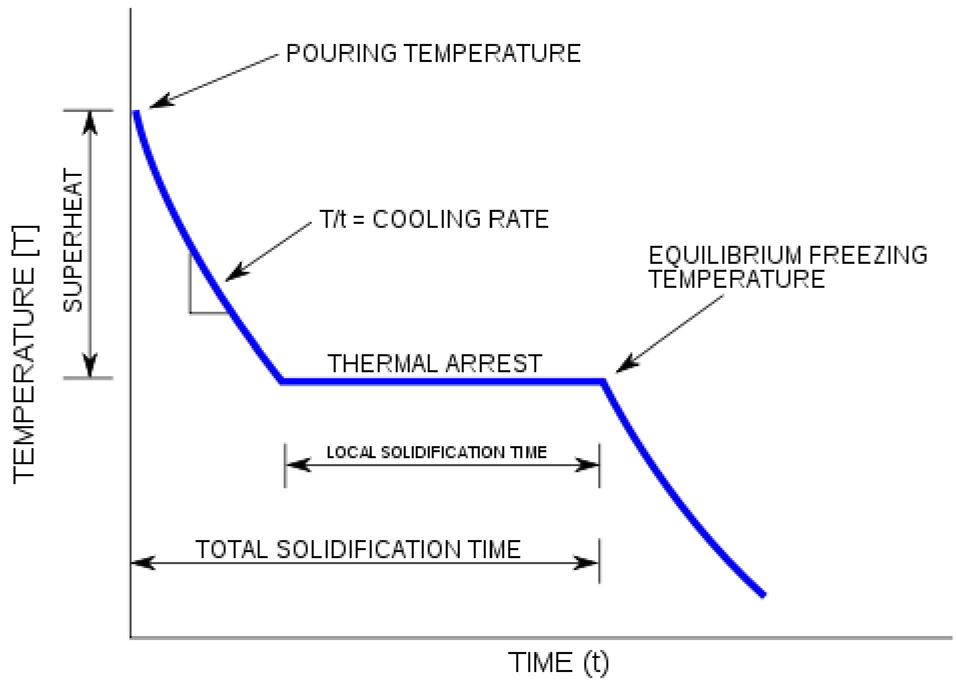
All of the nucleations represent a crystal, which grows as the heat of fusion is extracted from the liquid until there is no liquid left. The direction, rate, and type of growth can be controlled to maximize the properties of the casting. Directional solidification is when the material solidifies at one end and proceeds to solidify to the other end; this is the most ideal type of grain growth because it allows liquid material to compensate for shrinkage.

Cooling curves



Intermediate cooling rates from melt result in a dendritic microstructure. Primary and secondary dendrites can be seen in this image.

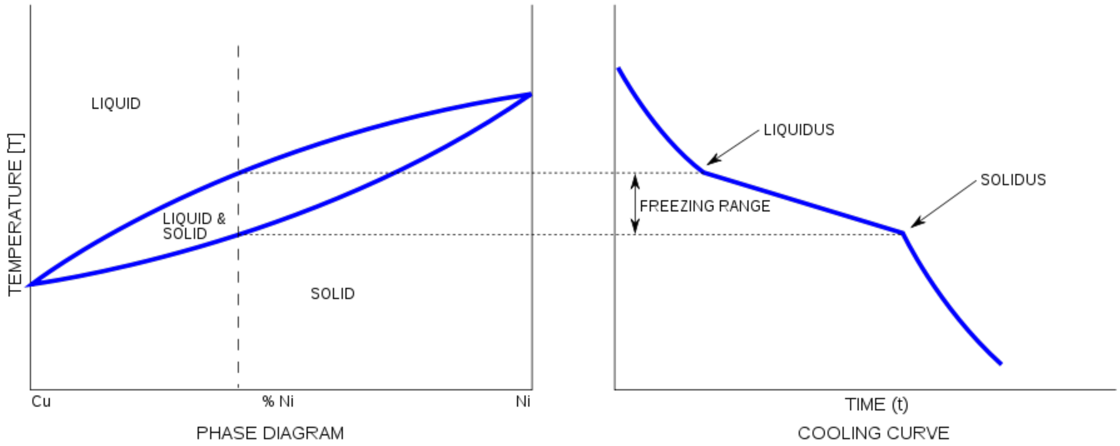
Cooling curves are important in controlling the quality of a casting. The most important part of the cooling curve is the *cooling rate* which affects the microstructure and properties. Generally speaking, an area of the casting which is cooled quickly will have a fine grain structure and an area which cools slowly will have a coarse grain structure. Below is an example cooling curve of a pure metal or eutectic alloy, with defining terminology.



Note that before the thermal arrest the material is a liquid and after it the material is a solid; during the thermal arrest the material is converting from a liquid to a solid. Also, note that the greater the superheat the more time there is for the liquid material to flow into intricate details.

The cooling rate is largely controlled by the mold material. When the liquid material is poured into the mold, the cooling begins. This happens because the heat within the molten metal flows into the relatively cooler parts of the mold. Molding materials transfer heat from the casting into the mold at different rates. For example, some molds made of plaster may transfer heat very slowly, while steel would transfer the heat quickly. Where heat should be removed quickly, the engineer will plan the mold to include special heat sinks to the mold, called chills. Fins may also be designed on a casting to extract heat, which are later removed in the cleaning (also called fettling) process. Both methods may be used at local spots in a mold where the heat will be extracted quickly. Where heat should be removed slowly, a riser or some padding may be added to a casting.

The above cooling curve depicts a basic situation with a pure alloy, however, most castings are of alloys, which have a cooling curve shaped as shown below.



Note that there is no longer a thermal arrest, instead there is a freezing range. The freezing range corresponds directly to the liquidus and solidus found on the phase diagram for the specific alloy.

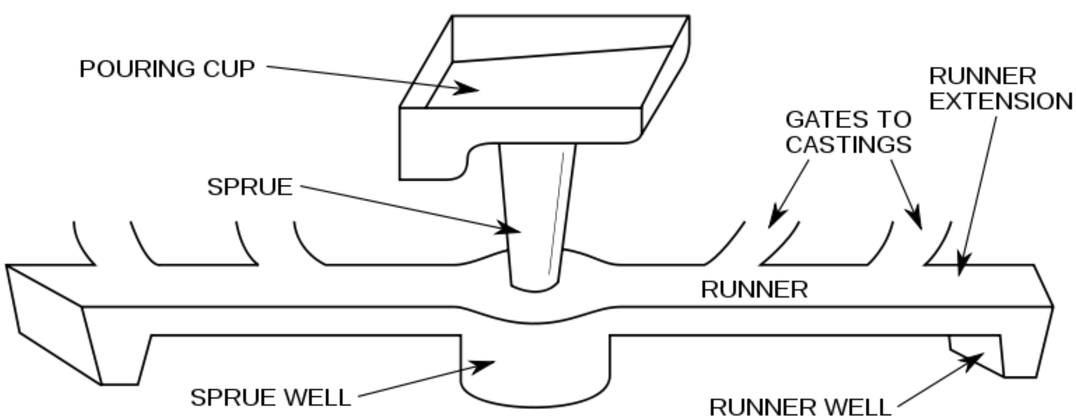
Chvorinov's rule

The local solidification time can be calculated using Chvorinov's rule, which is:

$$t = B\left(\frac{V}{A}\right)^{n}$$

Where t is the solidification time, V is the volume of the casting, A is the surface area of the casting that contacts the mold, n is a constant, and B is the mold constant. It is most useful in determining if a riser will solidify before the casting, because if the riser does solidify first then it is worthless.

The gating system



A simple gating system for a horizontal parting mold.

The gating system serves many purposes, the most important being conveying the liquid material to the mold, but also controlling shrinkage, the speed of the liquid, turbulence, and trapping dross. The gates are usually attached to the thickest part of the casting to assist in controlling shrinkage. In especially large castings multiple gates or runners may be required to introduce metal to more than one point in the mold cavity. The speed of the material is important because if the material is traveling too slowly it can cool before completely filling, leading to misruns and cold shuts. If the material is moving too fast then the liquid material can erode the mold and contaminate the final casting. The shape and length of the gating system can also control how quickly the material cools; short round or square channels minimize heat loss.

The gating system may be designed to minimize turbulence, depending on the material being cast. For example, steel, cast iron, and most copper alloys are turbulent insensitive, but aluminium and magnesium alloys are turbulent sensitive. The turbulent insensitive materials usually have a short and open gating system to fill the mold as quickly as possible. However, for turbulent sensitive materials short sprues are used to minimize the distance the material must fall when entering the mold. Rectangular pouring cups and tapered sprues are used to prevent the formation of a vortex as the material flows into the mold; these vortices tend to suck gas and oxides into the mold. A large sprue well is used to dissipate the kinetic energy of the liquid material as it falls down the sprue, decreasing turbulence. The *choke*, which is the smallest cross-sectional area in the gating system used to control flow, can be placed near the sprue well to slow down and smooth out the flow. Note that on some molds the choke is still placed on the gates to make separation of the part easier, but induces extreme turbulence. The gates are usually attached to the bottom of the casting to minimize turbulence and splashing.

The gating system may also be designed to trap dross. One method is to take advantage of the fact that some dross has a lower density than the base material so it floats to the top of the gating system. Therefore long flat runners with gates that exit from the bottom of the runners can trap dross in the runners; note that long flat runners will cool the material more rapidly than round or square runners. For materials where the dross is a similar density to the base material, such as aluminium, *runner extensions* and *runner wells* can be advantageous. These take advantage of the fact that the dross is usually located at the beginning of the pour, therefore the runner is extended past the last gate(s) and the contaminates are contained in the wells. Screens or filters may also be used to trap contaminates.

It is important to keep the size of the gating system small, because it all must be cut from the casting and remelted to be reused. The efficiency, or *yield*, of a casting system can be calculated by dividing the weight of the casting by the weight of the metal poured. Therefore, the higher the number the more efficient the gating system/risers.

Shrinkage

There are three types of shrinkage: *shrinkage of the liquid*, *solidification shrinkage* and *patternmaker's shrinkage*. The shrinkage of the liquid is rarely a problem because more material is flowing into the mold behind it. Solidification shrinkage occurs because metals are less dense as a liquid than a solid, so during solidification the metal density dramatically increases. Patternmaker's shrinkage refers to the shrinkage that occurs when the material is cooled from the solidification temperature to room temperature, which occurs due to thermal contraction.

Solidification shrinkage

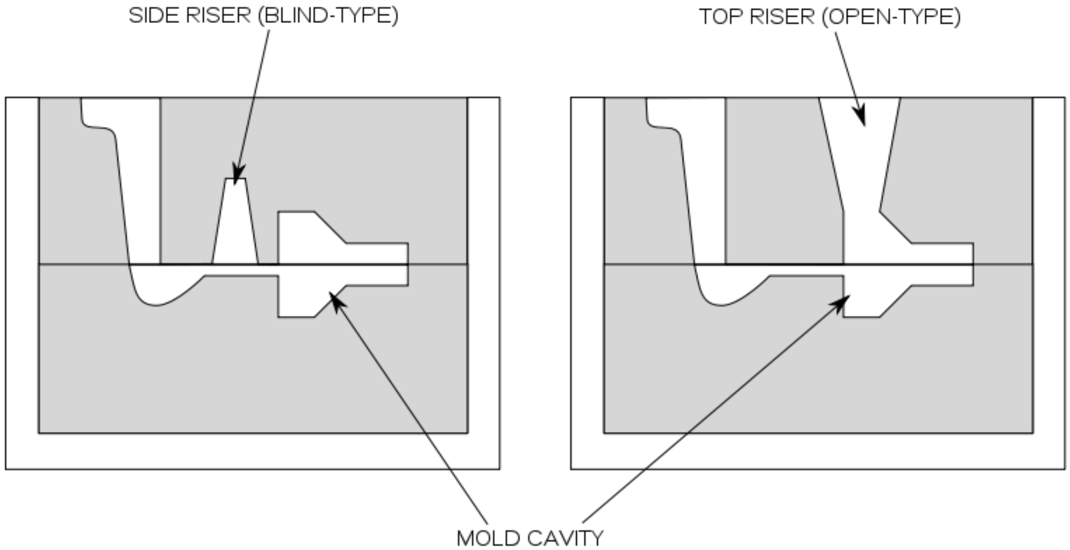
Solidification shrinkage of various metals

Metal	Percentage
Aluminium	6.6
Copper	4.9
Magnesium	4.0 or 4.2
Zinc	3.7 or 6.5
Low carbon steel	2.5–3.0
High carbon steel	4.0
White cast iron	4.0–5.5
Gray cast iron	−2.5–1.6
Ductile cast iron	−4.5–2.7

Most materials shrink as they solidify, but, as the table to the right shows, a few materials do not, such as gray cast iron. For the materials that do shrink upon solidification the type of shrinkage depends on how wide the freezing range is for the material. For materials with a narrow freezing range, less than 50 °C (122 °F), a cavity, known as a *pipe*, forms in the center of the casting, because the outer shell freezes first and progressively solidifies to the center. Pure and eutectic metals usually have narrow solidification ranges. These materials tend to form a *skin* in open air molds, therefore they are known as *skin forming alloys*. For materials with a wide freezing range, greater than 110 °C (230 °F), much more of the casting occupies the *mushy* or *slushy* zone (the temperature range between the solidus and the liquidus), which leads to small pockets of liquid trapped throughout and ultimately porosity. These castings tend to have poor ductility, toughness, and fatigue resistance. Moreover, for these types of materials to be fluid-tight a secondary operation is required to impregnate the casting with a lower melting point metal or resin.

For the materials that have narrow solidification ranges pipes can be overcome by designing the casting to promote directional solidification, which means the casting freezes first at the point farthest from the gate, then progressively solidifies towards the gate. This allows a continuous feed of liquid material to be present at the point of solidification to compensate for the shrinkage. Note that there is still a shrinkage void where the final material solidifies, but if designed properly this will be in the gating system or riser.

Risers and riser aids



Different types of risers

Risers, also known as *feeders*, are the most common way of providing directional solidification. It supplies liquid metal to the solidifying casting to compensate for solidification shrinkage. For a riser to work properly the riser must solidify after the casting, otherwise it cannot supply liquid metal to shrinkage within the casting. Risers add cost to the casting because it lowers the *yield* of each casting; i.e. more metal is lost as scrap for each casting. Another way to promote directional solidification is by adding chills to the mold. A chill is any material which will conduct heat away from the casting more rapidly that the material used for molding.

Risers are classified by three criteria. The first is if the riser is open to the atmosphere, if it is then its called an *open* riser, otherwise its known as a *blind* type. The second criterion is where the riser is located; if it is located on the casting then it is known as a *top riser* and if it is located next to the casting it is known as a *side riser*. Finally, if riser is located on the gating system so that it fills after the molding cavity, it is known as a *live riser* or *hot riser*, but if the riser fills with materials that's already flowed through the molding cavity it is known as a *dead riser* or *cold riser*.

Riser aids are items used to assist risers in creating directional solidification or reducing the number of risers required. One of these items are *chills* which accelerate cooling in a certain part of the mold. There are two types: external and internal chills. External chills are masses of high-heat-capacity and high-thermal-conductivity material that are placed on an edge of the molding cavity. Internal chills are pieces of the same metal that is being poured, which are placed inside the mold cavity and become part of the casting. Insulating sleeves and toppings may also be installed around the riser cavity to slow the solidification of the riser. Heater coils may also be installed around or above the riser cavity to slow solidification.

Patternmaker's shrink

Typical patternmaker's shrinkage of various metals

Metal	Percentage	in/ft
Aluminium	1.0–1.3	$\frac{1}{8}$–$\frac{5}{32}$
Brass	1.5	$\frac{3}{16}$
Magnesium	1.0–1.3	$\frac{1}{8}$–$\frac{5}{32}$
Cast iron	0.8–1.0	$\frac{1}{10}$–$\frac{1}{8}$
Steel	2.5–3.0	$\frac{3}{16}$–$\frac{1}{4}$

Shrinkage after solidification can be dealt with by using an oversized pattern designed specifically for the alloy used. *Contraction rules*, or *shrink rules*, are used to make the patterns oversized to compensate for this type of shrinkage. These rulers are up to 2% oversize, depending on the material being cast. These rulers are mainly referred to by their percentage change. A pattern made to match an existing part would be made as follows: First, the existing part would be measured using a standard ruler, then when constructing the pattern, the pattern maker would use a contraction rule, ensuring that the casting would contract to the correct size.

Note that patternmaker's shrinkage does not take phase change transformations into account. For example, eutectic reactions, martensitic reactions, and graphitization can cause expansions or contractions.

Mold cavity

The mold cavity of a casting does not reflect the exact dimensions of the finished part due to a number of reasons. These modifications to the mold cavity are known as *allowances* and account for patternmaker's shrinkage, draft, machining, and distortion. In non-expendable processes, these allowances are imparted directly into the permanent mold, but in expendable mold processes they are imparted into the patterns, which later form the mold cavity. Note that for non-expendable molds an allowance is required for the dimensional change of the mold due to heating to operating temperatures.

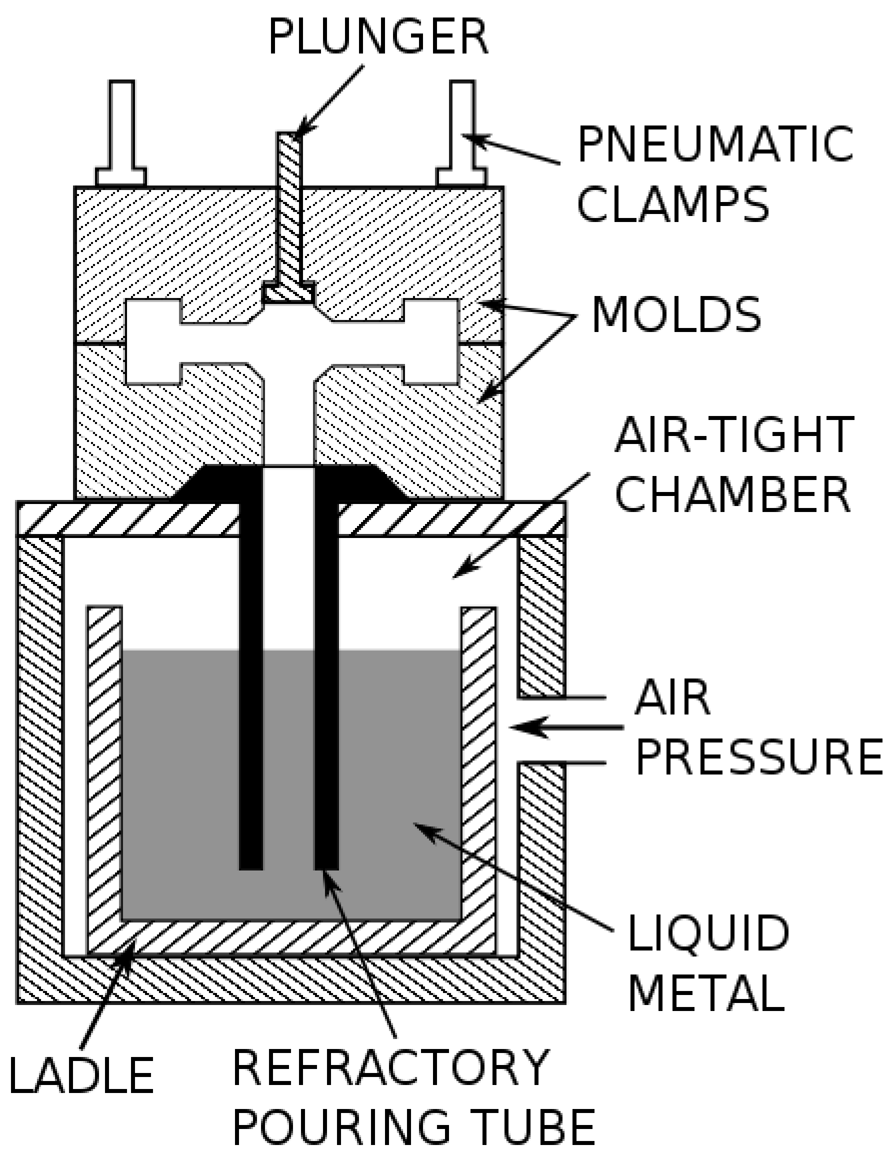
For surfaces of the casting that are perpendicular to the parting line of the mold a draft must be included. This is so that the casting can be released in non-expendable processes or the pattern can be released from the mold without destroying the mold in expendable processes. The required draft angle depends on the size and shape of the feature, the depth of the mold cavity, how the part or pattern is being removed from the mold, the pattern or part material, the mold material, and the process type. Usually the draft is not less than 1%.

The machining allowance varies drastically from one process to another. Sand castings generally have a rough surface finish, therefore need a greater machining allowance, whereas die casting has a very fine surface finish, which may not need any machining tolerance. Also, the draft may provide enough of a machining allowance to begin with.

The distortion allowance is only necessary for certain geometries. For instance, U-shaped castings will tend to distort with the legs splaying outward, because the base of the shape can contract while the legs are constrained by the mold. This can be overcome by designing the mold cavity to slope the leg inward to begin with. Also, long horizontal sections tend to sag in the middle if ribs are not incorporated, so a distortion allowance may be required.

Cores may be used in expendable mold processes to produce internal features. The core can be of metal but it is usually done in sand.

Filling



Schematic of the low-pressure permanent mold casting process

There are a few common methods for filling the mold cavity: *gravity*, *low-pressure*, *high-pressure*, and *vacuum*.

Vacuum filling, also known as *counter-gravity* filling, is more metal efficient than gravity pouring because less material solidifies in the gating system. Gravity pouring only has a 15 to 50% metal yield as compared to 60 to 95% for vacuum pouring. There is also less turbulence, so the gating system can be simplified since it does not have to control turbulence. Plus, because the metal is drawn from below the top of the pool the metal is free from dross and slag, as these are lower density (lighter) and float to the top of the pool. The pressure differential helps the metal flow into every intricacy of the mold. Finally, lower temperatures can be used, which improves the grain structure. The first patented vacuum casting machine and process dates to 1879.

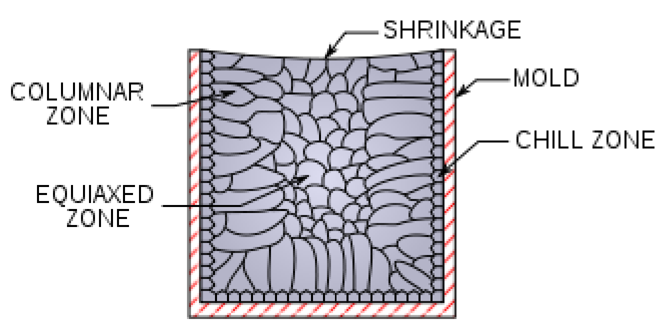
Low-pressure filling uses 5 to 15 psig (35 to 100 kPag) of air pressure to force liquid metal up a feed tube into the mold cavity. This eliminates turbulence found in gravity casting and increases density, repeatability, tolerances, and grain uniformity. After the casting has solidified the pressure is released and any remaining liquid returns to the crucible, which increases yield.

Tilt filling

Tilt filling, also known as *tilt casting*, is an uncommon filling technique where the crucible is attached to the gating system and both are slowly rotated so that the metal enters the mold cavity with little turbulence. The goal is to reduce porosity and inclusions by limiting turbulence. For most uses tilt filling is not feasible because the following inherent problem: if the system is rotated slow enough to not induce turbulence, the front of the metal stream begins to solidify, which results in mis-runs. If the system is rotated faster then it induces turbulence, which defeats the purpose. Durville of France was the first to try tilt casting, in the 1800s. He tried to use it to reduce surface defects when casting coinage from aluminum bronze.

Macrostructure

The grain macrostructure in ingots and most castings have three distinct regions or zones: the chill zone, columnar zone, and equiaxed zone. The image below depicts these zones.



The chill zone is named so because it occurs at the walls of the mold where the wall *chills* the material. Here is where the nucleation phase of the solidification process takes place. As more heat is removed the grains grow towards the center of the casting. These are thin, long *columns* that are perpendicular to the casting surface, which are undesirable because they have anisotropic properties. Finally, in the center the equiaxed zone contains spherical, randomly oriented crystals. These are desirable because they have isotropic properties. The creation of this zone can be promoted by using a low pouring temperature, alloy inclusions, or inoculants.

Inspection

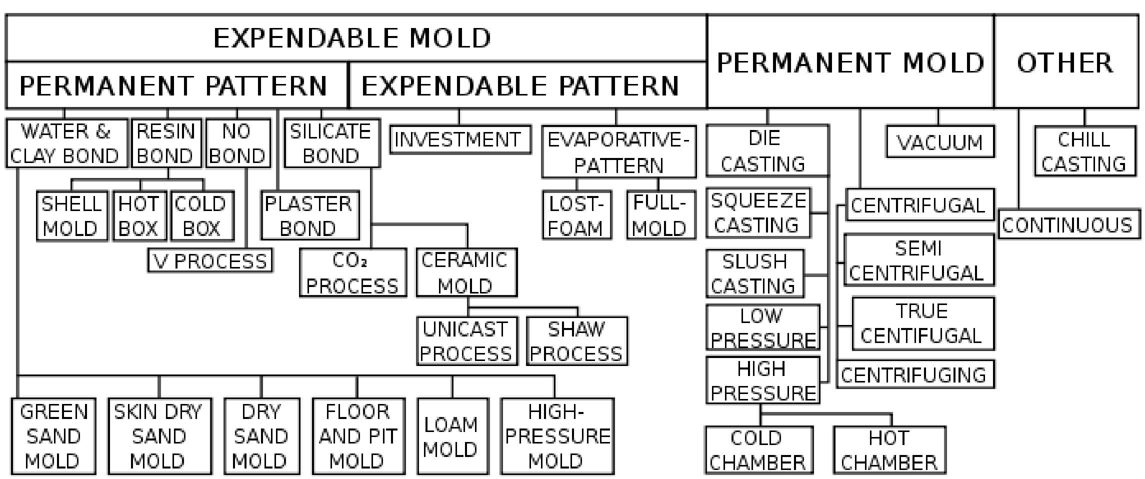
Common inspection methods for steel castings are *magnetic particle* and *liquid penetrant*. Common inspection methods for aluminum castings are *radiography*, *ultrasonic*, and *liquid penetrant*.

Defects

There are a number of problems that can be encountered during the casting process. The main types are: *gas porosity*, *shrinkage defects*, *mold material defects*, *pouring metal defects*, and *metallurgical defects*.

Expendable mold casting

Expendable mold casting is a generic classification that includes sand, plastic, shell, plaster, and investment (lost-wax technique) moldings. This method of mold casting involves the use of temporary, non-reusable molds.



Waste molding of plaster

A durable plaster intermediate is often used as a stage toward the production of a bronze sculpture or as a pointing guide for the creation of a carved stone. With the completion of a plaster, the work is more durable (if stored indoors) than a clay original which must be kept moist to avoid cracking. With the low cost plaster at hand, the expensive work of bronze casting or stone carving may be deferred until a patron is found, and as such work is considered to be a technical, rather than artistic process, it may even be deferred beyond the lifetime of the artist.

In waste molding a simple and thin plaster mold, reinforced by sisal or burlap, is cast over the original clay mixture. When cured, it is then removed from the damp clay, incidentally destroying the fine details in undercuts present in the clay, but which are now captured in the mold. The mold may then at any later time (but only once) be used to cast a plaster positive image, identical to the original clay. The surface of this plaster may be further refined and may be painted and waxed to resemble a finished bronze casting.

Sand casting

Sand casting is one of the most popular and simplest types of casting that has been used for centuries. Sand casting allows for smaller batches to be made compared to permanent mold casting and at a very reasonable cost. Not only does this method allow manufacturers to create products at a low cost, but there are other benefits to sand casting, such as very small size operations. From castings that fit in the palm of your hand to train beds (one casting can create the entire bed for one rail car), it can all be done with sand casting. Sand casting also allows most metals to be cast depending on the type of sand used for the molds.

Sand casting requires a lead time of days for production at high output rates (1–20 pieces/hr-mold) and is unsurpassed for large-part production. Green (moist) sand has almost no part weight limit, whereas dry sand has a practical part mass limit of 2,300–2,700 kg (5,100–6,000 lb). Minimum part weight ranges from 0.075–0.1 kg (0.17–0.22 lb). The sand is bonded together using clays, chemical binders, or polymerized oils (such as motor oil). Sand can be recycled many times in most operations and requires little maintenance.

Plaster mold casting

Plaster casting is similar to sand casting except that plaster of paris is substituted for sand as a mold material. Generally, the form takes less than a week to prepare, after which a production rate of 1–10 units/hr-mold is achieved, with items as massive as 45 kg (99 lb) and as small as 30 g (1 oz) with very good surface finish and close tolerances. Plaster casting is an inexpensive alternative to other molding processes for complex parts due to the low cost of the plaster and its ability to produce near net shape castings. The biggest disadvantage is that it can only be used with low melting point non-ferrous materials, such as aluminium, copper, magnesium, and zinc.

Shell molding

Shell molding is similar to sand casting, but the molding cavity is formed by a hardened "shell" of sand instead of flask filled with sand. The sand is finer than sand casting sand

and is mixed with a resin so that it can be heated by the pattern and harden into a shell around the pattern. Because of the resin it gives a much finer surface finish. The process is easily automated and more precise than sand casting. Common metals that are cast include cast iron, aluminium, magnesium, and copper alloys. This process is ideal for complex items that are small to medium sized.

Investment casting

An investment-cast valve cover

Investment casting (known as lost-wax casting in art) is a process that has been practised for thousands of years, with the lost-wax process being one of the oldest known metal forming techniques. From 5000 years ago, when beeswax formed the pattern, to today's high technology waxes, refractory materials and specialist alloys, the castings ensure high-quality components are produced with the key benefits of accuracy, repeatability, versatility and integrity.

Investment casting derives its name from the fact that the pattern is invested, or surrounded, with a refractory material. The wax patterns require extreme care for they are not strong enough to withstand forces encountered during the mold making. One advantage of investment casting is that the wax can be reused.

The process is suitable for repeatable production of net shape components from a variety of different metals and high performance alloys. Although generally used for small castings, this process has been used to produce complete aircraft door frames, with steel castings of up to 300 kg and aluminium castings of up to 30 kg. Compared to other casting processes such as die casting or sand casting, it can be an expensive process, however the components that can be produced using investment casting can incorporate intricate contours, and in most cases the components are cast near net shape, so requiring little or no rework once cast.

Evaporative-pattern casting

This is a class of casting processes that use pattern materials that evaporate during the pour, which means there is no need to remove the pattern material from the mold before casting. The two main processes are lost-foam casting and full-mold casting.

Lost-foam casting

Lost-foam casting is a type of evaporative-pattern casting process that is similar to investment casting except foam is used for the pattern instead of wax. This process takes advantage of the low boiling point of foam to simplify the investment casting process by removing the need to melt the wax out of the mold.

Full-mold casting

Full-mold casting is an evaporative-pattern casting process which is a combination of sand casting and lost-foam casting. It uses a expanded polystyrene foam pattern which is then surrounded by sand, much like sand casting. The metal is then poured directly into the mold, which vaporizes the foam upon contact.

Non-expendable mold casting

The permanent molding process

Non-expendable mold casting differs from expendable processes in that the mold need not be reformed after each production cycle. This technique includes at least four different methods: permanent, die, centrifugal, and continuous casting. This form of casting also results in improved repeatability in parts produced and delivers Near Net Shape results.

Permanent mold casting

Permanent mold casting is metal casting process that employs reusable molds ("permanent molds"), usually made from metal. The most common process uses gravity to fill the mold, however gas pressure or a vacuum are also used. A variation on the typical gravity casting process, called slush casting, produces hollow castings. Common casting metals are aluminum, magnesium, and copper alloys. Other materials include tin, zinc, and lead alloys and iron and steel are also cast in graphite molds. Permanent molds, while lasting more than one casting still have a limited life before wearing out.

Die casting

The die casting process forces molten metal under high pressure into mold cavities (which are machined into dies). Most die castings are made from nonferrous metals, specifically zinc, copper, and aluminium based alloys, but ferrous metal die castings are possible. The die casting method is especially suited for applications where many small to medium sized parts are needed with good detail, a fine surface quality and dimensional consistency.

Semi-solid metal casting

Semi-solid metal (SSM) casting is a modified die casting process that reduces or eliminates the residual porosity present in most die castings. Rather than using liquid metal as the feed material, SSM casting uses a higher viscosity feed material that is partially solid and partially liquid. A modified die casting machine is used to inject the semi-solid slurry into re-usable hardened steel dies. The high viscosity of the semi-solid metal, along with the use of controlled die filling conditions, ensures that the semi-solid metal fills the die in a non-turbulent manner so that harmful porosity can be essentially eliminated.

Used commercially mainly for aluminium and magnesium alloys, SSM castings can be heat treated to the T4, T5 or T6 tempers. The combination of heat treatment, fast cooling rates (from using un-coated steel dies) and minimal porosity provides excellent combinations of strength and ductility. Other advantages of SSM casting include the ability to produce complex shaped parts net shape, pressure tightness, tight dimensional tolerances and the ability to cast thin walls.

Centrifugal casting

Centrifugal casting is both gravity- and pressure-independent since it creates its own force feed using a temporary sand mold held in a spinning chamber at up to 900 N. Lead time varies with the application. Semi- and true-centrifugal processing permit 30-50 pieces/hr-mold to be produced, with a practical limit for batch processing of approximately 9000 kg total mass with a typical per-item limit of 2.3-4.5 kg.

Industrially, the centrifugal casting of railway wheels was an early application of the method developed by German industrial company Krupp and this capability enabled the rapid growth of the enterprise.

Small art pieces such as jewelry are often cast by this method using the lost wax process, as the forces enable the rather viscous liquid metals to flow through very small passages and into fine details such as leaves and petals. This effect is similar to the benefits from vacuum casting, also applied to jewelry casting.

Continuous casting

Continuous casting is a refinement of the casting process for the continuous, high-volume production of metal sections with a constant cross-section. Molten metal is poured into an open-ended, water-cooled copper mold, which allows a 'skin' of solid metal to form over the still-liquid centre. The strand, as it is now called, is withdrawn from the mold and passed into a chamber of rollers and water sprays; the rollers support the thin skin of the strand while the sprays remove heat from the strand, gradually solidifying the strand from the outside in. After solidification, predetermined lengths of the strand are cut off by either mechanical shears or travelling oxyacetylene torches and transferred to further forming processes, or to a stockpile. Cast sizes can range from strip (a few millimetres thick by about five metres wide) to billets (90 to 160 mm square) to slabs (1.25 m wide by 230 mm thick). Sometimes, the strand may undergo an initial hot rolling process before being cut.

Continuous casting is used due to the lower costs associated with continuous production of a standard product, and also increases the quality of the final product. Metals such as steel, copper and aluminium are continuously cast, with steel being the metal with the greatest tonnages cast using this method.

Chapter 2

Riser (Casting) & Chill (Casting)

Riser (Casting)

A bronze casting showing the sprue and risers

A **riser**, also known as a **feeder**, is a reservoir built into a metal casting mold to prevent cavities due to shrinkage. Most metals are less dense as a liquid than as a solid so castings shrink upon cooling, which can leave a void at the last point to solidify. Risers prevent this by providing molten metal to the casting as it solidifies, so that the cavity forms in the riser and not the casting. Risers are not effective on materials that have a large freezing range, because directional solidification is not possible. They are also not needed for casting processes that utilized pressure to fill the mold cavity. A feeder operated by a treadle is called an **underfeeder**.

The activity of planning of how a casting will be gated and risered is called *foundry methoding* or *foundry engineering*.

Theory

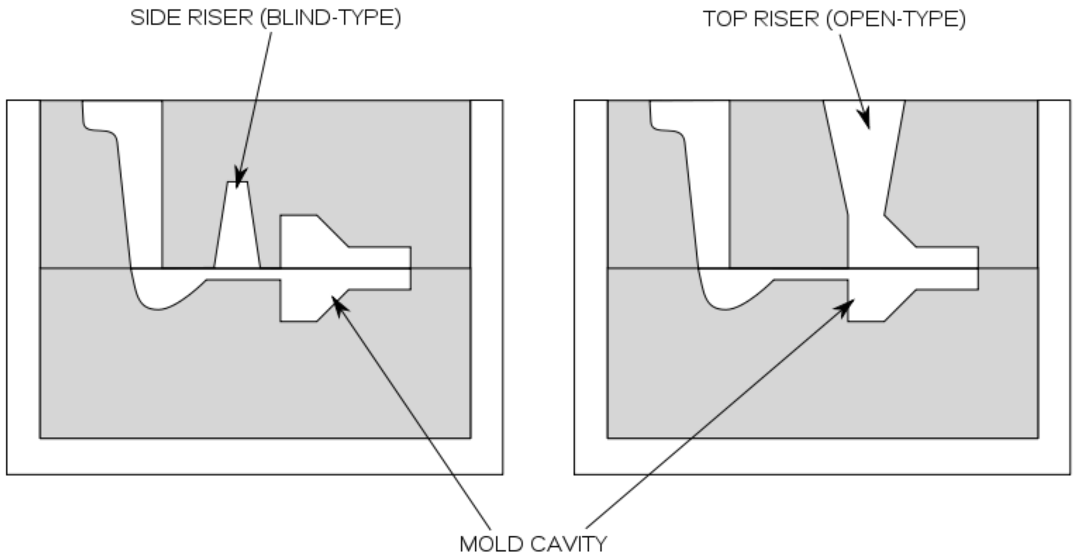
Risers are only effective if three conditions are met: the riser cools after the casting, the riser has enough material compensate for the casting shrinkage, and the casting directionally solidifies towards the riser.

For the riser to cool after the casting the riser must cool more slowly than the casting. Chvorinov's rule briefly states that the slowest cooling time is achieved with the greatest volume and the least surface area; geometrically speaking, this is a sphere. So, ideally, a riser should be a sphere, but this isn't a very practical shape to insert into a mold, so a cylinder is used instead. The height to diameter ratio of the cylinder varies depending on the material, location of the riser, size of the flask, etc.

The shrinkage must be calculated for the casting to confirm that there is enough material in the riser to compensate for the shrinkage. If it appears there is not enough material then the size of the riser must be increased. This requirement is more important for plate-like shapes, while the first requirement is more important for chunky shapes.

Finally, the casting must be designed to produce directional solidification, which sweeps from the extremities of the mold cavity toward the riser(s). In this way, the riser can feed molten metal continuously to part of the casting that is solidifying. One part of achieving this end is by placing the riser near the thickest and largest part of the casting, as that part of the casting will cool and solidify last. If this type of solidification is not possible, multiple risers that feed various sections of the casting or chills may be necessary.

Types



Different types of risers

Risers are categorized based on three criteria: location, if it is open to the atmosphere, and how it is filled. If the riser is located on the casting then it is known as a *top riser*, but if it is located next to the casting it is known as a *side riser*. Top risers are advantageous because they take up less space in the flask than a side riser, plus they have a shorter feeding distance. If the riser is open to the atmosphere it is known as an *open riser*, but if the risers is completely contained in the mold it is known as a *blind riser*. A blind riser is usually bigger than an open riser because the blind riser loses more heat to mold through the top of the riser. Finally, if the riser receives material from the gating system and fills after the mold cavity it is known as a *live riser* or *hot riser*. If the riser fills with material that has already flowed through the mold cavity it is known as a *dead riser* or *cold riser*. Live risers are usually smaller than dead risers. Note that top risers are almost always dead risers and risers in the gating system are almost always live risers.

Note that the connection of the riser to the molding cavity can be an issue for side risers. On one hand the connection should be as small as possible to make separation as easy as possible, but, on the other, the connection must be big enough for it to not solidify before the riser. The connection is usually made short to take advantage of the heat of both the riser and the molding cavity, which will keep it hot throughout the process.

There are risering aids that can be implemented to slow the cooling of a riser or decrease its size. One is using an insulating sleeve and top around the riser. Another is placing a heater around only the riser.

Hot tops

A *hot top*, also known as a *feeder head*, is a specialized riser that is used when casting ingots. It is essentially a live open riser, except a hot ceramic liner is used instead of just the mold material. The ingot is mostly poured and then the hot top is placed at the top of the mold. The rest of the metal is then poured. This keeps piping to a minimum. Robert Forester Mushet invented the hot top, but then called it a *dozzle*. With a hot top only 1 to 2% of the ingot is waste, prior up to 25% of the ingot was wasted.

Yield

The efficiency, or *yield*, of a casting is defined as the weight of the casting divided by the weight of the total amount of metal poured. Risers can add a lot to the total weight being poured, so it is important to optimize their size and shape. Because risers exist only to ensure the integrity of the casting, they are removed after the part has cooled, and their metal is remelted to be used again. As a result, riser size, number, and placement should be carefully planned to reduce waste while filling all the shrinkage in the casting.

One way to calculate the minimum size of a riser is to use Chvorinov's rule by setting the solidification time for the riser to be longer than that of the casting. Any time can be chosen but 25% longer is usually a safe choice, which is written as follows:

$$t_{\text{riser}} = 1.25t_{\text{casting}}$$

or

$$\left(\frac{V}{A}\right)_{\text{riser}}^{n} = 1.25\left(\frac{V}{A}\right)_{\text{casting}}^{n}$$

Because all of the mold and material factors are the same for n. If a cylinder is chosen for the geometry of the riser and the height to diameter ratio is locked, then the equation can be solved for a diameter, which makes this method a simple way to calculate the minimum size for a riser. Note that if a top riser is used the surface area that is shared between the riser and the casting should be subtracted from the area on the casting and the riser.

Chill (casting)

A **chill** is an object used to promote solidification in a specific portion of a metal casting mold. Normally the metal in the mold cools at a certain rate relative to thickness of the casting. When the geometry of the molding cavity prevents directional solidification from occurring naturally, a chill can be strategically placed to help promote it. There are two types of chills: *internal* and *external* chills.

Types

Internal chills are pieces of metal that are placed inside the molding cavity. When the cavity is filled, part of the chill will melt and ultimately become part of the casting, thus the chill must be the same material as the casting. Note that internal chills will absorb both heat capacity and heat of fusion energy.

External chills are masses of material that have a high heat capacity and thermal conductivity. They are placed on the edge of the molding cavity, and effectively become part of the wall of the molding cavity. This type of chill can be used to increase the feeding distance of a riser or reduce the number of risers required.

Materials

A chill that is commonly used in sand castings is made of iron, which has a higher density, thermal conductivity and thermal capacity than the mold material. Chills can be made of many materials, including iron, copper, bronze, aluminium, graphite, and silicon carbide. Other sand materials with higher densities, thermal conductivity or thermal capacity can also be used as a chill. For example, chromite sand or zircon sand can be used when molding with silica sand.

Chapter 3

Full-Mold Casting & Semi-Solid Metal Casting

Full-Mold Casting

Full-mold casting is a evaporative-pattern casting process which is a combination of sand casting and lost-foam casting. It uses a expanded polystyrene foam pattern which is then surrounded by sand, much like sand casting. The metal is then poured directly into the mold, which vaporizes the foam upon contact.

Process

First, a pattern is made from polystyrene foam, which can be done many different ways. For small volume runs the pattern can be hand cut or machined from a solid block of foam; if the geometry is simple enough it can even be cut using a hot-wire foam cutter. If the volume is large, then the pattern can be mass-produced by a process similar to injection molding. Pre-expanded beads of polystyrene are injected into a preheated aluminium mold at low pressure. Steam is then applied to the polystyrene which causes it to expand more to fill the die. The final pattern is approximately 97.5% air and 2.5% polystyrene. Once the pattern is made pre-made pouring basins, runners, and risers can be hot glued to form the final pattern.

The pattern is then coated with a refractory material. The coated pattern is then placed in a flask and packed carefully with green sand or a chemically bonded sand. Finally, the molten metal is poured into the mold, which vaporizes the foam allowing the metal to fill the entire mold. The casting is allowed to cool and then dumped out of the flask ready to use. The sand does not need to be reprocessed so it can be directly reused.

Details

The minimum wall thickness for a full-mold casting is 2.5 mm (0.10 in). Typical dimensional tolerances are 0.3% and typical surface finishes are from 2.5 to 25 µm (100 to 1000 µin) RMS. The size range is from 400 g (0.88 lb) to several tonnes (tons).

Full-mold casting is often used to produce cylinder heads, engine blocks, pump housings, automotive brake components, and manifolds. Commonly employed materials include aluminium, iron, steel, nickel alloys, and copper alloys.

Advantages and disadvantages

This casting process advantageous for very complex castings, that would regularly require cores. It is also dimensionally accurate, requires no draft, and has no parting lines so no flash is formed. As compared to investment casting, it is cheaper because it is a simpler process and the foam is cheaper than the wax. Risers are not usually required due to the nature of the process; because the molten metal vaporizes the foam the first metal into the mold cools more quickly than the rest, which results in natural directional solidification.

The two main disadvantages are that pattern costs can be high for low volume applications and the patterns are easily damaged or distorted due to their low strength. If a die is used to create the patterns there is a large initial cost.

History

The first patent for an evaporative-pattern casting process was filed in April 1956, by H.F. Shroyer. He patented the use of foam patterns embedded in traditional green sand for metal casting.

Semi-Solid Metal Casting

Semi-solid metal casting (**SSM**) is a near net shape variant of die casting. The process is used with non-ferrous metals, such as aluminium, copper, and magnesium. The process combines the advantages of casting and forging. The process is named after the fluid property thixotropy, which is the phenomenon that allows this process to work. Simply, thixotropic fluids shear when the material flows, but thicken when standing. The potential for this type of process was first recognized in the early 1970s. There are four different processes: *thixocasting*, *rheocasting*, *thixomolding*, and *SIMA*.

SSM is done at a temperature that puts the metal between its liquidus and solidus temperature. Ideally, the metal should be 30 to 65% solid. The metal must have a low viscosity to be usable, and to reach this low viscosity the material needs a globular primary surrounded by the liquid phase. The temperature range possible depends on the material and for aluminum alloys is 5-10°C, but for narrow melting range copper alloys can be only several tenths of a degree.

Semi-solid casting is typically used for high-end castings. For aluminum alloys typical parts include engine suspension mounts, air manifold sensor harness, engine blocks and oil pump filter housing.

Processes

There are a number of different techniques to produce semi-solid castings. For aluminum alloys the more common processes are *thixocasting* and *rheocasting*. Other process such as *strain induced melt activation* (*SIMA*) and *RAP* can also be used with aluminum alloys, although are less common commercially.

With magnesium alloys, the most common process is *thixomolding*.

Thixocasting

Thixocasting utilizes a pre-cast billet with a non-dendritic microstructure that is normally produced by vigorously stirring the melt as the bar is being cast. Induction heating is normally used to re-heat the billets to the semi-solid temperature range, and die casting machines are used to inject the semi-solid material into hardened steels dies. Thixocasting is being performed commercially in North America, Europe and Asia. Thixocasting has the ability to produce extremely high quality components due to the product consistency that results from using pre-cast billet that is manufactured under the same ideal continuous processing conditions that are employed to make forging or rolling stock. The main disadvantage is that it is expensive due to the special billets that must be used. Other disadvantages include a limited number of alloys, and scrap cannot be directly reused.

Rheocasting

Unlike thixocasting, which re-heats a billet, rheocasting develops the semi-solid slurry from the molten metal produced in a typical die casting furnace/machine. This is a big advantage over thixocasting because it results in less expensive feedstock, in the form of typical die casting alloys, and allows for direct recycling.

There are a large number of rheocasting processes that have been proposed over the past ten years or so, and they generally differ in the method used to generate the semi-solid slurry. 18 different rheocasting techniques were documented in a recent publication. The first commercial rheocasting process was the *New Rheocasting Process* (*NRC*) developed by Ube Industries.

Thixomolding

For magnesium alloys, thixomolding uses a machine similar to injection molding. In a single step process, room temperature magnesium alloy chips are fed into the back end of a heated barrel through a volumetric feeder. The barrel is maintained under an argon atmosphere to prevent oxidation of the magnesium chips. A screw feeder located inside the barrel feeds the magnesium chips forward as they are heated into the semi-solid temperature range. The screw rotation provides the necessary shearing force to generate the globular structure needed for semi-solid casting. Once enough slurry has accumulated, the screw moves forward to inject the slurry into a steel die.

SIMA

In the SIMA method the material is first heated to the SMM temperature. As it nears the solidus temperature the grains recrystallize to form a fine grain structure. After the solidus temperature is passed the grain boundaries melt to form the SSM microstructure. For this method to work the material should be extruded or cold rolled in the half-hard tempered state. This method is limited in size to bar diameters smaller than 37 mm (1.5 in); because of this only smaller parts can be cast.

Advantages and disadvantages

The advantages of semi-solid casting are as follows:

- Complex parts produced net shape
- Porosity free
- Excellent mechanical performance
- Pressure tightness
- Tight tolerances
- Thin walls
- Heat treatable (T4/T5/T6)

Due to the lower pressures and temperatures required to die cast semi-solid metal the die material does not need to be as exotic. Oftentimes graphite or softer stainless steels are used. Even non-ferrous dies can be used for one time shots. Because of this the process can be applied to rapid prototyping needs and mass production. This also allows for the casting of high melting point metals, such as tool steel and stellite, if a higher temperature die material is used. Other advantages include: easily automated, consistent, production rates are equal to or better than die casting rates, no air entrapment, low shrinkage rates, and a uniform microstructure.

The disadvantages to SSM are: high cost of raw material due to a low number of suppliers, higher die development costs, and operators require a higher level of training. SSM cannot cast as complex or thin of parts as high-pressure die casting, however in thicker walled castings SSM has less porosity.

Chapter 4

Permanent Mold Casting

Permanent mold casting

Permanent mold casting is metal casting process that employs reusable molds ("permanent molds"), usually made from metal. The most common process uses gravity to fill the mold, however gas pressure or a vacuum are also used. A variation on the typical gravity casting process, called **slush casting**, produces hollow castings. Common casting metals are aluminum, magnesium, and copper alloys. Other materials include tin, zinc, and lead alloys and iron and steel are also cast in graphite molds.

Typical parts include gears, splines, wheels, gear housings, pipe fittings, fuel injection housings, and automotive engine pistons.

Process

There are four main types of permanent mold casting: gravity, slush, low-pressure, and vacuum.

Gravity process

The gravity process begins by preheating the mold to 150-200 °C (300-400 °F) to ease the flow and reduce thermal damage to the casting. The mold cavity is then coated with a refractory material or a mold wash, which prevents the casting from sticking to the mold and prolongs the mold life. Any sand or metal cores are then installed and the mold is clamped shut. Molten metal is then poured into the mold. Soon after solidification the mold is opened and the casting removed to reduce chances of hot tears. The process is then started all over again, but preheating is not required because the heat from the previous casting is adequate and the refractory coating should last several castings. Because this process is usually carried out on large production run workpieces automated equipment is used to coat the mold, pour the metal, and remove the casting.

The metal is poured at the lowest practical temperature in order to minimize cracks and porosity. The pouring temperature can range greatly depending on the casting material; for instance zinc alloys are poured at approximately 700 °F (371 °C), while gray iron is poured at approximately 2,500 °F (1,370 °C).

Mold

Molds for the casting process consist of two halves. Casting molds are usually formed from gray cast iron because it has about the best thermal fatigue resistance, but other materials include steel, bronze, and graphite. These metals are chosen because of their resistance to erosion and thermal fatigue. They are usually not very complex because the mold offers no collapsibility to compensate for shrinkage. Instead the mold is opened as soon as the casting is solidified, which prevents hot tears. Cores can be used and are usually made from sand or metal.

As stated above, the mold is heated prior to the first casting cycle and then used continuously in order to maintain as uniform a temperature as possible during the cycles.

This decreases thermal fatigue, facilitates metal flow, and helps control the cooling rate of the casting metal.

Venting usually occurs through the slight crack between the two mold halves, but if this is not enough then very small vent holes are used. They are small enough to let the air escape but not the molten metal. A riser must also be included to compensate for shrinkage. This usually limits the yield to less than 60%.

Mechanical ejectors in the form of pins are used when coatings are not enough to remove casts from the molds. These pins are placed throughout the mold and usually leave small round impressions on the casting.

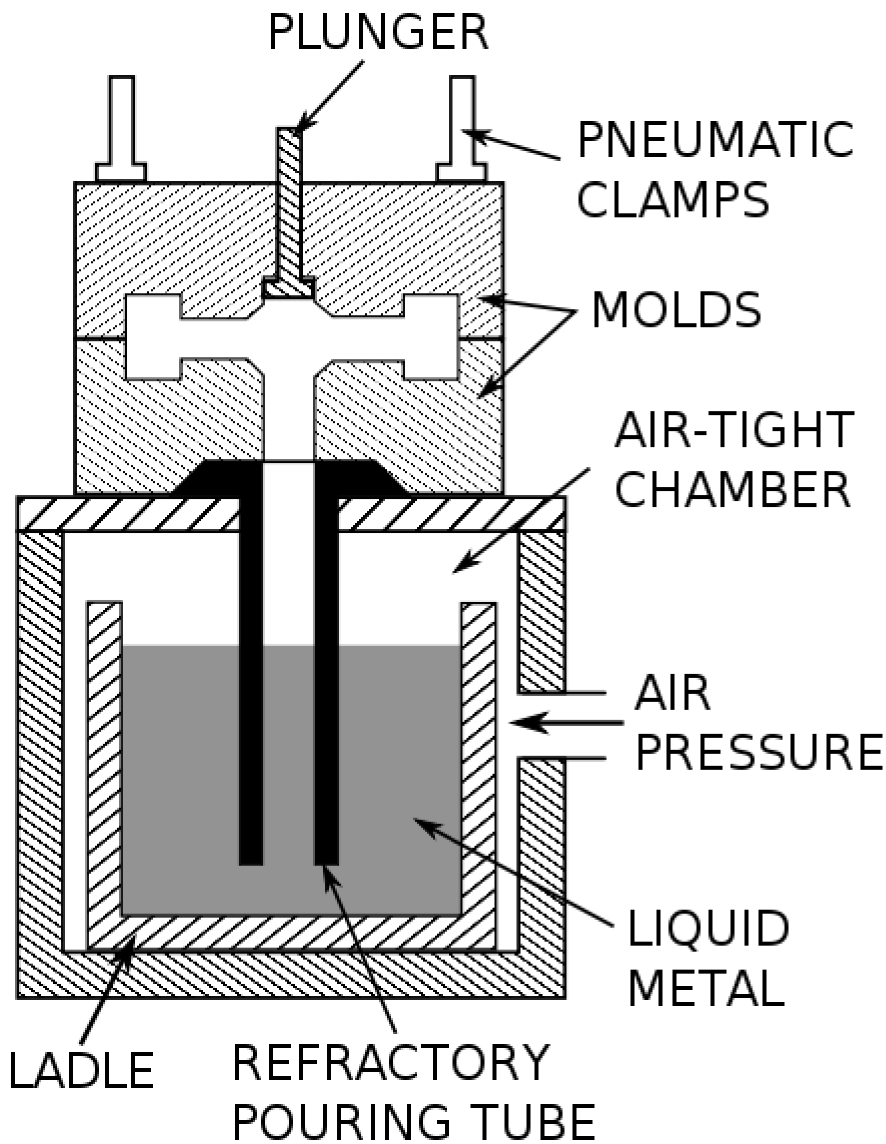
Slush

Slush casting is a variant of permanent molding casting to create a *hollow casting* or *hollow cast*. In the process the material is poured into the mold and allowed to cool until a shell of material forms in the mold. The remaining liquid is then poured out to leave a hollow shell. The resulting casting has good surface detail but the wall thickness can vary. The process is usually used to cast ornamental products, such as candlesticks, lamp bases, and statuary, from low-melting-point materials. A similar technique is used to make hollow chocolate figures for Easter and Christmas.

The method was developed by William Britain in 1893 for the production of lead toy soldiers. It uses less material than solid casting, and results in a lighter and less expensive product. Hollow cast figures generally have a small hole where the excess liquid was poured out.

Hollow casting is also used extensively for vitreous china products, such as sinks, urinals, and toilets.

Low-pressure



Schematic of the low-pressure permanent mold casting process

Low-pressure permanent mold (*LPPM*) casting uses a gas at low pressure, usually between 3 and 15 psig (20 to 100 kPag) to push the molten metal into the mold cavity. The pressure is applied to the top of the pool of liquid, which forces the molten metal up a refractory pouring tube and finally into the bottom of the mold. The pouring tube extends to the bottom of the ladle so that the material being pushed into the mold is exceptionally clean. No risers are required because the applied pressure forces molten metal in to compensate for shrinkage. Yields are usually greater than 85% because there is no riser and any metal in the pouring tube just falls back into the ladle for reuse.

The vast majority of LPPM casting are from aluminum and magnesium, but some are copper alloys. Advantages include very little turbulence when filling the mold because of the constant pressure, which minimizes gas porosity and dross formation. Mechanical properties are about 5% better than gravity permanent mold castings. The disadvantage is that cycles times are longer than gravity permanent mold castings.

Vacuum

Vacuum permanent mold casting retains all of the advantages of LPPM casting, plus the dissolved gases in the molten metal are minimized and molten metal cleanliness is even better. The process can handle thin-walled profiles and gives an excellent surface finish. Mechanical properties are usually 10 to 15% better than gravity permanent mold castings. The process is limited in weight to 0.2 to 5 kg (0.44 to 11 lb).

Advantages and disadvantages

The main advantages are the reusable mold, good surface finish, and good dimensional accuracy. Typical tolerances are 0.4 mm for the first 25 mm (0.015 in for the first inch) and 0.02 mm for each additional centimeter (0.002 in per in); if the dimension crosses the parting line add an additional 0.25 mm (0.0098 in). Typical surface finishes are 2.5 to 7.5 µm (100–250 µin) RMS. A draft of 2 to 3° is required. Wall thicknesses are limited to 3 to 50 mm (0.12 to 2.0 in). Typical part sizes range from 100 g to 75 kg (several ounces to 150 lb). Other advantages include the ease of inducing directional solidification by changing the mold wall thickness or by heating or cooling portions of the mold. The fast cooling rates created by using a metal mold results in a finer grain structure than sand casting. Retractable metal cores can be used to create undercuts while maintaining a quick action mold.

There are three main disadvantages: high tooling cost, limited to low-melting-point metals, and short mold life. The high tooling costs make this process uneconomical for small production runs. When the process is used to cast steel or iron the mold life is extremely short. For lower melting point metals the mold life is longer but thermal fatigue and erosion usually limit the life to 10,000 to 120,000 cycles. The mold life is dependent on four factors: the mold material, the pouring temperature, the mold temperature, and the mold configuration. The pouring temperature is dependent on the casting metal, but the higher the pouring temperature the shorter the mold life. A high pouring temperature can also induce shrinkage problems and create longer cycle times. If the mold temperature is too low misruns are produced, but if the mold temperature is too high then the cycle time is prolonged and mold erosion is increased. Large differences in section thickness in the mold or casting can decrease mold life as well.

Chapter 5

Sand Casting

Sand casting, also known as **sand molded casting**, is a metal casting process characterized by using sand as the mold material.

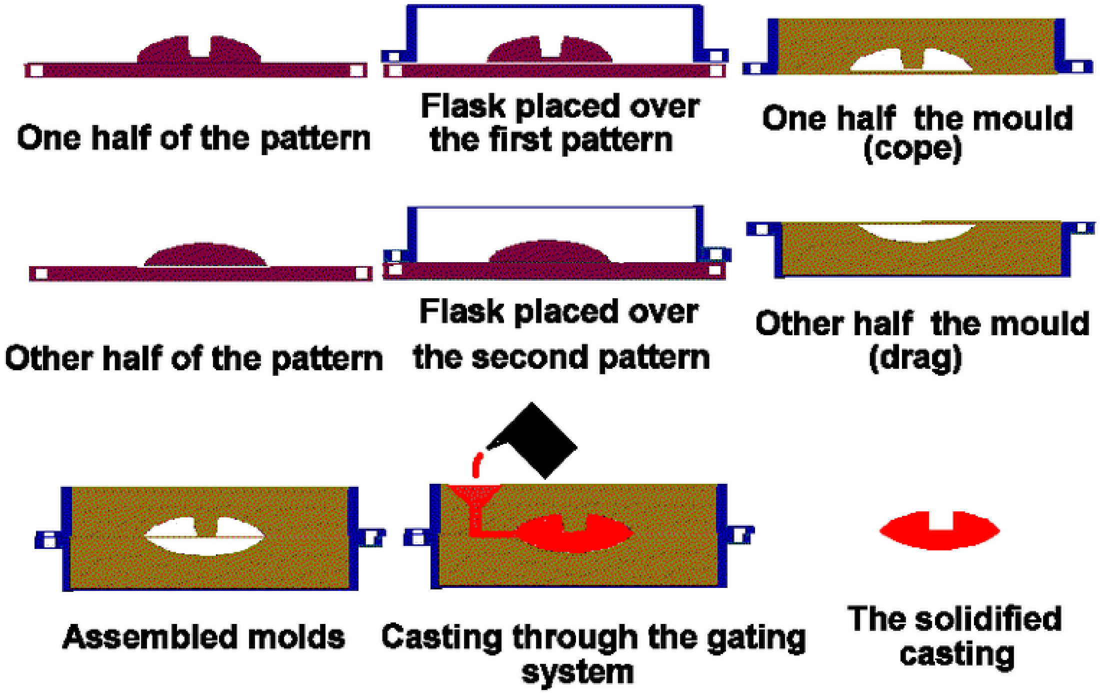
It is relatively cheap and sufficiently refractory even for steel foundry use. A suitable bonding agent (usually clay) is mixed or occurs with the sand. The mixture is moistened with water to develop strength and plasticity of the clay and to make the aggregate suitable for molding. The term "sand casting" can also refer to a casting produced via the sand casting process. Sand castings are produced in specialized factories called foundries.

Over 70% of all metal castings are produced via a sand casting process.

Basic process

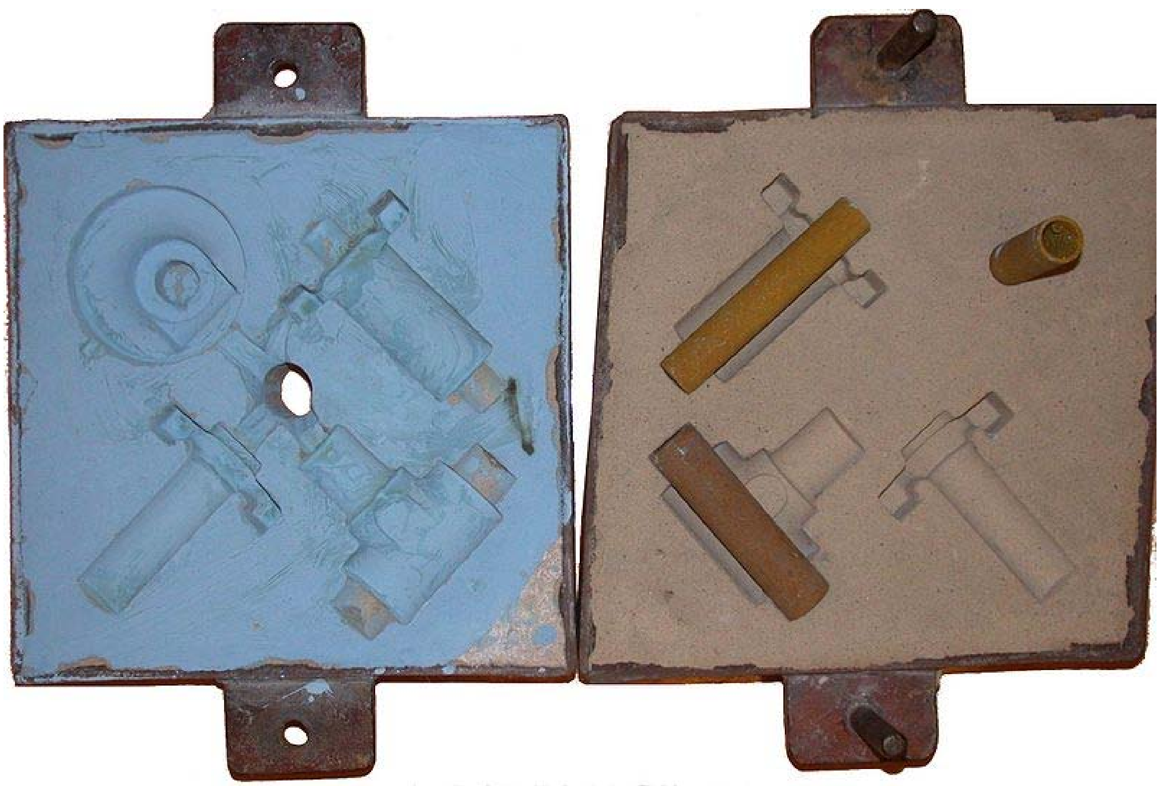
There are six steps in this process:

1. Place a pattern in sand to create a mold.
2. Incorporate the pattern and sand in a gating system.
3. Remove the pattern.
4. Fill the mold cavity with molten metal.
5. Allow the metal to cool.
6. Break away the sand mold and remove the casting.



Components

Patterns



Cope & drag (top and bottom halves of a sand mold), with cores in place on the drag

From the design, provided by an engineer or designer, a skilled *pattern maker* builds a *pattern* of the object to be produced, using wood, metal, or a plastic such as expanded polystyrene. Sand can be ground, swept or even strickled into shape. The metal to be cast will contract during solidification, and this may be non-uniform due to uneven cooling. Therefore, the pattern must be slightly larger than the finished product, a difference known as *contraction allowance*. Pattern-makers are able to produce suitable patterns using 'Contraction rules' (these are sometimes called "shrink allowance rulers" where the ruled markings are deliberately made to a larger spacing according to the percentage of extra length needed). Different scaled rules are used for different metals because each metal and alloy contracts by an amount distinct from all others. Patterns also have core prints that create registers within the molds into which are placed sand '*cores*. Such cores, sometimes reinforced by wires, are used to create under cut profiles and cavities which cannot be molded with the cope and drag, such as the interior passages of valves or cooling passages in engine blocks.

Paths for the entrance of metal into the mold cavity constitute the runner system and include the sprue, various feeders which maintain a good metal 'feed', and in-gates which attach the runner system to the casting cavity. Gas and steam generated during casting exit through the permeable sand or via risers, which are added either in the pattern itself, or as separate pieces.

Molding box and materials

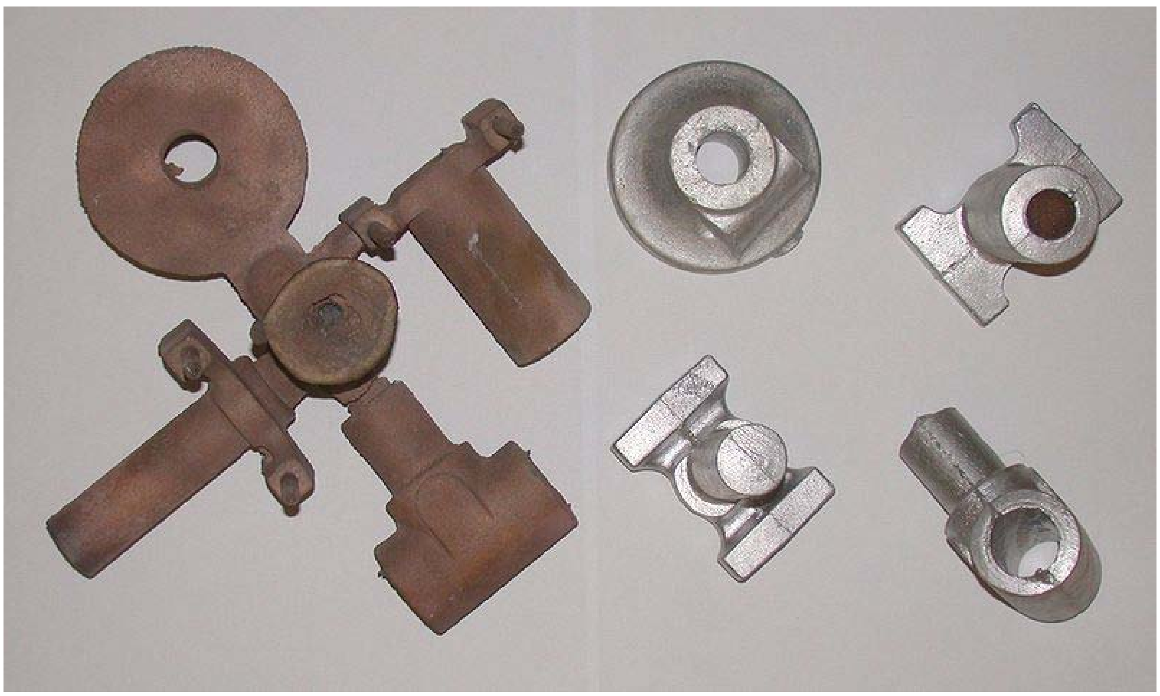
A multi-part molding box (known as a casting flask, the top and bottom halves of which are known respectively as the cope and drag) is prepared to receive the pattern. Molding boxes are made in segments that may be latched to each other and to end closures. For a simple object—flat on one side—the lower portion of the box, closed at the bottom, will be filled with a molding sand. The sand is packed in through a vibratory process called ramming and, in this case, periodically screeded level. The surface of the sand may then be stabilized with a sizing compound. The pattern is placed on the sand and another molding box segment is added. Additional sand is rammed over and around the pattern. Finally a cover is placed on the box and it is turned and unlatched, so that the halves of the mold may be parted and the pattern with its sprue and vent patterns removed. Additional sizing may be added and any defects introduced by the removal of the pattern are corrected. The box is closed again. This forms a "green" mold which must be dried to receive the hot metal. If the mold is not sufficiently dried a steam explosion can occur that can throw molten metal about. In some cases, the sand may be oiled instead of moistened, which makes possible casting without waiting for the sand to dry. Sand may also be bonded by chemical binders, such as furane resins or amine-hardened resins.

Chills

To control the solidification structure of the metal, it is possible to place metal plates, *chills*, in the mold. The associated rapid local cooling will form a finer-grained structure and may form a somewhat harder metal at these locations. In ferrous castings the effect is similar to quenching metals in forge work. The inner diameter of an engine cylinder is made hard by a chilling core. In other metals chills may be used to promote directional solidification of the casting. In controlling the way a casting freezes it is possible to prevent internal voids or porosity inside castings.

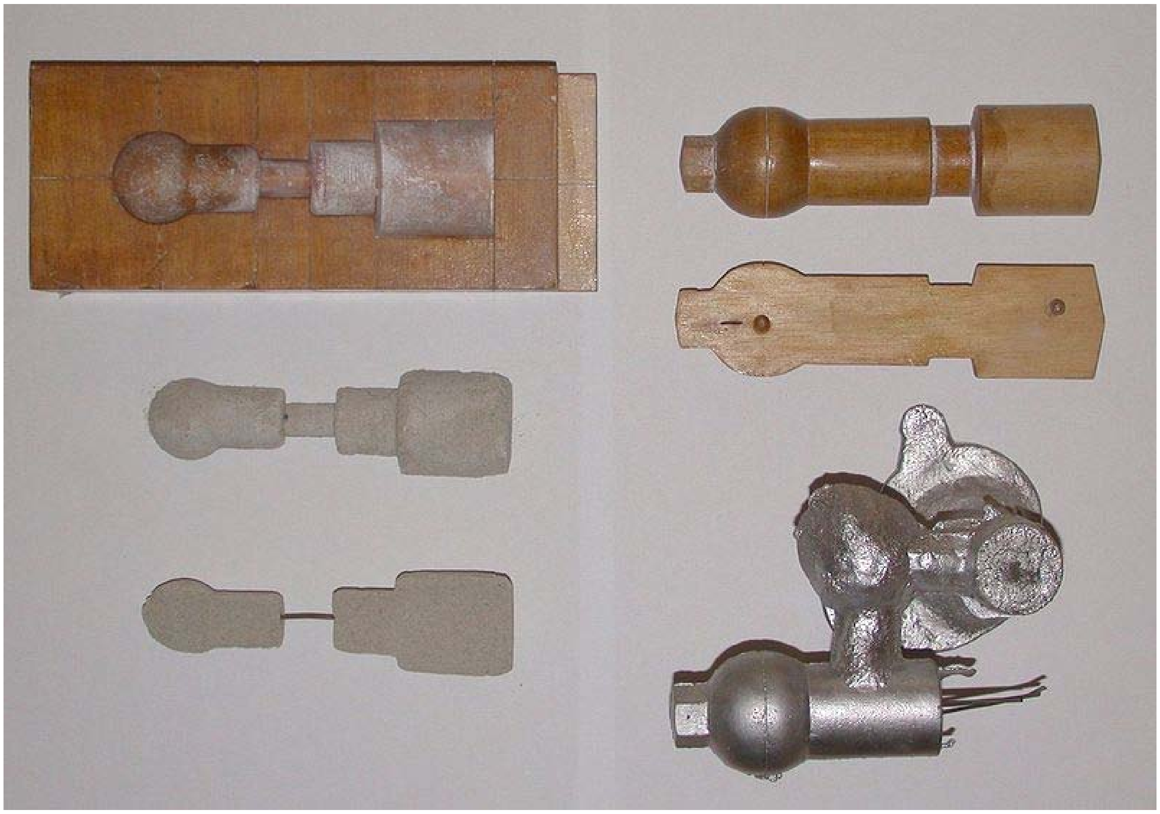
Cores

To produce cavities within the casting—such as for liquid cooling in engine blocks and cylinder heads—negative forms are used to produce *cores*. Usually sand-molded, cores are inserted into the casting box after removal of the pattern. Whenever possible, designs are made that avoid the use of cores, due to the additional set-up time and thus greater cost.



Two sets of castings (bronze and aluminium) from the above sand mold

With a completed mold at the appropriate moisture content, the box containing the sand mold is then positioned for filling with molten metal—typically iron, steel, bronze, brass, aluminium, magnesium alloys, or various pot metal alloys, which often include lead, tin, and zinc. After filling with liquid metal the box is set aside until the metal is sufficiently cool to be strong. The sand is then removed revealing a rough casting that, in the case of iron or steel, may still be glowing red. When casting with metals like iron or lead, which are significantly heavier than the casting sand, the casting flask is often covered with a heavy plate to prevent a problem known as *floating the mold*. Floating the mold occurs when the pressure of the metal pushes the sand above the mold cavity out of shape, causing the casting to fail.



Left: Corebox, with resulting (wire reinforced) cores directly below. Right:- Pattern (used with the core) and the resulting casting below (the wires are from the remains of the core)

After casting, the cores are broken up by rods or shot and removed from the casting. The metal from the sprue and risers is cut from the rough casting. Various heat treatments may be applied to relieve stresses from the initial cooling and to add hardness—in the case of steel or iron, by quenching in water or oil. The casting may be further strengthened by surface compression treatment—like shot peening—that adds resistance to tensile cracking and smooths the rough surface.

Design requirements

The part to be made and its pattern must be designed to accommodate each stage of the process, as it must be possible to remove the pattern without disturbing the molding sand and to have proper locations to receive and position the cores. A slight taper, known as draft, must be used on surfaces perpendicular to the parting line, in order to be able to remove the pattern from the mold. This requirement also applies to cores, as they must be removed from the core box in which they are formed. The sprue and risers must be arranged to allow a proper flow of metal and gasses within the mold in order to avoid an incomplete casting. Should a piece of core or mold become dislodged it may be embedded in the final casting, forming a *sand pit*, which may render the casting unusable. Gas pockets can cause internal voids. These may be immediately visible or may only be revealed after extensive machining has been performed. For critical applications, or where the cost of wasted effort is a factor, non-destructive testing methods may be applied before further work is performed.

Processes

In general, we can distinguish between two methods of sand casting; the first one using *green sand* and the second being the *air set* method.

Green sand

These expendable molds are made of wet sands that are used to make the mold's shape. The name comes from the fact that wet sands are used in the molding process. Green sand is not green in color, but "green" in the sense that it is used in a wet state (akin to green wood). Unlike the name suggests, "green sand" is not a type of sand on its own, but is rather a mixture of:

- silica sand (SiO_2), or chromite sand ($FeCr_2O$), or zircon sand ($ZrSiO_4$), 75 to 85%
- bentonite (clay), 5 to 11%
- water, 2 to 4%
- inert sludge 3 to 5%
- anthracite (0 to 1%)

There are many recipes for the proportion of clay, but they all strike different balances between moldability, surface finish, and ability of the hot molten metal to degas. The coal, typically referred to in foundries as sea-coal, which is present at a ratio of less than 5%, partially combusts in the presence of the molten metal leading to offgassing of organic vapors.

The "air set" method

The *air set* method uses dry sand bonded with materials other than clay, using a fast curing adhesive. The latter may also be referred to as no bake mold casting. When these are used, they are collectively called "air set" sand castings to distinguish them from "green sand" castings. Two types of molding sand are natural bonded (bank sand) and synthetic (lake sand); the latter is generally preferred due to its more consistent composition.

With both methods, the sand mixture is packed around a master *pattern*, forming a mold cavity. If necessary, a temporary plug is placed in the sand and touching the pattern in order to later form a channel into which the casting fluid can be poured. Air-set molds are often formed with the help of a two-part mold having a top and bottom part, termed the cope and drag. The sand mixture is tamped down as it is added around the pattern, and the final mold assembly is sometimes vibrated to compact the sand and fill any unwanted voids in the mold. Then the pattern is removed along with the channel plug, leaving the mold cavity. The casting liquid (typically molten metal) is then poured into the mold cavity. After the metal has solidified and cooled, the casting is separated from the sand mold. There is typically no mold release agent, and the mold is generally destroyed in the removal process.

The accuracy of the casting is limited by the type of sand and the molding process. Sand castings made from coarse green sand impart a rough texture to the surface, and this makes them easy to identify. Air-set molds can produce castings with much smoother surfaces. Surfaces can also be later ground and polished, for example when making a large bell. After molding, the casting is covered with a residue of oxides, silicates and other compounds. This residue can be removed by various means, such as grinding, or shot blasting.

During casting, some of the components of the sand mixture are lost in the thermal casting process. Green sand can be reused after adjusting its composition to replenish the lost moisture and additives. The pattern itself can be reused indefinitely to produce new sand molds. The sand molding process has been used for many centuries to produce castings manually. Since 1950, partially-automated casting processes have been developed for production lines.

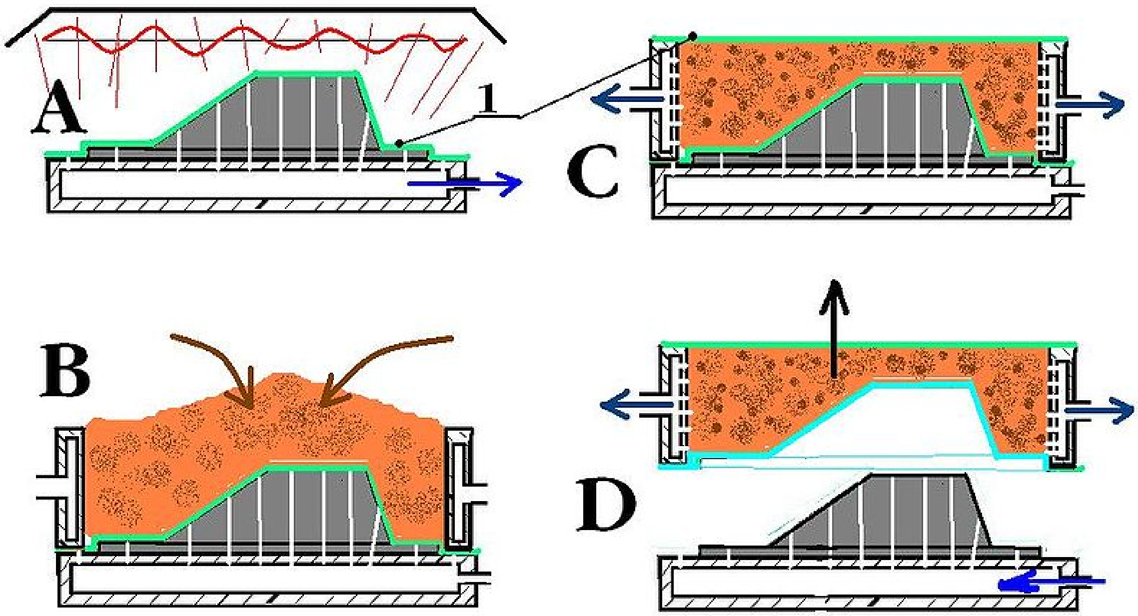
Cold box

Uses organic and inorganic binders that strengthen the mold by chemically adhering to the sand. This type of mold gets its name from not being baked in an oven like other sand mold types. This type of mold is more accurate dimensionally than green-sand molds but are more expensive.

No bake molds

No bake molds are expendable sand molds, similar to typical sand molds, except they also contain a quick-setting liquid resin and catalyst. Rather than being rammed, the molding sand is poured into the flask and held until the resin solidifies, which occurs at room temperature. This type of molding also produces a better surface finish than other types of sand molds. Because no heat is involved it is called a cold-setting process. Common flask materials that are used are wood, metal, and plastic. Common metals cast into no bake molds are brass, ferric, and aluminum alloys.

Vacuum molding



A schematic of vacuum molding

Vacuum molding (*V-process*) is a variation of the sand casting process for most ferrous and non-ferrous metals, in which unbonded sand is held in the flask with a vacuum. The pattern is specially vented so that a vacuum can be pulled through it. A heat-softened thin sheet (0.003 to 0.008 in (0.076 to 0.20 mm)) of plastic film is draped over the pattern and a vacuum is drawn (200 to 400 mmHg (27 to 53 kPa)). A special vacuum forming flask is placed over the plastic pattern and is filled with a free-flowing sand. The sand is vibrated to compact the sand and a sprue and pouring cup are formed in the cope. Another sheet of plastic is placed over the top of the sand in the flask and a vacuum is drawn through the special flask; this hardens and strengthens the unbonded sand. The vacuum is then released on the pattern and the cope is removed. The drag is made in the same way (without the sprue and pouring cup). Any cores are set in place and the mold is closed. The molten metal is poured while the cope and drag are still under a vacuum, because the plastic vaporizes but the vacuum keeps the shape of the sand while the metal solidifies. When the metal has solidified, the vacuum is turned off and the sand runs out freely, releasing the casting.

The V-process is known for not requiring a draft because the plastic film has a certain degree of lubricity and it expands slightly when the vacuum is drawn in the flask. The process has high dimensional accuracy, with a tolerance of ±0.010 in for the first inch and ±0.002 in/in thereafter. Cross-sections as small as 0.090 in (2.3 mm) are possible. The surface finish is very good, usually between 150 to 125 rms. Other advantages include no moisture related defects, no cost for binders, excellent sand permeability, and no toxic fumes from burning the binders. Finally, the pattern does not wear out because the sand does not touch it. The main disadvantage is that the process is slower than traditional sand casting so it is only suitable for low to medium production volumes; approximately 10 to 15,000 pieces a year. However, this makes it perfect for prototype work, because the pattern can be easily modified as it is made from plastic.

DISAMATIC

Fast mold making processes

With the fast development of the car and machine building industry the casting consuming areas called for steady higher productivity. The basic process stages of the mechanical molding and casting process are similar to those described under the manual sand casting process. The technical and mental development however was so rapid and profound that the character of the sand casting process changed radically.

Mechanized sand molding

The first mechanized molding lines consisted of sand slingers and/or jolt-squeeze devices that compacted the sand in the flasks. Subsequent mold handling was mechanical using cranes, hoists and straps. After core setting the copes and drags were coupled using guide pins and clamped for closer accuracy. The molds were manually pushed off on a roller conveyor for casting and cooling.

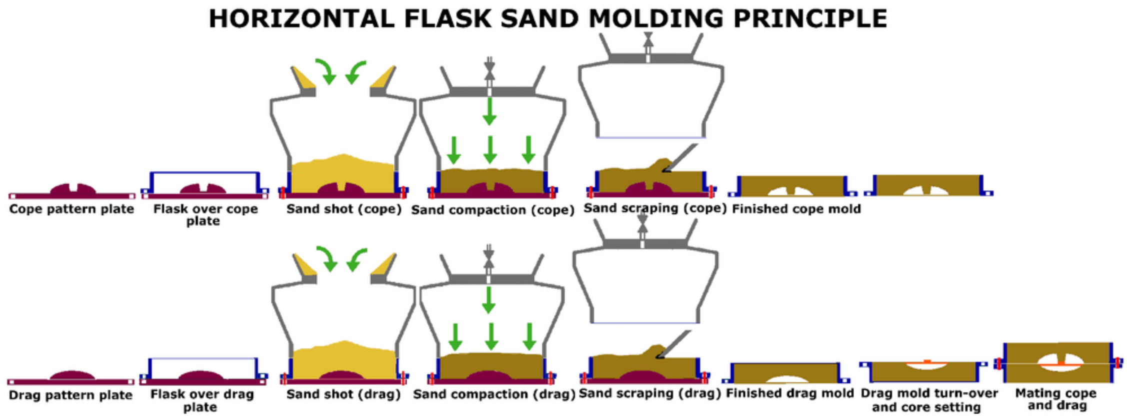
Automatic high pressure sand molding lines

Increasing quality requirements made it necessary to increase the mold stability by applying steadily higher squeeze pressure and modern compaction methods for the sand in the flasks. In early fifties the high pressure molding was developed and applied in mechanical and later automatic flask lines. The first lines were using jolting and vibrations to pre-compact the sand in the flasks and compressed air powered pistons to compact the molds.

Horizontal sand flask molding

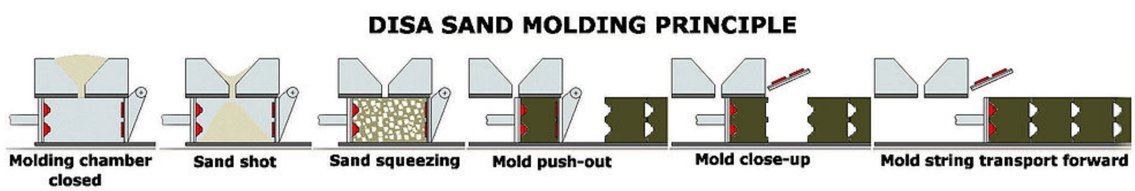
In the first automatic horizontal flask lines the sand was shot or slung down on the pattern in a flask and squeezed with hydraulic pressure of up to 140 bars. The subsequent mold handling including turn-over, assembling, pushing-out on a conveyor were accomplished either manually or automatically. In the late fifties hydraulically powered pistons or multi-piston systems were used for the sand compaction in the flasks. This method produced much more stable and accurate molds than it was possible manually or pneumatically. In the late sixties mold compaction by fast air pressure or gas pressure drop over the pre-compacted sand mold was developed (sand-impulse and gas-impact). The general working principle for most of the horizontal flask line systems is shown on the sketch below.

Today there are many manufacturers of the automatic horizontal flask molding lines. The major disadvantages of these systems is high spare parts consumption due to multitude of movable parts, need of storing, transporting and maintaining the flasks and productivity limited to approximately 90–120 molds per hour.



Vertical sand flaskless molding

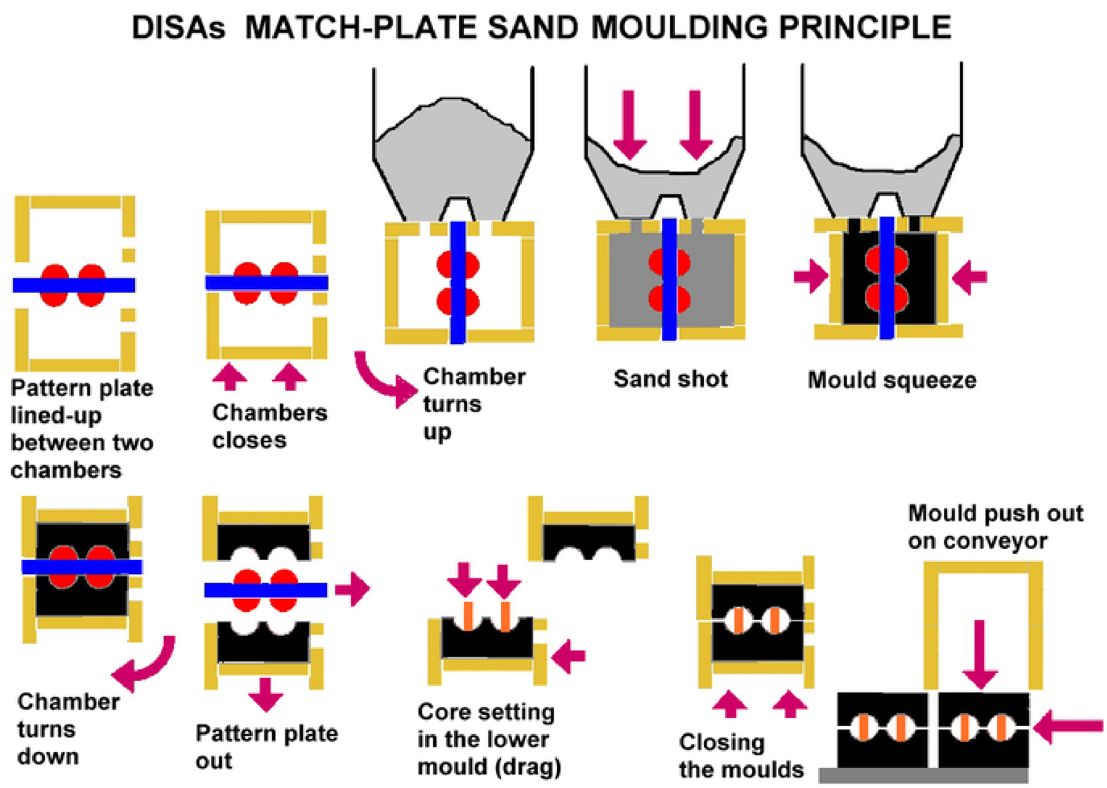
In 1962, Dansk Industri Syndikat A/S (DISA) invented a flask-less molding process by using vertically parted and poured molds. The first line could produce up to 240 complete sand molds per hour. Today molding lines can achieve a molding rate of 550 sand molds per hour and requires only one monitoring operator. Maximum mismatch of two mold halves is 0.1 mm (0.0039 in).



Matchplate sand molding

The principle of the matchplate, meaning pattern plates with two patterns on each side of the same plate, was developed and patented in 1910, fostering the perspectives for future sand molding improvements. However, first in the early sixties the American company Hunter Automated Machinery Corporation launched its first automatic flaskless, horizontal molding line applying the matchplate technology.

The method alike to the DISA's vertical moulding is flaskless, however horizontal. The matchplate molding technology is today used widely. Its great advantage is inexpensive pattern tooling, easiness of changing the molding tooling, thus suitability for manufacturing castings in short series so typical for the jobbing foundries. Modern matchplate molding machine is capable of high molding quality, less casting shift due to machine-mold mismatch (in some cases less than 0.15 mm (0.0059 in)), consistently stable molds for less grinding and improved parting line definition. In addition, the machines are enclosed for a cleaner, quieter working environment with reduced operator exposure to safety risks or service-related problems.



Mold materials

There are four main components for making a sand casting mold: *base sand*, a *binder*, *additives*, and a *parting compound*.

Molding sands

Molding sands, also known as *foundry sands*, are defined by eight characteristics: refractoriness, chemical inertness, permeability, surface finish, cohesiveness, flowability, collapsibility, and availability/cost.

Refractoriness — This refers to the sand's ability to withstand the temperature of the liquid metal being cast without breaking down. For example some sands only need to withstand 650 °C (1,202 °F) if casting aluminum alloys, whereas steel needs a sand that will withstand 1,500 °C (2,730 °F). Sand with too low a refractoriness will melt and fuse to the casting.

Chemical inertness — The sand must not react with the metal being cast. This is especially important with highly reactive metals, such as magnesium and titanium.

Permeability — This refers to the sand's ability to exhaust gases. This is important because during the pouring process many gases are produced, such as hydrogen, nitrogen, carbon dioxide, and steam, which must leave the mold otherwise casting defects, such as blow holes and gas holes, occur in the casting. Note that for each cubic centimeter (cc) of water added to the mold 16,000 cc of steam is produced.

Surface finish — The size and shape of the sand particles defines the best surface finish achievable, with finer particles producing a better finish. However, as the particles become finer (and surface finish improves) the permeability becomes worse.

Cohesiveness (or **bond**) — This is the ability of the sand to retain a given shape after the pattern is removed.

Flowability – The ability for the sand to flow into intricate details and tight corners without special processes or equipment.

Collapsibility — This is the ability of the sand to be easily stripped off the casting after it has solidified. Sands with poor collapsibility will adhere strongly to the casting. When casting metals that contract a lot during cooling or with long freezing temperature ranges a sand with poor collapsibility will cause cracking and hot tears in the casting. Special additives can be used to improve collapsibility.

Availability/cost — The availability and cost of the sand is very important because for every ton (0.9 tonne) of metal poured three to six tons (2.7–5.4 tonnes) of sand is required. Moreover, most of the sand cannot be reused after it is used, because it is damaged during the casting process.

In large castings it is economical to use two different sands, because the majority of the sand will not be in contact with the casting, so it does not need any special properties. The sand that is in contact with the casting is called *facing sand*, and is designed for the casting on hand. This sand will be built up around the pattern to a thickness of 30 to 100 mm (1.2 to 3.9 in). The sand that fills in around the facing sand is called *backing sand*. This sand is simply silica sand with only a small amount of binder and no special additives.

Types of base sands

Base sand is the type used to make the mold or core without any binder. Because it does not have a binder it will not bond together and is not usable in this state.

Silica sand

Silica (SiO_2) sand is the stereotype sand (i.e. the sand found on a beach) and is also the most commonly used sand. It is made by either crushing sandstone or taken from natural occurring locations, such as beaches and river beds. The fusion point of pure silica is 1,760 °C (3,200 °F), however the sands used have a lower melting point due to impurities. For high melting point casting, such as steels, a minimum of 98% pure silica sand must be used; however for lower melting point metals, such as cast iron and non-ferrous metals, a lower purity sand can be used (between 94 and 98% pure).

Silica sand is the most commonly used sand because of its great abundance, and, thus, low cost (therein being its greatest advantage). Its disadvantages are high thermal expansion, which can cause casting defects with high melting point metals, and low thermal conductivity, which can lead to unsound casting. It also cannot be used with certain basic metal because it will chemically interact with the metal forming surface defect. Finally, it causes silicosis in foundry workers.

Olivine sand

Olivine is a mixture of orthosilicates of iron and magnesium from the mineral dunite. Its main advantage is that it is free from silica, therefore it can be used with basic metals, such as manganese steels. Other advantages include a low thermal expansion, high thermal conductivity, and high fusion point. Finally, it is safer to use than silica, therefore it is popular in Europe.

Chromite sand

Chromite sand is a solid solution of spinels. Its advantages are a low percentage of silica, a very high fusion point (1,850 °C (3,360 °F)), and a very high thermal conductivity. Its disadvantage is its costliness, therefore its only used with expensive alloy steel casting and to make cores.

Zircon sand

Zircon sand is a compound of approximately two-thirds zircon oxide (Zr_2O) and one-third silica. It has the highest fusion point of all the base sands at 2,600 °C (4,710 °F), a very low thermal expansion, and a high thermal conductivity. Because of these good properties it is commonly used when casting alloy steels and other expensive alloys. It is also used as a mold wash (a coating applied to the molding cavity) to improve surface finish. However, it is expensive and not readily available.

Chamotte sand

Chamotte is made by calcining fire clay (Al_2O_3-SiO_2) above 1,100 °C (2,010 °F). Its fusion point is 1,750 °C (3,180 °F) and has low thermal expansion. It is the second cheapest sand, however it is still twice as expensive as silica. Its disadvantages are very coarse grains, which result in a poor surface finish, and it is limited to dry sand molding. Mold washes are used to overcome the surface finish problem. This sand is usually used when casting large steel workpieces.

Other materials

Modern casting production methods can manufacture thin and accurate molds—of a material superficially resembling papier-mâché, such as is used in egg cartons, but that is refractory in nature—that are then supported by some means, such as dry sand surrounded by a box, during the casting process. Due to the higher accuracy it is possible to make thinner and hence lighter castings, because extra metal need not be present to allow for variations in the molds. These thin-mold casting methods have been used since the 1960s in the manufacture of cast-iron engine blocks and cylinder heads for automotive applications.

Binders

Binders are added to a base sand to bond the sand particles together (i.e. it is the glue that holds the mold together).

Clay and water

A mixture of clay and water is the most commonly used binder. There are two types of clay commonly used: bentonite and kaolinite, with the former being the most common.

Oil

Oils, such as linseed oil, other vegetable oils and marine oils, used to be used as a binder, however due to their increasing cost, they have been mostly phased out. The oil also required careful baking at 100 to 200 °C (212 to 392 °F) to cure (if overheated the oil becomes brittle, wasting the mold).

Resin

Resin binders are natural or synthetic high melting point gums. The two common types used are urea formaldehyde (UF) and phenol formaldehyde (PF) resins. PF resins have a higher heat resistance than UF resins and cost less. There are also cold-set resins, which use a catalyst instead of a heat to cure the binder. Resin binders are quite popular because different properties can be achieved by mixing with various additives. Other advantages include good collapsability, low gassing, and they leave a good surface finish on the casting.

Sodium silicate

Sodium silicate [Na_2SiO_3 or $(Na_2O)(SiO_2)$] is a high strength binder used with silica molding sand. To cure the binder carbon dioxide gas is used, which creates the following reaction:

$$Na_2O(SiO_2) + CO_2 \rightleftharpoons Na_2CO_3 + 2SiO_2 + Heat$$

The advantage to this binder is that it occurs at room temperature and quickly. The disadvantage is that its high strength leads to shakeout difficulties and possibly hot tears in the casting.

Additives

Additives are added to the molding components to improve: surface finish, dry strength, refractoriness, and "cushioning properties".

Up to 5% of *reducing agents*, such as coal powder, pitch, creosote, and fuel oil, may be added to the molding material to prevent wetting (prevention of liquid metal sticking to sand particles, thus leaving them on the casting surface), improve surface finish, decrease metal penetration, and burn-on defects. These additives achieve this by creating gases at the surface of the mold cavity, which prevent the liquid metal from adhering to the sand. Reducing agents are not used with steel casting, because they can carburize the metal during casting.

Up to 3% of "cushioning material", such as wood flour, saw dust, powdered husks, peat, and straw, can be added to reduce scabbing, hot tear, and hot crack casting defects when casting high temperature metals. These materials are beneficial because burn-off when the metal is poured creating voids in the mold, which allow it to expand. They also increase collapsibility and reduce shakeout time.

Up to 2% of *cereal binders*, such as dextrin, starch, sulphite lye, and molasses, can be used to increase dry strength (the strength of the mold after curing) and improve surface finish. Cereal binders also improve collapsibility and reduce shakeout time because they burn-off when the metal is poured. The disadvantage to cereal binders is that they are expensive.

Up to 2% of iron oxide powder can be used to prevent mold cracking and metal penetration, essentially improving refractoriness. Silica flour (fine silica) and zircon flour also improve refractoriness, especially in ferrous castings. The disadvantages to these additives is that they greatly reduce permeability.

Parting compounds

To get the pattern out of the mold, prior to casting, a parting compound is applied to the pattern to ease removal. They can be a liquid or a fine powder (particle diameters between 75 and 150 micrometres (0.0030 and 0.0059 in)). Common powders include talc, graphite, and dry silica; common liquids include mineral oil and water-based silicon solutions. The latter are more commonly used with metal and large wooden patterns.

History

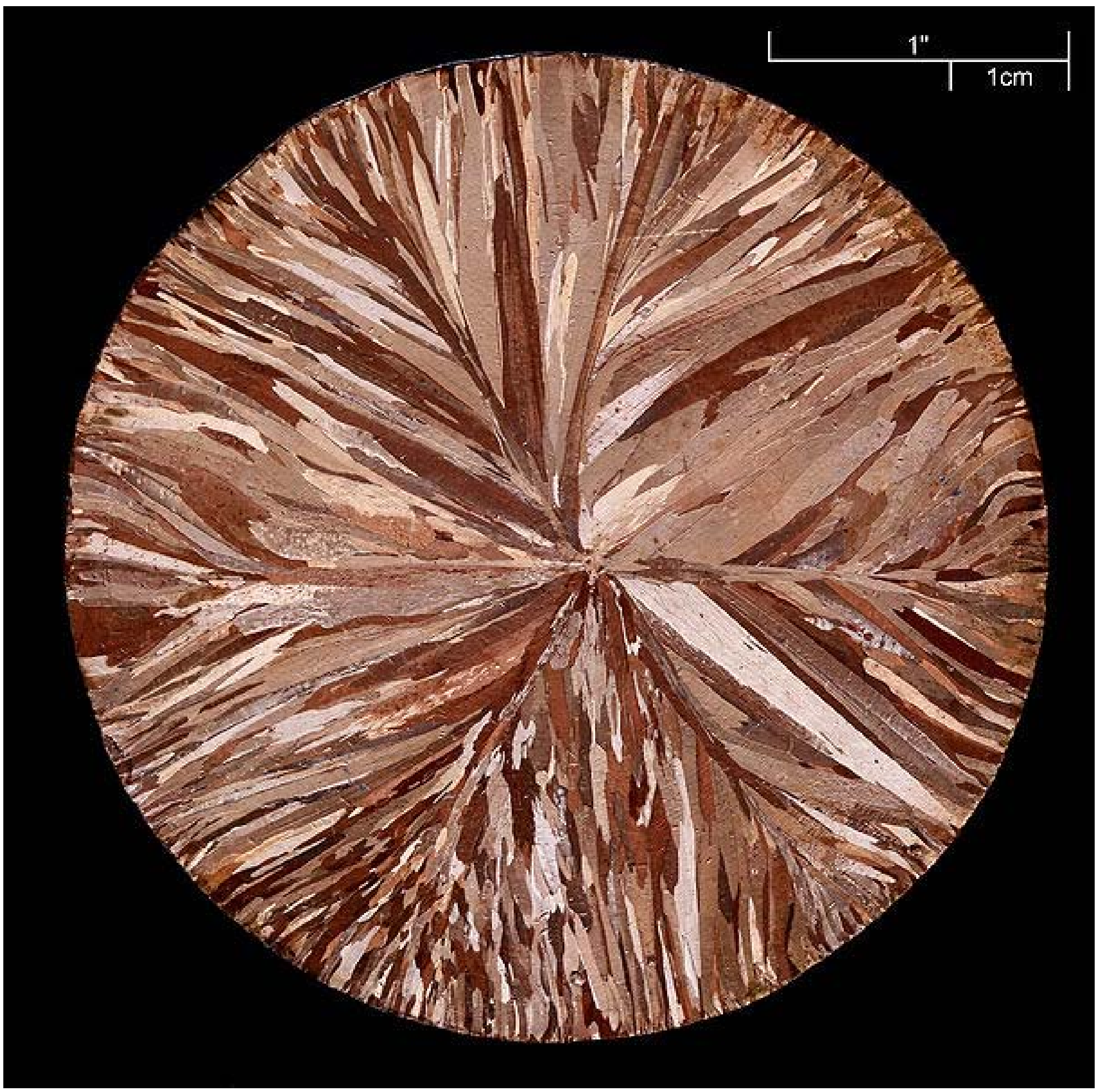
In 1924, the Ford automobile company set a record by producing 1 million cars, in the process consuming one-third of the total casting production in the U.S. As the automobile industry grew the need for increased casting efficiency grew. The increasing demand for castings in the growing car and machine building industry during and after World War I and World War II, stimulated new inventions in mechanization and later automation of the sand casting process technology.

There was not one bottleneck to faster casting production but rather several. Improvements were made in molding speed, molding sand preparation, sand mixing, core manufacturing processes, and the slow metal melting rate in cupola furnaces. In 1912, the sand slinger was invented by the American company Birdsley & Piper. In 1912, the first sand mixer with individually mounted revolving plows was marketed by the Simpson Company. In 1915, the first experiments started with bentonite clay instead of simple fire clay as the bonding additive to the molding sand. This increased tremendously the green and dry strength of the molds. In 1918, the first fully automated foundry for fabricating hand grenades for the U.S. Army went into production. In the 1930s the first high-frequency coreless electric furnace was installed in the U.S. In 1943, ductile iron was invented by adding magnesium to the widely used grey iron. In 1940, thermal sand reclamation was applied for molding and core sands. In 1952, the "D-process" was developed for making shell molds with fine, pre-coated sand. In 1953, the hotbox core sand process in which the cores are thermally cured was invented. In 1954, a new core binder - water glass hardened with CO_2 from the ambient air, was applied.

Chapter 6

Continuous Casting & Lost-Foam Casting

Continuous Casting

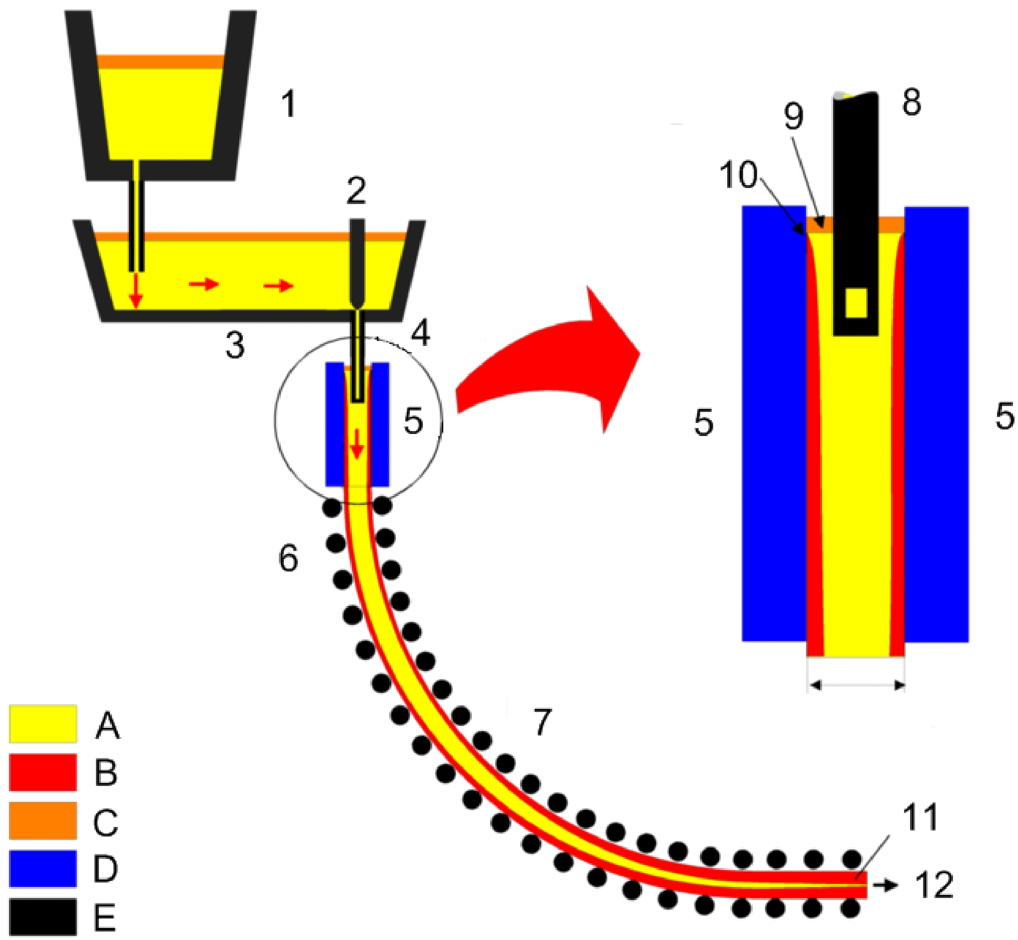


The macrosctructure of continuously cast copper (99.95% pure), etched, ⌀ ≈ 83 mm.

Continuous casting, also called **strand casting**, is the process whereby molten metal is solidified into a "semifinished" billet, bloom, or slab for subsequent rolling in the finishing mills. Prior to the introduction of continuous casting in the 1950s, steel was poured into stationary molds to form ingots. Since then, "continuous casting" has evolved to achieve improved yield, quality, productivity and cost efficiency. It allows lower-cost production of metal sections with better quality, due to the inherently lower costs of continuous, standardised production of a product, as well as providing increased control over the process through automation. This process is used most frequently to cast steel (in terms of tonnage cast). Aluminium and copper are also continuously cast.

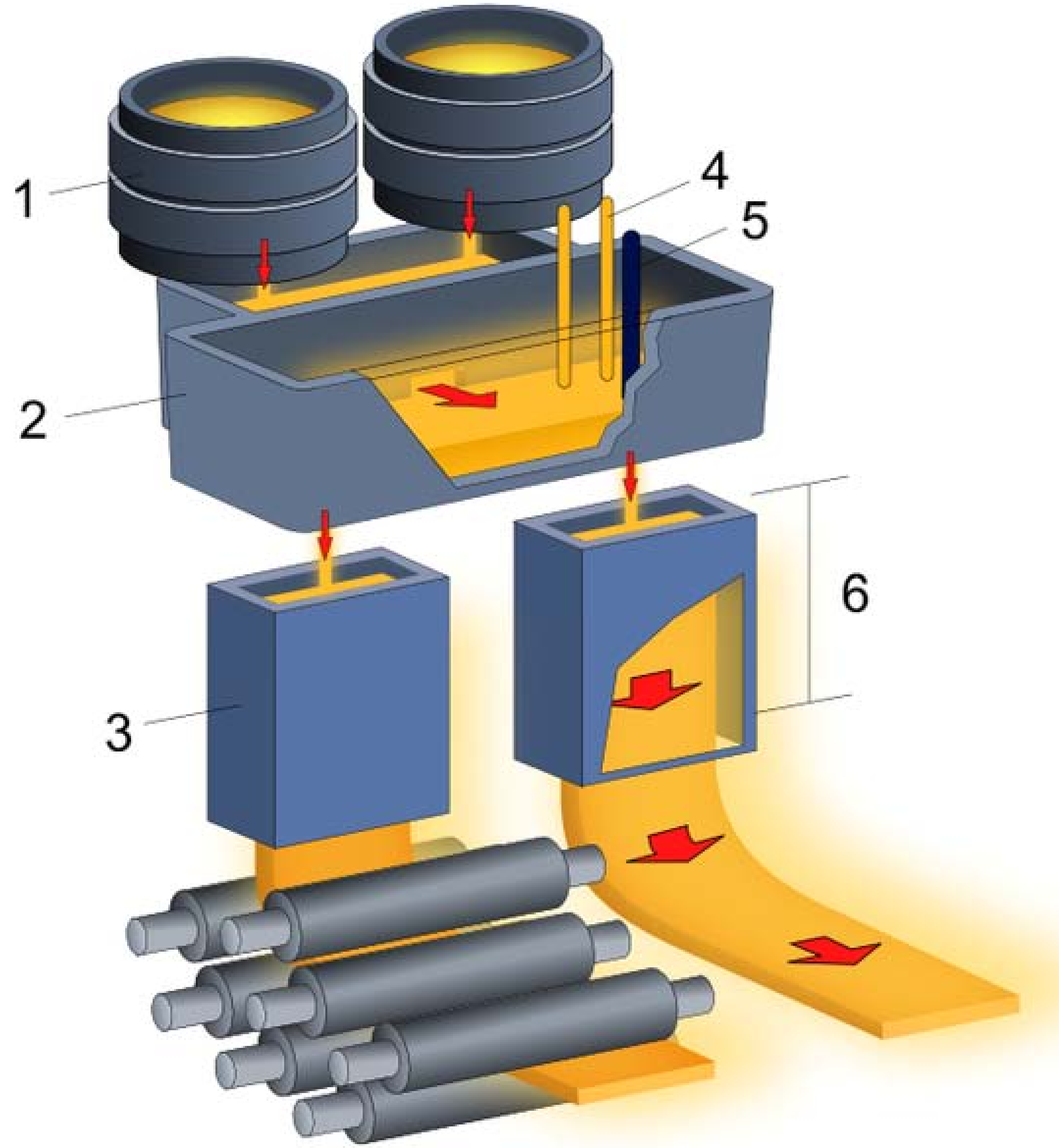
Sir Henry Bessemer, of Bessemer converter fame, received a patent in 1857 for casting metal between two contra-rotating rollers. The basic outline of this system has recently been implemented today in the casting of steel strip.

Equipment and process



1. Ladle 2. Stopper 3. Tundish 4. Shroud 5. Mold 6. Roll support 7. Turning zone 8. Shroud 9. Bath level 10. Meniscus 11. Withdrawal unit 12. Slab

A. Liquid metal B. Solidified metal C. Slag D. Water-cooled copper plates E. Refractory material



A 3D schematic

Molten metal (known as *hot metal* in industry) is tapped into the ladle from furnaces. After undergoing any ladle treatments, such as alloying and degassing, and arriving at the correct temperature, the ladle is transported to the top of the casting machine. Usually, the ladle sits in a slot on a rotating turret at the casting machine; one ladle is 'on cast' (feeding the casting machine) while the other is made ready, and is switched to the casting position once the first ladle is empty.

From the ladle, the hot metal is transferred via a refractory shroud (pipe) to a holding bath called a tundish. The tundish allows a reservoir of metal to feed the casting machine while ladles are switched, thus acting as a buffer of hot metal, as well as smoothing out flow, regulating metal feed to the molds and cleaning the metal.

Metal is drained from the tundish through another shroud into the top of an open-base copper mold. The depth of the mold can range from 0.5 to 2 metres (20 to 79 in), depending on the casting speed and section size. The mold is water-cooled to solidify the hot metal directly in contact with it; this is the *primary cooling* process. It also oscillates vertically (or in a near vertical curved path) to prevent the metal sticking to the mold walls. A lubricant can also be added to the metal in the mold to prevent sticking, and to trap any slag particles—including oxide particles or scale—that may still be present in the metal and bring them to the top of the pool to form a floating layer of slag. Often, the shroud is set so the hot metal exits it below the surface of the slag layer in the mold and is thus called a submerged entry nozzle (SEN). In some cases, shrouds may not be used between tundish and mold; in this case, interchangeable metering nozzles in the base of the tundish direct the metal into the moulds. Some continuous casting layouts feed several molds from the same tundish.

In the mold, a thin shell of metal next to the mold walls solidifies before the middle section, now called a strand, exits the base of the mold into a spray-chamber; the bulk of metal within the walls of the strand is still molten. The strand is immediately supported by closely spaced, water cooled rollers; these act to support the walls of the strand against the ferrostatic pressure (compare hydrostatic pressure) of the still-solidifying liquid within the strand. To increase the rate of solidification, the strand is also sprayed with large amounts of water as it passes through the spray-chamber; this is the *secondary cooling* process. Final solidification of the strand may take place after the strand has exited the spray-chamber.

It is here that the design of continuous casting machines may vary. This describes a 'curved apron' casting machine; vertical configurations are also used. In a curved apron casting machine, the strand exits the mold vertically (or on a near vertical curved path) and as it travels through the spray-chamber, the rollers gradually curve the strand towards the horizontal. In a vertical casting machine, the strand stays vertical as it passes through the spray-chamber. Molds in a curved apron casting machine can be straight or curved, depending on the basic design of the machine.

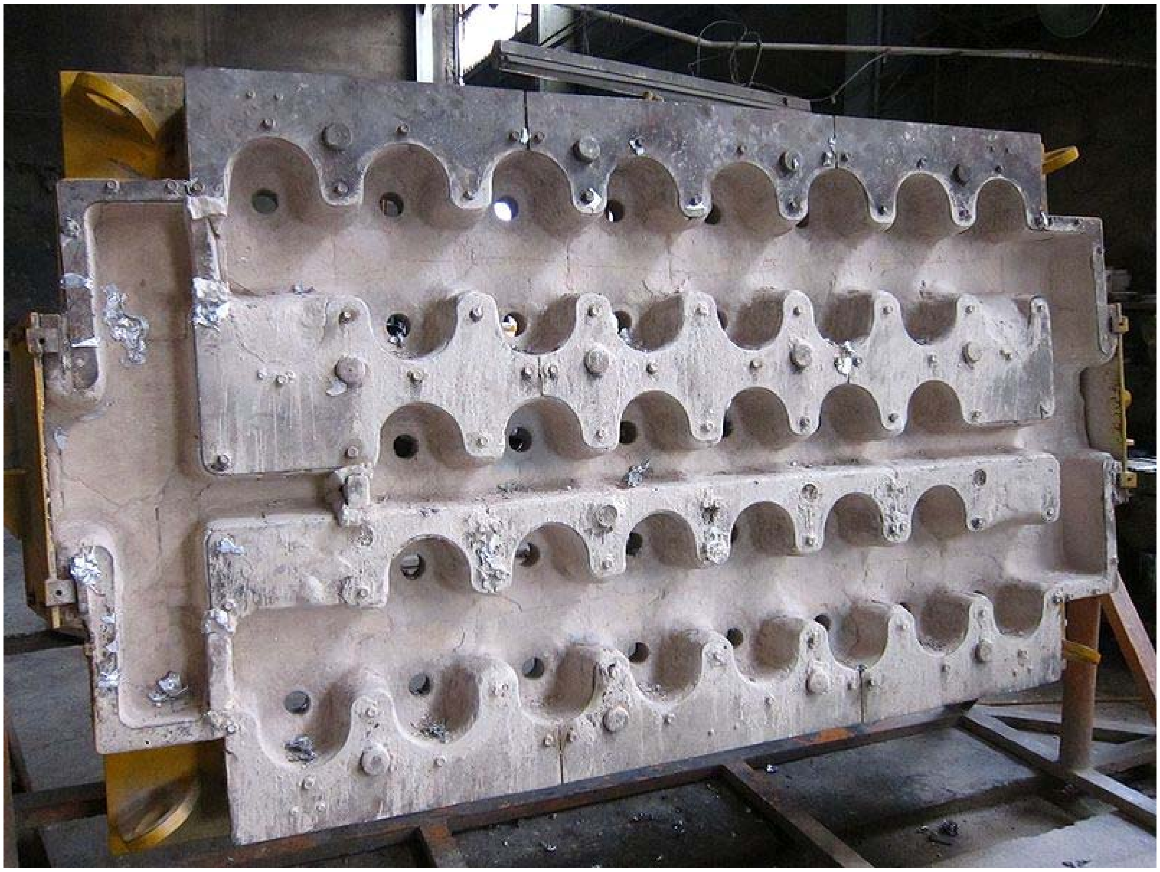
In a true "Horizontal Casting Machine", the mold axis is horizontal and the flow of steel is horizontal from liquid to thin shell to solid (no bending). In this type of machine, either strand oscillation or mold oscillation is used to prevent sticking in the mold.

After exiting the spray-chamber, the strand passes through straightening rolls (if cast on other than a vertical machine) and withdrawal rolls. There may be a hot rolling stand after withdrawal, in order to take advantage of the metal's hot condition to pre-shape the final strand. Finally, the strand is cut into predetermined lengths by mechanical shears or by travelling oxyacetylene torches, is marked for identification and either taken to a stockpile or the next forming process.

In many cases the strand may continue through additional rollers and other mechanisms which might flatten, roll or extrude the metal into its final shape.

Casting machines for aluminium and copper

continuous hot vertical casting in process (aluminum)



molten aluminum pours into this casting die (top view of die)

bottom end of casting die

the resulting Aluminum blanks (after cutting to size)

Aluminium and copper can be cast horizontally and can be more easily cast into near net shape, especially strip, due to their lower melting temperatures.

Range of continuously cast sections

- Casting machines are designated to be billet, bloom or slab casters.
- Slab casters tend to cast sections with an aspect ratio that is much wider than it is thick:
    - Conventional slabs lie in the range 100–1600 mm wide by 180–250 mm thick and up to 12 m long with conventional casting speeds of up to 1.4 m/minute, (however slab widths and casting speeds are currently increasing).
    - Wider slabs are available up to 3250×150 mm, for example at Nanjing Iron & Steel in China.
    - Thick slabs are available up to 2400×400 mm, for example at Shougang Shouqin in Qinhuangdao, China.
    - Thin slabs: 1680×50 mm
- Conventional bloom casters cast sections above 200×200 mm e.g. the Aldwarke Bloom caster in Rotherham, UK, casts sections of 560×400 mm. The bloom length can vary from 4 to 10 m

- Billet casters cast smaller section sizes, such as below 200 mm square, with lengths up to 12 m long. Cast speeds can reach up to 4 m/minute.
- Rounds: either 500 mm or 140 mm in diameter
- Conventional beam blanks: look similar to I-beams in cross-section; 1048×450 mm or 438×381 mm overall
- Near net shape beam blanks: 850×250 mm overall
- Strip: 2–5 mm thick by 760–1330 mm wide

Startup, control of the process and problems

Starting a continuous casting machine involves placing a dummy bar (essentially a curved metal beam) up through the spray chamber to close off the base of the mould. Metal is poured into the mould and withdrawn with the dummy bar once it solidifies. It is extremely important that the metal supply afterwards be guaranteed to avoid unnecessary shutdowns and restarts, known as 'turnarounds'. Each time the caster stops and restarts, a new tundish is required, as any uncast metal in the tundish cannot be drained and instead freezes into a 'skull'. Avoiding turnarounds requires the meltshop, including ladle furnaces (if any) to keep tight control on the temperature of the metal, which can vary dramatically with alloying additions, slag cover and deslagging, and the preheating of the ladle before it accepts metal, among other parameters. However, the cast rate may be lowered by reducing the amount of metal in the tundish (although this can increase wear on the tundish), or if the caster has multiple strands, one or more strands may be shut down to accommodate upstream delays. Turnarounds may be scheduled into a production sequence if the tundish temperature becomes too high after a certain number of heats.

Many continuous casting operations are now fully computer-controlled. Several electromagnetic and thermal sensors in the ladle shroud, tundish and mould sense the metal level or weight, flow rate and temperature of the hot metal, and the programmable logic controller (PLC) can set the rate of strand withdrawal via speed control of the withdrawal rolls. The flow of metal into the moulds can be controlled via two methods:

- By slide gates or stopper rods at the top of the mould shrouds
- If the metal is open-poured, then the metal flow into the moulds is controlled solely by the internal diameter of the metering nozzles. These nozzles are usually interchangeable.

Overall casting speed can be adjusted by altering the amount of metal in the tundish, via the ladle slide gate. The PLC can also set the mould oscillation rate and the rate of mould powder feed, as well as the spray water flow. Computer control also allows vital casting data to be repeated to other manufacturing centres (particularly the steelmaking furnaces), allowing their work rates to be adjusted to avoid 'overflow' or 'underrun' of product.

While the large amount of automation helps produce castings with no shrinkage and little segregation, continuous casting is of no use if the metal is not clean beforehand, or becomes 'dirty' during the casting process. One of the main methods through which hot metal may become dirty is by oxidation, which occurs rapidly at molten metal temperatures (up to 1700 °C); inclusions of gas, slag or undissolved alloys may also be present. To prevent oxidation, the metal is isolated from the atmosphere as much as possible. To achieve this, exposed metal surfaces are covered – by the shrouds, or in the case of the ladle, tundish and mould, by synthetic slag. In the tundish, any inclusions – gas bubbles, other slag or oxides, or undissolved alloys – may also be trapped in the slag layer.

A major problem that may occur in continuous casting is *breakout*. This is when the thin shell of the strand breaks, allowing the still-molten metal inside the strand to spill out and foul the machine, requiring a turnaround. Often, breakout is due to too high a withdrawal rate, as the shell has not had the time to solidify to the required thickness, or the metal is too hot, which means that final solidification takes place well below the straightening rolls and the strand breaks due to stresses applied during straightening. A breakout can also occur if solidifying steel sticks to the mould surface, causing a tear in the shell of the strand. If the incoming metal is overheated, it is preferable to stop the caster than to risk a breakout. Additionally, lead contamination of the metal (caused by counterweights or lead-acid batteries in the initial steel charge) can form a thin film between the mould wall and the steel, inhibiting heat removal and shell growth and increasing the risk of breakouts.

Another problem that may occur is a *carbon boil* – oxygen dissolved in the steel reacts with also-present carbon to generate bubbles of carbon monoxide. As the term *boil* suggests, this reaction is extremely fast and violent, generating large amounts of hot gas, and is especially dangerous if it occurs in the confined spaces of a casting machine. Oxygen can be removed through the addition of silicon or aluminium to the steel, which reacts to form silicon oxide (silica) or aluminium oxide (alumina). However, too much alumina in the steel will clog the casting nozzles and cause the steel to 'choke off'.

Computational fluid dynamics and other fluid flow techniques are being used extensively in the design of new continuous casting operations, especially in the tundish, to ensure that inclusions and turbulence are removed from the hot metal, yet ensure that all the metal reaches the mould before it cools too much. Slight adjustments to the flow conditions within the tundish or the mould can mean the difference between high and low rejection rates of the product.

Starter bar

The starter bar has a free end portion which is flexible for storage and a substantially rigid portion at the end which plugs the mold. The starter bar is constructed in discrete blocks secured to one side of a planar spine provided in segments and arranged end to end. Adjustable spacers in the form of tapered blocks are disposed between the blocks of the bar to allow the starter bar to be self-supporting in a curved configuration corresponding to the casting path. A more flexible spine in the end portion of the starter bar allows the starter bar to be curved to a tighter radius than that of the casting path while the blocks fan out in an unsupported configuration. A storage ramp is provided to support the flexible end in the stored position.

Direct strip casting

Direct strip casting is a continuous casting process for producing metallic sheet directly from the molten state that minimises the need for substantial secondary processing.

Lost-Foam Casting

Lost-foam casting (**LFC**) is a type of evaporative-pattern casting process that is similar to investment casting except foam is used for the pattern instead of wax. This process takes advantage of the low boiling point of foam to simplify the investment casting process by removing the need to melt the wax out of the mold.

Process

First, a pattern is made from polystyrene foam, which can be done many different ways. For small volume runs the pattern can be hand cut or machined from a solid block of foam; if the geometry is simple enough it can even be cut using a hot-wire foam cutter. If the volume is large, then the pattern can be mass-produced by a process similar to injection molding. Pre-expanded beads of polystyrene are injected into a preheated aluminum mold at low pressure. Steam is then applied to the polystyrene which causes it to expand more to fill the die. The final pattern is approximately 97.5% air and 2.5% polystyrene. Pre-made pouring basins, runners, and risers can be hot glued to the pattern to finish it.

Next, the foam cluster is coated with ceramic investment, also known as the refractory coating, via dipping, brushing, spraying or flow coating. This coating creates a barrier between the smooth foam surface and the coarse sand surface. Secondly it controls permeability, which allows the gas created by the vaporized foam pattern to escape through the coating and into the sand. Controlling permeability is a crucial step to avoid sand erosion. Finally, it forms a barrier so that molten metal does not penetrate or cause sand erosion during pouring. After the coating dries, the cluster is placed into a flask and backed up with un-bonded sand. The sand is then compacted using a vibration table. Once compacted, the mold is ready to be poured. Automatic pouring is commonly used in LFC, as the pouring process is significantly more critical than in conventional foundry practice.

Details

Commonly cast metals include cast irons, aluminium alloys, steels, and nickel alloys; less frequently stainless steels and copper alloys are also cast. The size range is from 0.5 kg (1.1 lb) to several tonnes (tons). The minimum wall thickness is 2.5 mm (0.098 in) and there is no upper limit. Typical surface finishes are from 2.5 to 25 µm (100 to 1000 µin) RMS. Typical linear tolerances are ±0.005 mm/mm (0.005 in/in).

Advantages and disadvantages

This casting process is advantageous for very complex castings that would regularly require cores. It is also dimensionally accurate, maintains an excellent surface finish, requires no draft, and has no parting lines so no flash is formed. As compared to investment casting, it is cheaper because it is a simpler process and the foam is cheaper than the wax. Risers are not usually required due to the nature of the process; because the molten metal vaporizes the foam the first metal into the mold cools more quickly than the rest, which results in natural directional solidification. Foam is easy to manipulate, carve and glue, due to its unique properties. The flexibility of LFC often allows for consolidating the parts into one integral component; other forming processes would require the production of one or more parts to be assembled.

The two main disadvantages are that pattern costs can be high for low volume applications and the patterns are easily damaged or distorted due to their low strength. If a die is used to create the patterns there is a large initial cost.

History

Lost-foam casting was invented in 1964 by M.C. Flemmings. Public recognition of the benefits of LFC was made by General Motors in the mid 1980s when it announced its new car line, Saturn, would utilize LFC for production of all engine blocks, cylinder heads, crankshafts, differential carriers, and transmission cases.

Chapter 7

Plaster Mold Casting & Shell Molding

Plaster Mold Casting

Plaster mold casting is a metalworking casting process similar to sand casting except the molding material is plaster of paris instead of sand. Like sand casting, plaster mold casting is an expendable mold processes, however it can only be used with non-ferrous materials. It is used for castings as small as 30 g (1 oz) to as large as 45 kg (99 lb). Generally, the form takes less than a week to prepare, after which a production rate of 1–10 units/hr-mold is achieved.

Parts that are typically made by plaster casting are lock components, gears, valves, fittings, tooling, and ornaments.

Details

The plaster is not pure plaster of paris, but rather has additives to improve green strength, dry strength, permeability, and castability. For instance, talc or magnesium oxide are added to prevent cracking and reduce setting time; lime and cement limit expansion during baking; glass fibers increase strength; sand can be used as a filler. The ratio of ingredients is 70–80% gypsum and 20–30% additives.

The pattern is usually made from metal, however rubber molds may be used for complex geometry; these molds are called Rubber plaster molds. For example, if the casting includes reentrant angles or complex angular surfaces then the rubber is flexible enough to be removed, unlike metal. These molds are also inexpensive, reusable, more accurate than steel molds, fast to produce, and easy to change.

Typical tolerances are 0.1 mm (0.0039 in) for the first 50 mm (2.0 in) and 0.02 mm per additional centimeter (0.002 in per additional inch). A draft of 0.5 to 1 degree is required. Standard surface finishes that are attainable are 1.3 to 4 micrometres (50–125 μin).

Process

First, the plaster is mixed and the pattern is sprayed with a thin film of parting compound to prevent the plaster from sticking to the pattern. The plaster is then poured over the pattern and the unit shaken so that the plaster fills any small features. The plaster sets, usually in about 15 minutes, and the pattern is removed. The mold is then baked, between 120 °C (248 °F) and 260 °C (500 °F), to remove any excess water. The dried mold is then assembled, preheated, and the metal poured. Finally, after the metal has solidified, the plaster is broken from the cast part. The used plaster cannot be reused.

Advantages & disadvantages

Plaster mold casting is used to when an excellent surface finish and good dimensional accuracy is required. Because the plaster has a low thermal conductivity and heat capacity the metal cools more slowly than in a sand mold, which allows the metal to fill thin cross-sections; the minimum possible cross-section is 0.6 mm (0.024 in). This results in a near net shape casting, which can be a cost advantage on complex parts. It also produces minimal scrap material.

The major disadvantage of the process is that it can only be used with lower melting temperature non-ferrous materials, such as aluminium, copper, magnesium, and zinc. The most commonly used materials are aluminium and copper. The maximum working temperature of plaster is 1,200 °F (649 °C), so higher melting temperature materials would melt the plaster mold. Also, the sulfur in the gypsum reacts with iron, making it unsuitable for casting ferrous materials.

Another disadvantage is that its long cooling times restrict production volume.

Plaster is not as stable as sand, so it is dependent on several factors, including the consistency of the plaster composition, pouring procedures, and curing techniques. If these factors are not closely monitored the mold can be distorted, shrink upon drying, have a poor surface finish, or fail completely.

Shell Molding

Shell molding, also known as **shell-mold casting**, is an expendable mold casting process that uses a resin covered sand to form the mold. As compared to sand casting, this process has better dimensional accuracy, a higher productivity rate, and lower labor requirements. It is used for small to medium parts that require high precision.

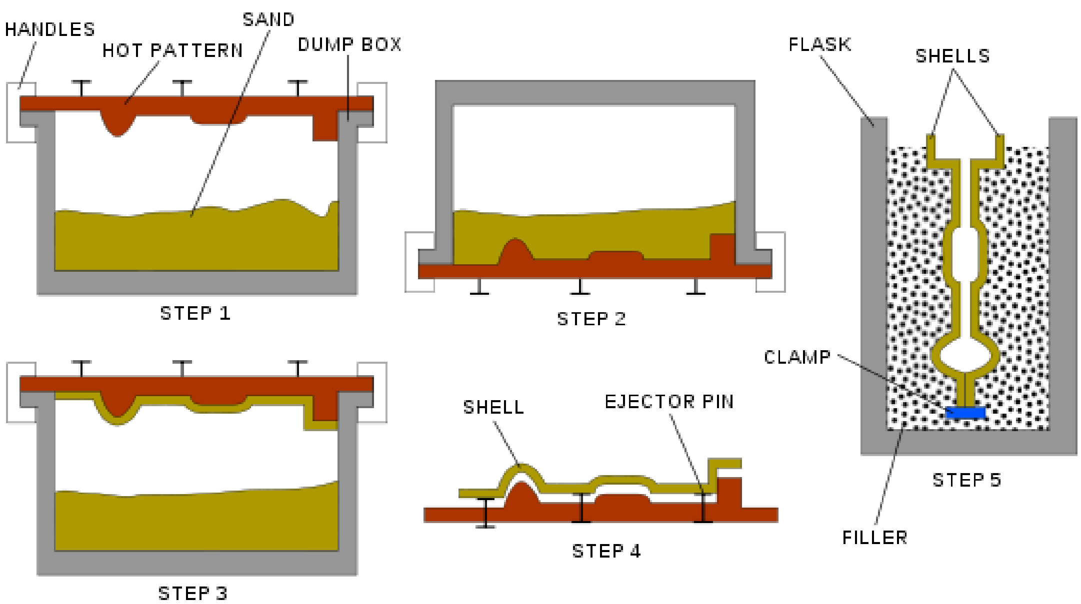
Examples of shell molded items include gear housings, cylinder heads and connecting rods. It is also used to make high-precision molding cores.

Process

The process of creating a shell mold consists of six steps:

1. Fine silica sand that is covered in a thin (3–6%) thermosetting phenolic resin and liquid catalyst is dumped, blown, or shot onto a hot pattern. The pattern is usually made from cast iron and is heated to 230 to 315 °C (450 to 600 °F). The sand is allowed to sit on the pattern for a few minutes to allow the sand to partially cure.
2. The pattern and sand are then inverted so the excess sand drops free of the pattern, leaving just the "shell". Depending on the time and temperature of the pattern the thickness of the shell is 10 to 20 mm (0.4 to 0.8 in).
3. The pattern and shell together are placed in an oven to finish curing the sand. The shell now has a tensile strength of 350 to 450 psi (2.4 to 3.1 MPa).
4. The hardened shell is then stripped from the pattern.
5. Two or more shells are then combined, via clamping or gluing using a thermoset adhesive, to form a mold. This finished mold can then be used immediately or stored almost indefinitely.
6. For casting the shell mold is placed inside a flask and surrounded with shot, sand, or gravel to reinforce the shell.

The machine that is used for this process is called a *shell molding machine*. It heats the pattern, applies the sand mixture, and bakes the shell.



Details

Setup and production of shell mold patterns takes weeks, after which an output of 5–50 pieces/hr-mold is attainable. Common materials include cast iron, aluminum and copper alloys. Aluminum and magnesium products average about 13.5 kg (30 lb) as a normal limit, but it is possible to cast items in the 45–90 kg (100–200 lb) range. The small end of the limit is 30 g (1 oz). Depending on the material, the thinnest cross-section castable is 1.5 to 6 mm (0.06 to 0.24 in). The minimum draft is 0.25 to 0.5 degrees.

Typical tolerances are 0.005 mm/mm or in/in because the sand compound is designed to barely shrink and a metal pattern is used. The cast surface finish is 0.3–4.0 micrometers (50–150 μin) because a finer sand is used. The resin also assists in forming a very smooth surface. The process, in general, produces very consistent castings from one casting to the next.

The sand-resin mix can be recycled by burning off the resin at high temperatures.

Advantages and disadvantages

One of the greatest advantages of this process is that it can be completely automated for mass production. The high productivity, low labor costs, good surface finishes, and precision of the process can more than pay for itself if it reduces machining costs. There are also few problems due to gases, because of the absence of moisture in the shell, and the little gas that is still present easily escapes through the thin shell. When the metal is poured some of the resin binder burns out on the surface of the shell, which makes shaking out easy.

One disadvantage is that the gating system must be part of the pattern because the entire mold is formed from the pattern, which can be expensive. Another is the resin for the sand is expensive, however not much is required because only a shell is being formed.

Chapter 8

Investment Casting

Inlet-outlet cover of a valve for a nuclear power station produced using investment casting

Investment casting is an industrial process based on and also called *lost-wax casting*, one of the oldest known metal-forming techniques. From 5,000 years ago, when beeswax formed the pattern, to today's high-technology waxes, refractory materials and specialist alloys, the castings allow the production of components with accuracy, repeatability, versatility and integrity in a variety of metals and high-performance alloys. Lost foam casting is a modern form of investment casting that eliminates certain steps in the process.

The process is generally used for small castings, but has been used to produce complete aircraft door frames, steel castings of up to 300 kg and aluminium castings of up to 30 kg. It is generally more expensive per unit than die casting or sand casting, but has lower equipment costs. It can produce complicated shapes that would be difficult or impossible with die casting, yet like that process, it requires little surface finishing and only minor machining.

Process

Casts can be made of the wax model itself, the direct method; or of a wax copy of a model that need not be of wax, the indirect method. The following steps are for the indirect process which can take two days to one week to complete.

1. *Produce a master pattern*: An artist or mould-maker creates an original pattern from wax, clay, wood, plastic, steel, or another material.
2. *Mouldmaking*: A mould, known as the *master die*, is made of the master pattern. The master pattern may be made from a low-melting-point metal, steel, or wood. If a steel pattern was created then a low-melting-point metal may be cast directly from the master pattern. Rubber moulds can also be cast directly from the master pattern. The first step may also be skipped if the master die is machined directly into steel.
3. *Produce the wax patterns*: Although called a *wax pattern* pattern materials also include plastic and frozen mercury. Wax patterns may be produced in one of two ways. In one process the wax is poured into the mold and swished around until an even coating, usually about 3 mm (0.12 in) thick, covers the inner surface of the mould. This is repeated until the desired thickness is reached. Another method is filling the entire mould with molten wax, and let it cool, until a desired thickness has set on the surface of the mould. After this the rest of the wax is poured out again, the mould is turned upside down and the wax layer is left to cool and harden. With this method it is more difficult to control the overall thickness of the wax layer.
   If a core is required, there are two options: soluble wax or ceramic. Soluble wax cores are designed to melt out of the investment coating with the rest of the wax pattern, whereas ceramic cores remain part of the wax pattern and are removed after the workpiece is cast.
4. *Assemble the wax patterns*: The wax pattern is then removed from the mould. Depending on the application multiple wax patterns may be created so that they can all be cast at once. In other applications, multiple different wax patterns may be created and then assembled into one complex pattern. In the first case the multiple patterns are attached to a wax sprue, with the result known as a pattern cluster, or *tree*; as many as several hundred patterns may be assembled into a tree. Foundries often use registration marks to indicate exactly where they go. The wax patterns are attached to the sprue or each other by means of a heated metal tool. The wax pattern may also be *chased*, which means the parting line or flashing are rubbed out using the heated metal tool. Finally it is *dressed*, which means any other imperfections are addressed so that the wax now looks like the finished piece.
5. *Investment*: The ceramic mould, known as the *investment*, is produced by three repeating steps: coating, stuccoing, and hardening. The first step involves dipping the cluster into a slurry of fine refractory material and then letting any excess drain off, so a uniform surface is produced. This fine material is used first to give a smooth surface finish and reproduce fine details. In the second step, the cluster is *stuccoed* with a coarse ceramic particle, by dipping it into a fluidised bed,

placing it in a rainfall-sander, or by applying by hand. Finally, the coating is allowed to harden. These steps are repeated until the investment is the required thickness, which is usually 5 to 15 mm (0.2 to 0.6 in). Note that the first coatings are known as *prime coats*. An alternative to multiple dips is to place the cluster upside-down in a flask and then liquid investment material is poured into the flask. The flask is then vibrated to allow entrapped air to escape and help the investment material fill in all of the details.

Common refractory materials used to create the investments are: silica, zircon, various aluminium silicates, and alumina. Silica is usually used in the fused silica form, but sometimes quartz is used because it is less expensive. Aluminium silicates are a mixture of alumina and silica, where commonly used mixtures have an alumina content from 42 to 72%; at 72% alumina the compound is known as mullite. During the primary coat(s), zircon-based refractories are commonly used, because zirconium is less likely to react with the molten metal. Chamotte is another refractory material that has been used. Prior to silica, a mixture of plaster and ground up old molds (chamotte) was used.
The binders used to hold the refractory material in place include: ethyl silicate (alcohol-based and chemically set), colloidal silica (water-based, also known as silica sol, set by drying), sodium silicate, and a hybrid of these controlled for pH and viscosity.

6. *Dewax*: The investment is then allowed to completely dry, which can take 16 to 48 hours. Drying can be enhanced by applying a vacuum or minimizing the environmental humidity. It is then turned upside-down and placed in a furnace or autoclave to melt out and/or vaporize the wax. Most shell failures occur at this point because the waxes used have a thermal expansion coefficient that is much greater than the investment material surrounding it, so as the wax is heated it expands and induces great stresses. In order to minimize these stresses the wax is heated as rapidly as possible so that the surface of the wax can melt into the surface of the investment or run out of the mold, which makes room for the rest of the wax to expand. In certain situations holes may be drilled into the mold beforehand to help reduce these stresses. Any wax that runs out of the mold is usually recovered and reused.
7. *Burnout & preheating*: The mold is then subjected to a *burnout*, which heats the mold between 870 °C and 1095 °C to remove any moisture and residual wax, and to sinter the mold. Sometimes this heating is also as the preheat, but other times the mold is allowed to cool so that it can be tested. If any cracks are found they can be repaired with ceramic slurry or special cements. The mold is preheated to allow the metal to stay liquid longer to fill any details and to increase dimensional accuracy, because the mold and casting cool together.
8. *Pouring*: The investment mold is then placed cup-upwards into a tub filled with sand. The metal may be gravity poured, but if there are thin sections in the mold it may be filled by applying positive air pressure, vacuum cast, tilt cast, pressure assisted pouring, or centrifugal cast.

9. *Removal*: The shell is hammered, media blasted, vibrated, waterjeted, or chemically dissolved (sometimes with liquid nitrogen) to release the casting. The sprue is cut off and recycled. The casting may then be cleaned up to remove signs of the casting process, usually by grinding.

The investment shell for casting a turbocharger rotor

A view of the interior investment shows the smooth surface finish and high level of detail

The completed workpiece

Counter-gravity pouring

A variation on the pouring technique is to fill the investment upside-down. A common form of this is called the *Hitchiner* process, which is named after the Hitchiner Manufacturing Company that invented the technique. In this technique the investment shell is placed in a vacuum tight mold chamber and then lowered into a pool of molten metal. A vacuum is then created, which draws the metal up into the investment shell. After the casting has solidified the vacuum is released, which allows any remaining liquid metal to flow back into the pool.

This technique is more metal efficient than traditional pouring because less material solidifies in the gating system. Gravity pouring only has a 15 to 50% metal yield as compared to 60 to 95% for counter-gravity pouring. There is also less turbulence, so the gating system can be simplified since it does not have to control turbulence. Plus, because the metal is drawn from below the top of the pool the metal is free from dross and slag, as these are lower density (lighter) and float to the top of the pool. The pressure differential helps the metal flow into every intricacy of the mold. Finally, lower temperatures can be used, which improves the grain structure.

This process is also used to cast refractory ceramics under the term *vacuum casting*.

Vacuum pressure casting

Vacuum pressure casting (VPC) uses gas pressure and a vacuum to improve the quality of the casting and minimize porosity. Typically VPC casting machines consist of an upper and a lower chamber. The upper chamber or melting chamber housing the crucible, and the lower casting chamber housing the investment mould. Both chambers are connected via a small hole containing a stopper. A vacuum is pulled in the lower chamber, while pressure is applied in the upper, and then the stopper is removed. This creates the greatest pressure differential to fill the molds.

Details

Investment casting is used with almost any castable metal, however aluminium alloys, copper alloys, and steel are the most common. In industrial usage the size limits are 3 g (0.1 oz) to about 5 kg (11 lb). The cross-sectional limits are 0.6 mm (0.024 in) to 75 mm (3.0 in). Typical tolerances are 0.1 mm for the first 25 mm (0.005 in for the first inch) and 0.02 mm for the each additional centimeter (0.002 in for each additional inch). A standard surface finish is 1.3–4 micrometres (50–125 μin) RMS.

The advantages of investment casting are:

- Excellent surface finish
- High dimensional accuracy
- Extremely intricate parts are castable
- Almost any metal can be cast
- No flash or parting lines

The main disadvantage is the overall cost. Some of the reasons for the high cost include specialized equipment, costly refractories and binders, many operations to make a mould, a lot of labor is needed and occasional minute defects. However, the cost is still less than producing the same part by machining from bar stock; for example, gun manufacturing has moved to investment casting to lower costs of producing pistols.

History

The history of lost-wax casting dates back thousands of years. Its earliest use was for idols, ornaments and jewellery, using natural beeswax for patterns, clay for the moulds and manually operated bellows for stoking furnaces. Examples have been found across the world in India's Harappan Civilisation (2500–2000 BC) idols, Egypt's tombs of Tutankhamun (1333–1324 BC), Mesopotamia, Aztec and Mayan Mexico, and the Benin civilization in Africa where the process produced detailed artwork of copper, bronze and gold.

The earliest known text that describes the investment casting process (Schedula Diversarum Artium) was written around 1100 A.D. by Theophilus Presbyter, a monk who described various manufacturing processes, including the recipe for parchment. This book was used by sculptor and goldsmith Benvenuto Cellini (1500–1571), who detailed in his autobiography the investment casting process he used for the Perseus with the Head of Medusa sculpture that stands in the Loggia dei Lanzi in Florence, Italy.

Investment casting came into use as a modern industrial process in the late 19th century, when dentists began using it to make crowns and inlays, as described by Dr. D. Philbrook of Council Bluffs, Iowa in 1897. Its use was accelerated by Dr. William H. Taggart of Chicago, whose 1907 paper described his development of a technique. He also formulated a wax pattern compound of excellent properties, developed an investment material, and invented an air-pressure casting machine.

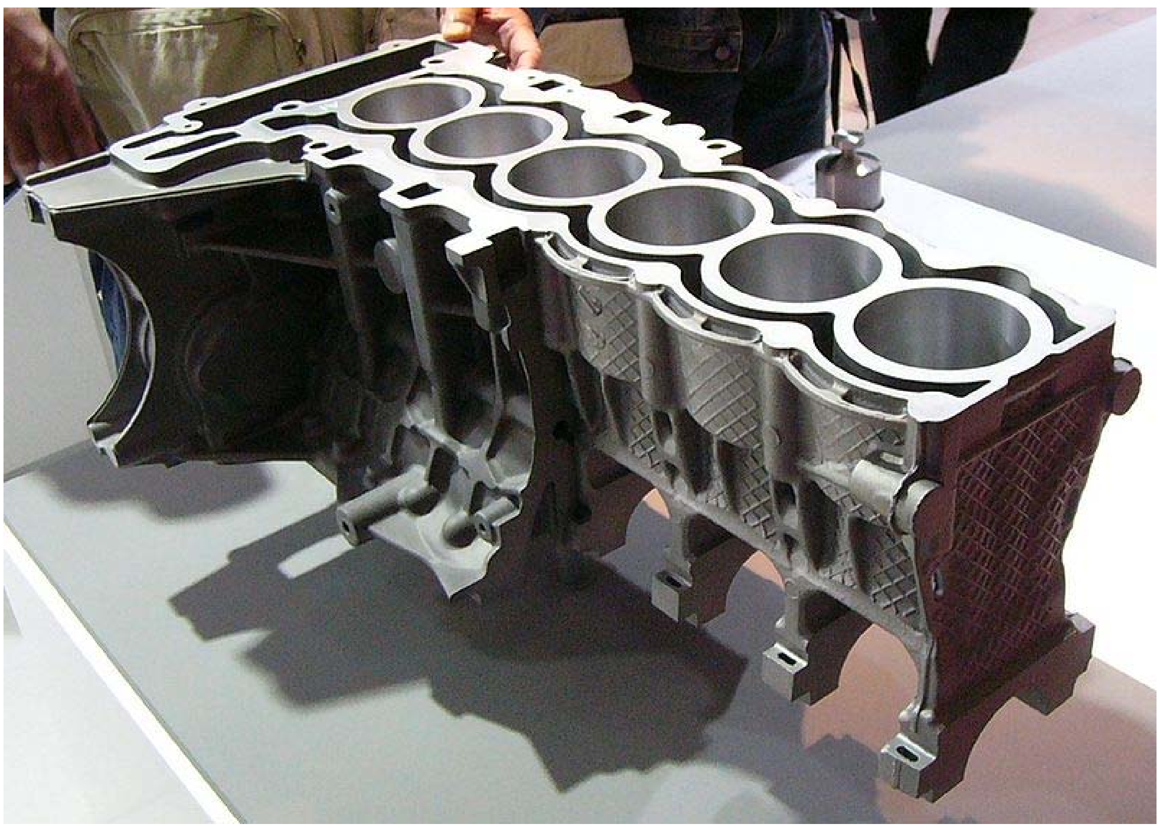
In the 1940s, World War II increased the demand for precision net shape manufacturing and specialized alloys that could not be shaped by traditional methods, or that required too much machining. Industry turned to investment casting. After the war, its use spread to many commercial and industrial applications that used complex metal parts.

Applications

Investment casting is used in the aerospace and power generation industries to produce turbine blades with complex shapes or cooling systems. Blades produced by investment casting can include single-crystal (SX), directionally solidified (DS), or conventional equiaxed blades. Investment casting is also widely used by firearms manufacturers to fabricate firearm receivers, triggers, hammers, and other precision parts at low cost. Other industries that use standard investment-cast parts include military, medical, commercial and automotive.

Chapter 9

Die Casting



An engine block with aluminium and magnesium die castings.

Die casting is a metal casting process that is characterized by forcing molten metal under high pressure into a mold cavity. The mold cavity is created using two hardened tool steel dies which have been machined into shape and work similarly to molds during the process. Most die castings are made from non-ferrous metals, specifically zinc, copper, aluminium, magnesium, lead, pewter and tin based alloys. Depending on the type of metal being cast, a hot- or cold-chamber machine is used.

The casting equipment and the metal dies represent large capital costs and this tends to limit the process to high volume production. Manufacture of parts using die casting is relatively simple, involving only four main steps, which keeps the incremental cost per item low. It is especially suited for a large quantity of small to medium sized castings, which is why die casting produces more castings than any other casting process. Die castings are characterized by a very good surface finish (by casting standards) and dimensional consistency.

Two variants are pore-free die casting, which is used to eliminate gas porosity defects; and direct injection die casting, which is used with zinc castings to reduce scrap and increase yield.

History

Die casting equipment was invented in 1838 for the purpose of producing movable type for the printing industry. The first die casting-related patent was granted in 1849 for a small hand operated machine for the purpose of mechanized printing type production. In 1885, Otto Mergenthaler invented the linotype machine, an automated type casting device which became the prominent type of equipment in the publishing industry. Other applications grew rapidly, with die casting facilitating the growth of consumer goods and appliances by making affordable the production of intricate parts in high volumes.

In 1966, General Motors released the *acurad* process.

Cast metals

The main die casting alloys are: zinc, aluminium, magnesium, copper, lead, and tin; although uncommon, ferrous die casting is possible. Specific dies casting alloys include: ZAMAK; zinc aluminium; aluminium to, e.g. The Aluminum Association (AA) standards: AA 380, AA 384, AA 386, AA 390; and AZ91D magnesium. The following is a summary of the advantages of each alloy:

- Zinc: the easiest alloy to cast; high ductility; high impact strength; easily plated; economical for small parts; promotes long die life.
- Aluminium: lightweight; high dimensional stability for complex shapes and thin walls; good corrosion resistance; good mechanical properties; high thermal and electrical conductivity; retains strength at high temperatures.
- Magnesium: the easiest alloy to machine; excellent strength-to-weight ratio; lightest alloy commonly die cast.
- Copper: high hardness; high corrosion resistance; highest mechanical properties of alloys die cast; excellent wear resistance; excellent dimensional stability; strength approaching that of steel parts.
- Lead and tin: high density; extremely close dimensional accuracy; used for special forms of corrosion resistance. Such alloys are not used in foodservice applications for public health reasons.

Maximum weight limits for aluminium, brass, magnesium, and zinc castings are approximately 70 pounds (32 kg), 10 lb (5 kg), 44 lb (20 kg), and 75 lb (34 kg), respectively.

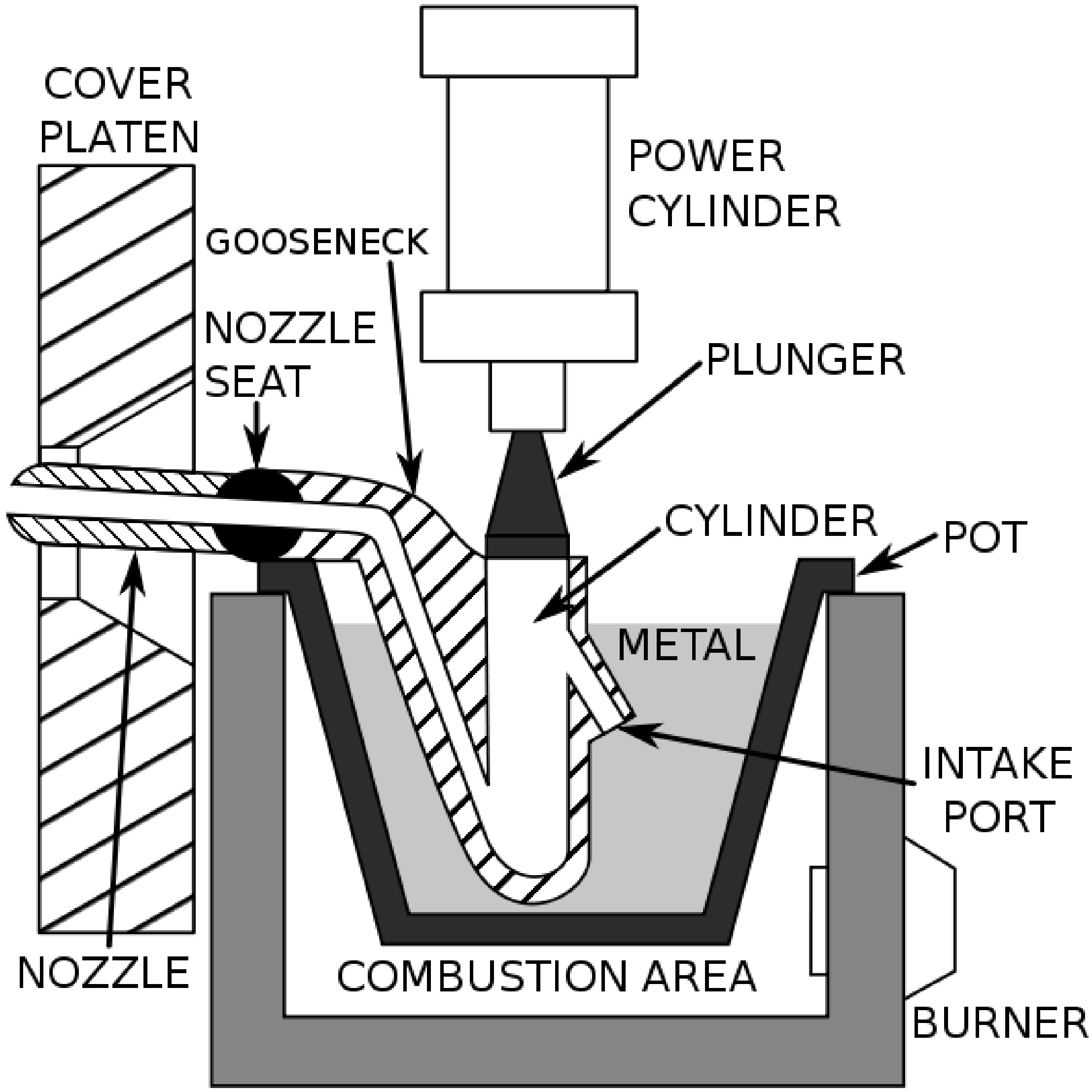
The material used defines the minimum section thickness and minimum draft required for a casting as outlined in the table below. The thickest section should be less than 13 mm (0.5 in), but can be greater.

Metal	Minimum section	Minimum draft
Aluminium alloys	0.89 mm (0.035 in)	1:100 (0.6°)
Brass and bronze	1.27 mm (0.050 in)	1:80 (0.7°)
Magnesium alloys	1.27 mm (0.050 in)	1:100 (0.6°)
Zinc alloys	0.63 mm (0.025 in)	1:200 (0.3°)

Equipment

There are two basic types of die casting machines: *hot-chamber machines* and *cold-chamber machines*. These are rated by how much clamping force they can apply. Typical ratings are between 400 and 4,000 st (2,500 and 25,000 kg).

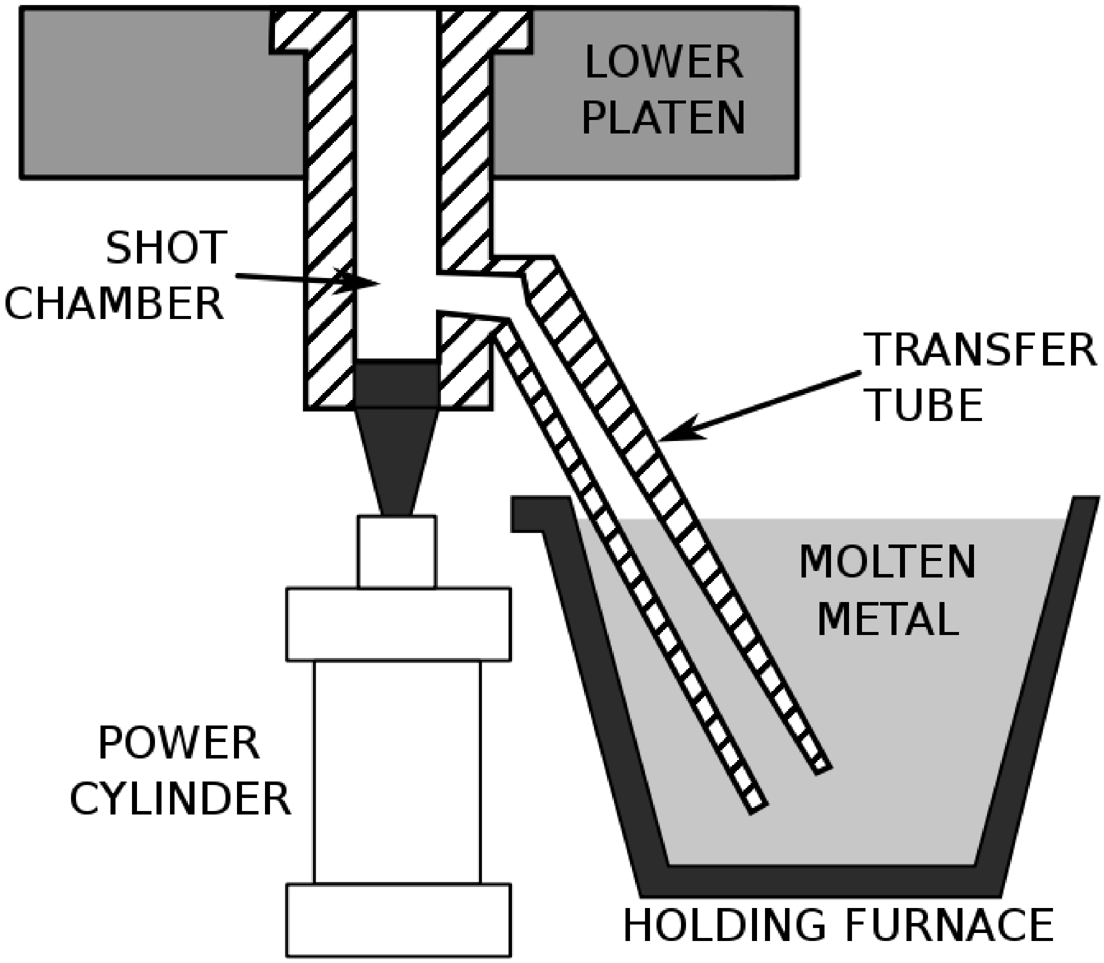
Hot-chamber machines



Schematic of a hot-chamber machine

Hot-chamber machines, also known as *gooseneck machines*, rely upon a pool of molten metal to feed the die. At the beginning of the cycle the piston of the machine is retracted, which allows the molten metal to fill the "gooseneck". The pneumatic or hydraulic powered piston then forces this metal out of the gooseneck into the die. The advantages of this system include fast cycle times (approximately 15 cycles a minute) and the convenience of melting the metal in the casting machine. The disadvantages of this system are that high-melting point metals cannot be utilized and aluminium cannot be used because it picks up some of the iron while in the molten pool. Due to this, hot-chamber machines are primarily used with zinc, tin, and lead based alloys.

Cold-chamber machines



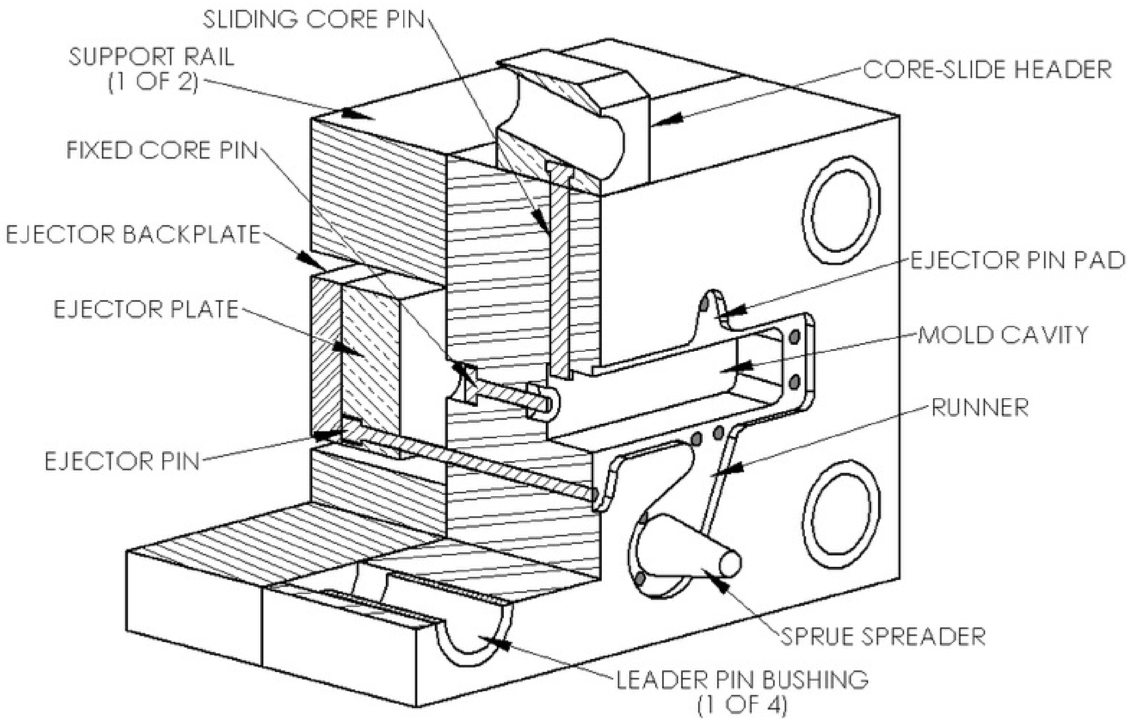
A schematic of a cold-chamber die casting machine.

These are used when the casting alloy cannot be used in hot-chamber machines; these include aluminium, zinc alloys with a large composition of aluminium, magnesium and copper. The process for these machines start with melting the metal in a separate furnace. Then a precise amount of molten metal is transported to the cold-chamber machine where it is fed into an unheated shot chamber (or injection cylinder). This shot is then driven into the die by a hydraulic or mechanical piston. This biggest disadvantage of this system is the slower cycle time due to the need to transfer the molten metal from the furnace to the cold-chamber machine.

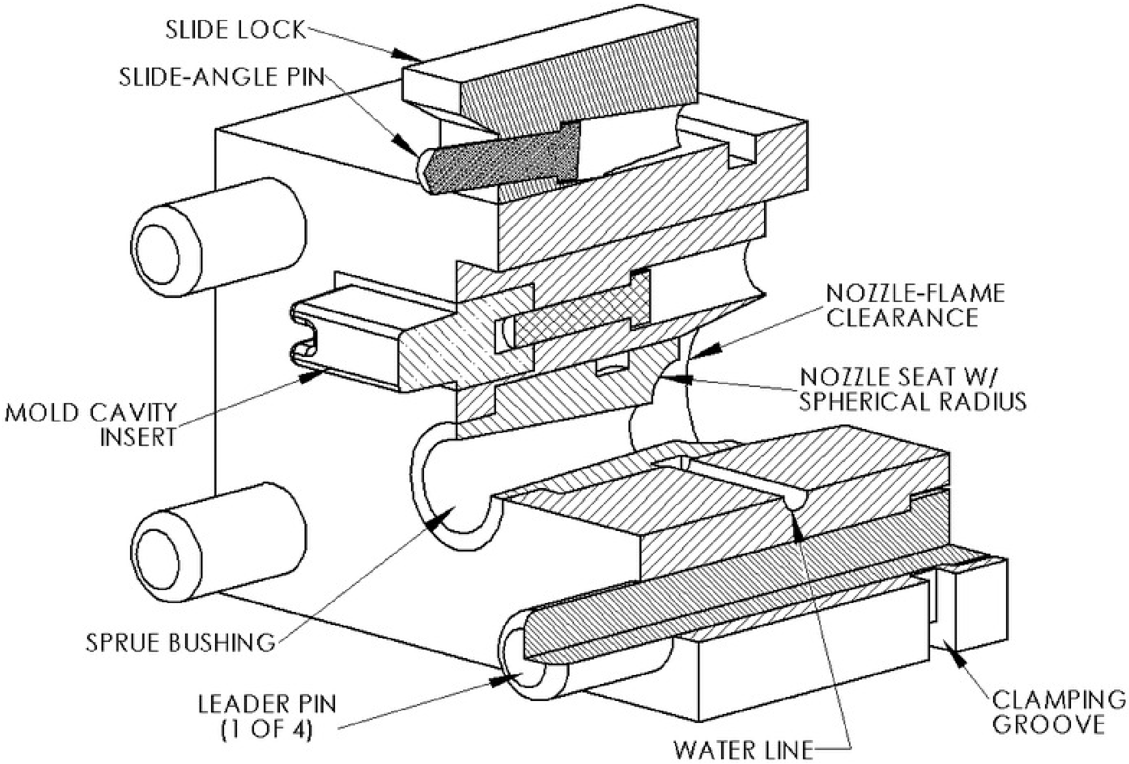
Open tooling and injection nozzle

Complete working cell

Dies



The ejector die half



The cover die half

Two dies are used in die casting; one is called the "cover die half" and the other the "ejector die half". Where they meet is called the parting line. The cover die contains the sprue (for hot-chamber machines) or shot hole (for cold-chamber machines), which allows the molten metal to flow into the dies; this feature matches up with the injector nozzle on the hot-chamber machines or the shot chamber in the cold-chamber machines. The ejector die contains the ejector pins and usually the runner, which is the path from the sprue or shot hole to the mold cavity. The cover die is secured to the stationary, or front, platen of the casting machine, while the ejector die is attached to the movable platen. The mold cavity is cut into two *cavity inserts*, which are separate pieces that can be replaced relatively easily and bolt into the die halves.

The dies are designed so that the finished casting will slide off the cover half of the die and stay in the ejector half as the dies are opened. This assures that the casting will be ejected every cycle because the ejector half contains the *ejector pins* to push the casting out of that die half. The ejector pins are driven by an *ejector pin plate*, which accurately drives all of the pins at the same time and with the same force, so that the casting is not damaged. The ejector pin plate also retracts the pins after ejecting the casting to prepare for the next shot. There must be enough ejector pins to keep the overall force on each pin low, because the casting is still hot and can be damaged by excessive force. The pins still leave a mark, so they must be located in places where these marks will not hamper the castings purpose.

Other die components include *cores* and *slides*. Cores are components that usually produce holes or opening, but they can be used to create other details as well. There are three types of cores: fixed, movable, and loose. Fixed cores are ones that are oriented parallel to the pull direction of the dies (i.e. the direction the dies open), therefore they are fixed, or permanently attached to the die. Movable cores are ones that are oriented in any other way than parallel to the pull direction. These cores must be removed from the die cavity after the shot solidifies, but before the dies open, using a separate mechanism. Slides are similar to movable cores, except they are used to form undercut surfaces. The use of movable cores and slides greatly increases the cost of the dies. Loose cores, also called *pick-outs*, are used to cast intricate features, such as threaded holes. These loose cores are inserted into the die by hand before each cycle and then ejected with the part at the end of the cycle. The core then must be removed by hand. Loose cores are the most expensive type of core, because of the extra labor and increased cycle time. Other features in the dies include water-cooling passages and vents along the parting lines. These vents are usually wide and thin (approximately 0.13 mm or 0.005 in) so that when the molten metal starts filling them the metal quickly solidifies and minimizes scrap. No risers are used because the high pressure ensures a continuous feed of metal from the gate.

The most important material properties for the dies are thermal shock resistance and softening at elevated temperature; other important properties include hardenability, machinability, heat checking resistance, weldability, availability (especially for larger dies), and cost. The longevity of a die is directly dependent on the temperature of the molten metal and the cycle time. The dies used in die casting are usually made out of hardened tool steels, because cast iron cannot withstand the high pressures involved, therefore the dies are very expensive, resulting in high start-up costs. Metals that are cast at higher temperatures require dies made from higher alloy steels.

Die and component material and hardness for various cast metals

Die component	Cast metal					
	Tin, lead & zinc		Aluminium & magnesium		Copper & brass	
	Material	**Hardness**	**Material**	**Hardness**	**Material**	**Hardness**
Cavity inserts	P20	290–330 HB	H13	42–48 HRC	DIN 1.2367	38–44 HRC
	H11	46–50 HRC	H11	42–48 HRC	H20, H21, H22	44–48 HRC
	H13	46–50 HRC				
Cores	H13	46–52 HRC	H13	44–48 HRC	DIN 1.2367	40–46 HRC
			DIN 1.2367	42–48 HRC		
Core pins	H13	48–52 HRC	DIN 1.2367 prehard	37–40 HRC	DIN 1.2367 prehard	37–40 HRC
Sprue parts	H13	48–52 HRC	H13 DIN 1.2367	46–48 HRC 44–46 HRC	DIN 1.2367	42–46 HRC
Nozzle	420	40–44 HRC	H13	42–48 HRC	DIN 1.2367 H13	40–44 HRC 42–48 HRC
Ejector pins	H13	46–50 HRC	H13	46–50 HRC	H13	46–50 HRC
Plunger shot sleeve	H13	46–50 HRC	H13 DIN 1.2367	42–48 HRC 42–48 HRC	DIN 1.2367 H13	42–46 HRC 42–46 HRC
Holder block	4140 prehard	~300 HB	4140 prehard	~300 HB	4140 prehard	~300 HB

The main failure mode for die casting dies is wear or erosion. Other failure modes are *heat checking* and *thermal fatigue*. Heat checking is when surface cracks occur on the die due to a large temperature change on every cycle. Thermal fatigue is when surface cracks occur on the die due to a large number of cycles.

Typical die temperatures and life for various cast materials

	Zinc	Aluminium	Magnesium	Brass (leaded yellow)
Maximum die life number of [cycles]	1,000,000	100,000	100,000	10,000
[Die temperature C° (F°)]	218 (425)	288 (550)	260 (500)	500 (950)
[Casting temperature C° (F°)]	400 (760)	660 (1220)	760 (1400)	1090 (2000)

Process

The following are the four steps in *traditional die casting*, also known as *high-pressure die casting*, these are also the basis for any of the die casting variations: die preparation, filling, ejection, and shakeout. The dies are prepared by spraying the mold cavity with lubricant. The lubricant both helps control the temperature of the die and it also assists in the removal of the casting. The dies are then closed and molten metal is injected into the dies under high pressure; between 10 and 175 megapascals (1,500 and 25,400 psi). Once the mold cavity is filled, the pressure is maintained until the casting solidifies. The dies are then opened and the shot (shots are different from castings because there can be multiple cavities in a die, yielding multiple castings per shot) is ejected by the ejector pins. Finally, the shakeout involves separating the scrap, which includes the gate, runners, sprues and flash, from the shot. This is often done using a special trim die in a power press or hydraulic press. Other methods of shaking out include sawing and grinding. A less labor-intensive method is to tumble shots if gates are thin and easily broken; separation of gates from finished parts must follow. This scrap is recycled by remelting it. The yield is approximately 67%.

The high-pressure injection leads to a quick fill of the die, which is required so the entire cavity fills before any part of the casting solidifies. In this way, discontinuities are avoided, even if the shape requires difficult-to-fill thin sections. This creates the problem of air entrapment, because when the mold is filled quickly there is little time for the air to escape. This problem is minimized by including vents along the parting lines, however, even in a highly refined process there will still be some porosity in the center of the casting.

Most die casters perform other secondary operations to produce features not readily castable, such as tapping a hole, polishing, plating, buffing, or painting.

Inspection

After the shakeout of the casting it is inspected for defects. The most common defects are misruns and cold shuts. These defects can be caused by bold dies, low metal temperature, dirty metal, lack of venting, or too much lubricant. Other possible defects are gas porosity, shrinkage porosity, hot tears, and flow marks. *Flow marks* are marks left on the surface of the casting due to poor gating, sharp corners, or excessive lubricant.

Lubricants

Water-based lubricants, called *emulsions*, are the most commonly used type of lubricant, because of health, environmental, and safety reasons. Unlike solvent-based lubricants, if water is properly treated to remove all minerals from it, it will not leave any by-product in the dies. If the water is not properly treated, then the minerals can cause surface defects and discontinuities. There are four types of water-based lubricants: oil in water, water in oil, semi-synthetic, and synthetic. Oil in water is the best, because when the lubricant is applied the water cools the die surface by evaporating while depositing the oil, which helps release the shot. A common mixture for this type of lubricants is thirty parts water to one part oil, however in extreme cases a ratio of 100:1 is used.

Oils that are used include heavy residual oil (HRO), animal fats, vegetable fats, and synthetic fats. HROs are gelatinous at room temperature, but at the high temperatures found in die casting, they form a thin film. Other substances are added to control the emulsions viscosity and thermal properties; these include graphite, aluminium, and mica. Other chemical additives are used to inhibit rusting and oxidation. Emulsifiers are added to water-based lubricants, so that oil based additives can be mixed into the water; these include soap, alcohol esters, and ethylene oxides.

Historically, solvent-based lubricants, such as diesel fuel and kerosene, were commonly used. These were good at releasing the part from the dies, but a small explosion occurred during each shot, which led to a build-up of carbon on the mold cavity walls. However, they were easier to apply evenly than water-based lubricants.

Advantages and disadvantages

Advantages:

- Excellent dimensional accuracy (dependent on casting material, but typically 0.1 mm for the first 2.5 cm (0.005 inch for the first inch) and 0.02 mm for each additional centimeter (0.002 inch for each additional inch).
- Smooth cast surfaces (Ra 1–2.5 micrometres or 0.04–0.10 thou rms).
- Thinner walls can be cast as compared to sand and permanent mold casting (approximately 0.75 mm or 0.030 in).
- Inserts can be cast-in (such as threaded inserts, heating elements, and high strength bearing surfaces).
- Reduces or eliminates secondary machining operations.
- Rapid production rates.
- Casting tensile strength as high as 415 megapascals (60 ksi).

The main disadvantage to die casting is the very high capital cost. Both the casting equipment required and the dies and related components are very costly, as compared to most other casting processes. Therefore to make die casting an economic process a large production volume is needed. Other disadvantages include: the process is limited to high-fluidity metals and casting weights must be between 30 grams (1 oz) and 10 kg (20 lb).In the standard die casting process the final casting will have a small amount of porosity. This prevents any heat treating or welding, because the heat causes the gas in the pores to expand, which causes micro-cracks inside the part and exfoliation of the surface.

Variants

Acurad

Acurad was a die casting process developed by General Motors in the late 1950s and 1960s. The name is an acronym for accurate, reliable, and dense. It was developed to combine a stable fill and directional solidification with the fast cycle times of the traditional die casting process. The process pioneered four breakthrough technologies for die casting: thermal analysis, flow and fill modeling, heat treatable and high integrity die castings, and indirect squeeze casting.

The thermal analysis was the first done for any casting process. This was done by creating an electrical analog of the thermal system. A cross-section of the dies were drawn on teledeltos paper and then thermal loads and cooling patterns were drawn onto the paper. Water lines were represented by magnets of various sizes. The thermal conductivity was represented by the reciprocal of the resistivity of the paper.

The Acurad system employed a bottom fill system that required a stable flow-front. Logical thought processes and trial and error were used because computerized analysis did not exist yet; however this modeling was the precursor to computerized flow and fill modeling.

The Acurad system was the first die casting process that could successfully cast low-iron aluminum alloys, such as A356 and A357. In a traditional die casting process these alloys would solder to the die. Similarly, Acurad castings could be heat treated and meet the U.S. military specification MIL-A-21180.

Finally, the Acurad system employed a patented double shot piston design. The idea was to use a second piston (located within the primary piston) to apply pressure after the shot had partially solidified around the perimeter of the casting cavity and shot sleeve. While the system was not very effective, it did lead the manufacturer of the Acurad machines, Ube Industries, to discover that it was just effective to apply sufficient pressure at the right time later in the cycle with the primary piston; this is indirect squeeze casting.

Pore-free

When no porosity is required for a casting then the **pore-free casting process** is used. It is identical to the standard process except oxygen is injected into the die before each shot to purge any air from the mold cavity. This causes small dispersed oxides to form when the molten metal fills the dies, which virtually eliminates gas porosity. An added advantage to this is greater strength. Unlike standard die castings, these castings can be heat treated and welded. This process can be performed on aluminium, zinc, and lead alloys.

Heated-manifold direct-injection

Heated-manifold direct-injection die casting, also known as **direct-injection die casting** or **runnerless die casting**, is a zinc die casting process where molten zinc is forced through a heated manifold and then through heated mini-nozzles, which lead into the molding cavity. This process has the advantages of lower cost per part, through the reduction of scrap (by the elimination of sprues, gates and runners) and energy conservation, and better surface quality through slower cooling cycles.

Semi-solid

Semi-solid die casting uses metal that is heated between its liquidus and solidus, so that it is "slushy". This allows for more complex parts and thinner walls.

Chapter 10

Bellfounding

A newly cast bell for Frankfurt's St. Paul's Church, cast in 1948 in Bochum, Germany

Bellfounding is the casting of bells in a foundry for use in churches, clocks, and public buildings. A practitioner of the craft is called a bellmaker or bellfounder. The process in Europe dates to the 4th or 5th century. In early times, when a town produced a bell it was a momentous occasion in which the whole community would participate. Archaeological excavations of churchyards in Britain have revealed furnaces, which suggests that bells were often cast on site in pits dug in the building grounds. In some instances bells were cast directly in the church. Before the nineteenth century, bellfounders tended to be itinerant, traveling from church to church to cast bells on site. It wasn't until the creation of railroads, that more centralized foundries were established. There are however examples of foundries producing bells prior to this, such as the Whitechapel Bell Foundry.

Bells intending to be rung are usually made by casting bell metal (a high-copper bronze alloy) of a size appropriate for the pitch the bell is intended to produce. Fine tuning of metal bells is achieved on a lathe where a precise amount of material is removed from the inside of the bell in order to produce a true tone with correct harmonics. Bells are used often to play a chime sequence and so must be well tuned in order to produce a correct scale of musical notes.

History

Bellfounding is a process that in Europe dates to the 4th or 5th century. In early times, when a town produced a bell it was a momentous occasion in which the whole community would participate. Archaeological excavations of churchyards in Britain have revealed furnaces, which suggests that bells were often cast on site in pits dug in the building grounds. Great Tom of Lincoln Cathedral was cast in the Minster yard in 1610, and the great bell of Canterbury in the Cathedral yard in 1762. When the casting was complete, a tower was built over the casting pit, and the bell raised directly up into the tower. In some instances, such as in Kirkby Malzeard and Haddenham the bells were actually cast in the church. Before the nineteenth century, bellfounders frequently traveled from church to church to cast bells on site and it wasn't until the creation of railroads, that more centralized foundries were established. There are however examples of foundries producing bells prior to this, such as the Whitechapel Bell Foundry.

Materials

The Tsar Bell showing crack caused by low melting point during casting

Bell metal

Functional bells with the intention of producing sound are usually made by casting bell metal— a high-copper bronze alloy, with approximately a 3:1 ratio of copper to tin (78% copper, 22% tin)— in a size appropriate for the pitch the bell is intended to produce. This metal combination produces a tough, long-wearing material that is resistant to oxidation and subject only to an initial surface weathering. This verdigris forms a protective patina on the surface of the bell which coats it against further oxidation. Bell metal of these ratios has been used for more than 3,000 years, and is known for its resonance and "attractive sound." Small bells were originally made with the lost-wax casting but this is no longer used in modern practice.

Both tin and copper are relatively soft metals; copper will deform in many directions when struck, as will tin, though to a lesser extent. Alloying the two elements creates a metal which is harder and less ductile and also one with more elasticity. This allows for a better bell resonance and causes the bell to "vibrate like a spring when struck", a necessary quality as the clapper may strike the bell at speeds of up to 600 miles per hour. The forces holding the tin and copper together cause vibrations rather than cracks when the bell is struck which creates a resonant tone.

The hardest and strongest bronze contains large amounts of tin and little lead though an alloy with more than 25% tin will have a low melting point and become brittle and susceptible to cracking. This low melting point proved to be the nemesis of Russia's third attempt at casting the Tsar Bell from 1733–1735. The bell was never rung, and a huge slab cracked off (11.5 tons) during a fire in the Kremlin in 1737 before it could ever be raised from its casting pit. Burning timber fell into the casting pit and the decision was whether to let it burn and risk melting the bell, or to pour water on it and risk causing it cracking from cooling it too quickly. The latter risk was chosen and, as feared, because of the low melting point of the bronze and uneven cooling, the bell was damaged. The present bell is sometimes referred to as Kolokol III (Bell III), because it is the third recasting; remnants from the old bell were melted down and the metal re-used to cast the new bell. This practice was fairly commonplace, as the metal materials were very costly. Bell metal was considered so valuable that the first bronze coins for England were made in France out of melted down old bells.

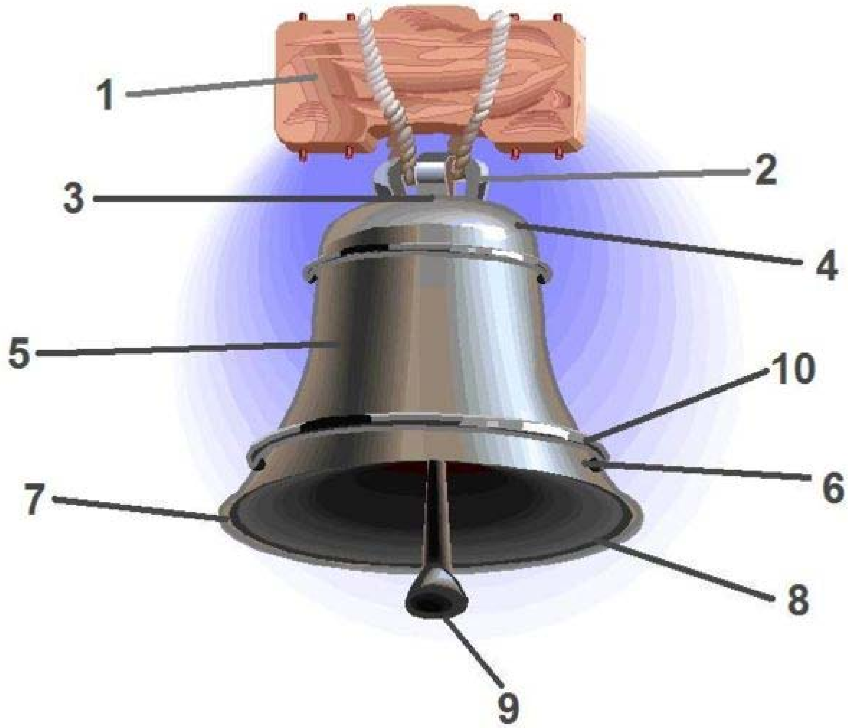
Other metals

Other materials occasionally used for bell casting are brass or iron. Steel was tried during the busy church-building period of mid-nineteenth England, for its economy over bronze, but was found not to be durable and manufacture ceased in the 1870s. They have also been made of glass, and though bells of this type produced a successful tone, this substance being very brittle was unable to withstand the continued use of the clapper.

By popular tradition the bell metal contained gold and silver, as component parts of the alloy, as it is recorded that rich and devout people threw coins into the furnace when bells were cast in the churchyard. The practice was believed to improve the tone of the bell. This however is likely erroneous and must be discredited as there are no authentic analyses of bell metal, ancient or modern, which show that gold or silver has ever been used as a component part of the alloy. If used to any great extent, the addition would injure the tone not improve it. Small quantities of other metals found in old bell metal are likely impurities in the metals used to form the alloy.

Decorative bells can be made of such materials as horn, wood, and clay.

Manufacturing process



Parts of a typical bell: 1. yoke, 2. crown, 3. head, 4. shoulder, 5. waist, 6. sound ring, 7. lip, 8. mouth, 9. clapper, 10. bead line

The craft of casting bells has remained essentially the same since the 12th century, being cast mouth down, in a two-part mould consisting of the core, and the shell, or cope, clamped to a base-plate. Though the process does have some variations the major differences are in the quality control standards.

Measurement and templating

Firstly the bell design is calculated to precise specifications where the bellmaker determines the shape that the bell will need to take in order to resonate with the proper number of vibrations and create the right sound and pitch. The bell pattern is then cut out in two wooden templates called "strickle boards". One of the boards matches the dimensions of the outer bell (called the case or cope); the other matches that of the inner bell (called the core). The boards are used to create the inner and outer molds of the final bell.

Bell molds in the bell museum (Glockenmuseum) in Gescher, Germany

Constructing the mold

An exact stone model of the outer bell, sometimes called a false bell, is built on a base-plate using porous materials such as coke, stone or brick. It is then covered first with sand or loam mixed with sometimes with straw and horse manure. This is given a profile corresponding to the inside shape of the finished bell, and dried with gentle heat. The false bell is then covered with molten wax and figures and inscriptions, also made of wax, applied on top by hand. The false bell is painted over with three coats of fireproof clay and then enclosed by a steel mantle overcasing. The empty space between the false bell and the mantle is filled in with cement and left to harden before the mantle is lifted off. The false bell is chipped away from the inner core to leave just the wax and cement. Any leftover scraps of the false bell are removed with a blow torch. The mold is then set over a coke fire to melt the remaining wax and to evaporate any water that has accumulated.

A model of the inner bell is then constructed of stone and coated with fireproof cement. It is then smoothed to remove any irregularities.

Bell casting mold demonstrating process at the Technical Museum Vienna, Austria

Casting the bell

After the outer steel mantle has been cleaned, it is again lowered over the outer bell model. The mantle and the outer bell mold are then lowered over the inner mold and the outer and inner sections are clamped together, leaving a space between them. The clamped mold is supported, by being buried in a *casting pit* which bears the weight of metal and allows even cooling. Ingots of bronze are melted in oil burners and heated until molten at a temperature of approximately 1566°F (870°C). The liquid metal is then skimmed to remove impurities before being transferred to drums. The drums are lifted over the pit and carefully tipped so that the hot metal flows into the space between the two molds. Holes in the top of the mantle insure that gases are able to escape. If gas remained in the metal, the bell would be too porous and be susceptible to cracking.

The bell is allowed to cool for several days. Large bells can take over a week to cool completely. Small bells, those under 500 pounds (227 kg), can be removed from the molding pit the following day.

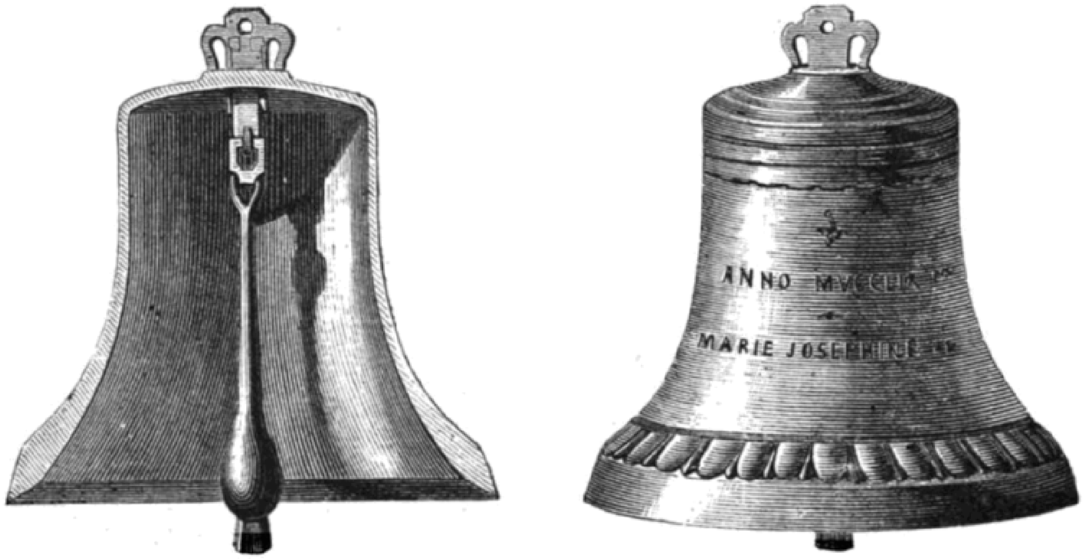
Tuning

Bells are made to exact formulas, so that given the diameter it is possible to calculate every dimension, and its musical note, or tone. The frequency of a bell's note varies with the square of its thickness, and inversely with its diameter. Much experimentation has been devoted to determining the exact shape that will give the best tone. The smaller the bell the higher the pitch. The thickness of a church bell at its thickest part, called the "sound bow", is usually one thirteenth its diameter. If the bell is mounted as cast, it is called a "maiden bell", Russian bells are treated in this way and cast for a certain tone.

"Tuned bells" are worked after casting to produce a precise note. This was a common practice in Britain and Europe. In the early days of bellfounding, bells were tuned using an imprecise method whereby the inside of the bell, or the edge of the lip, was chipped away. With the improvement of machinery, this was done using a lathe. The bell is cast with slightly thicker sides before being inverted, and gripped by vises, to keep it perfectly firm. The bell is then ground as it rotates on a circular lathe to acquire the precise tone. The bell tuner must be highly skilled as it takes years of experience to know how much metal to remove. By this means, bells can be very accurately tuned. In casting, bells are best left sharp, for flattening injures the tone much less than sharpening. A bell may readily be flattened one-eighth of a tone, or even more, but it cannot be sharpened so much; indeed, any sharpening is to be deprecated, and if at all possible should be avoided.

The bell tone is tested frequently during the tuning process usually with tuning forks or an electronic stroboscopic tuning device commonly called a Strobe tuner which registers the vibrations as the bell is struck. If the tone is too low, the lathe operator grinds more metal off the lower edge of the bell. If the tone is too high, the bell is thinned with a file.

The elements of the sound of a bell are split up into hum, second partial, tierce, quint and nominal/naming note. The bell's strongest harmonics are tuned to be at octave intervals below the nominal note, but other notes also need to be brought into their proper relationship.



Cutaway drawing of a bell, showing the clapper and interior.

Fitting the clapper

The clapper or tongue is manufactured in a similar process as the bell. Special care is given to cast the clapper at the proper weight as a clapper that is too light in weight will not bring out the true tones of the bell and a heavy clapper might cause the bell to crack. Holes are drilled into the top of the bell and the clapper is attached to the inside of the bell either by a metal link or by a leather strap. Finally the bell is installed in the tower.

Chapter 11

Casting Defect

A **casting defect** is an irregularity in the metal casting process that is undesired. Some defects can be tolerated while others can be repaired otherwise they must be eliminated. They are broken down into five main categories: *gas porosity*, *shrinkage defects*, *mold material defects*, *pouring metal defects*, and *metallurgical defects*.

Terminology

The terms "defect" and "discontinuity" refer to two specific and separate things in castings. Defects are defined as conditions in a casting that must be corrected or removed, or the casting must be rejected. Discontinuities, also known as "imperfections", are defined as "interruptions in the physical continuity of the casting". Therefore, if the casting is less-than-perfect, but still useful and in tolerance, the imperfections should be deemed "discontinuities".

Types

There are many types of defects which result from many different causes. Some of the solutions to certain defects can be the cause for another type of defect.

The following defects can occur in sand castings. Most of these also occur in other casing processes.

Shrinkage defects

Shrinkage defects occur when feed metal is not available to compensate for shrinkage as the metal solidifies. Shrinkage defects can be split into two different types: *open shrinkage defects* and *closed shrinkage defects*. Open shrinkage defects are open to the atmosphere, therefore as the shrinkage cavity forms air compensates. There are two types of open air defects: *pipes* and *caved surfaces*. Pipes form at the surface of the casting and burrow into the casting, while caved surfaces are shallow cavities that form across the surface of the casting.

Closed shrinkage defects, also known as *shrinkage porosity*, are defects that form within the casting. Isolated pools of liquid form inside solidified metal, which are called *hot spots*. The shrinkage defect usually forms at the top of the hot spots. They require a nucleation point, so impurities and dissolved gas can induce closed shrinkage defects. The defects are broken up into *macroporosity* and *microporosity* (or *microshrinkage*), where macroporosity can be seen by the naked eye and microporosity cannot.

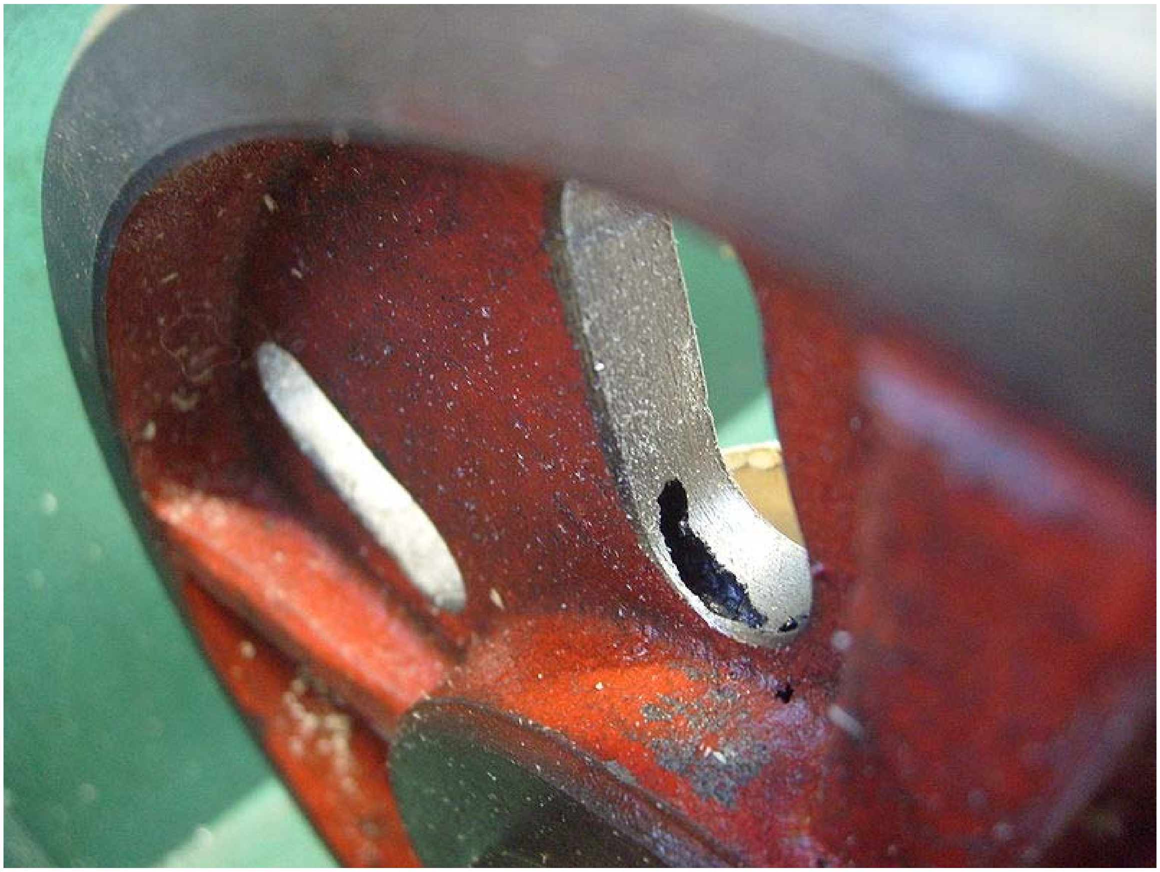
Gas porosity

Gas porosity is the formation of bubbles within the casting after it has cooled. This occurs because most liquid materials can hold a large amount of dissolved gas, but the solid form of the same material cannot, so the gas forms bubbles within the material as it cools. Gas porosity may present itself on the surface of the casting as porosity or the pore may be trapped inside the metal, leading to an increased risk of breaking or stress corrosion. Nitrogen, oxygen and hydrogen are the most encountered gases in cases of gas porosity. In aluminum castings, hydrogen is the only gas that dissolves in significant quantity, which can result in hydrogen gas porosity. For casting that are a few kilograms in weight the pores are usually 0.01 to 0.5 mm (0.00039 to 0.020 in) in size. In larger casting they can be up to a millimeter (0.040 in) in diameter.

To prevent gas porosity the material may be melted in a vacuum, in an environment of low-solubility gases, such as argon or carbon dioxide, or under a flux that prevents contact with the air. To minimize gas solubility the superheat temperatures can be kept low. Turbulence from pouring the liquid metal into the mold can introduce gases, so the molds are often streamlined to minimize such turbulence. Other methods include vacuum degassing, gas flushing, or precipitation. Precipitation involves reacting the gas with another element to form a compound that will form a dross that floats to the top. For instance, oxygen can be removed from copper by adding phosphorus, or aluminum or silicon can be added to steel to remove oxygen. A third source consists of reactions of the molten metal with grease or other residues in the mold.

Hydrogen is normally produced by the reaction of the metal with humidity or residual moisture in the mold. Drying of the mold can eliminate this source of hydrogen.

Gas porosity can sometimes be difficult to distinguish from microshrinkage because microshrinkage cavities can contain gases as well. In general, microporosities will form if the casting is not properly risered or if a material with a wide solidification range is cast. If neither of these are the case then most likely the porosity is due to gas formation.



Blowhole defect in a cast iron part.

Tiny gas bubbles are called porosities, but larger gas bubbles are called a *blowholes* or *blisters*. Such defects can be caused by air entrained in the melt, steam or smoke from the casting sand, other gasses from the melt or mold. (Vacuum holes caused by metal shrinkage may also be loosely referred to as 'blowholes'). Proper foundry practices, including melt preparation and mold design, can reduce the occurrence of these defects. Because they are often surrounded by a skin of sound metal, blowholes may be difficult to detect, requiring harmonic, ultrasonic, magnetic, or X-ray analysis.

Pouring metal defects

Pouring metal defects include *misruns*, *cold shuts*, and *inclusions*. A misrun occurs when the liquid metal does not completely fill the mold cavity, leaving an unfilled portion. Cold shuts occur when two fronts of liquid metal do not fuse properly in the mold cavity, leaving a weak spot. Both are caused by either a lack of fluidity in the molten metal or cross-sections that are too narrow. The fluidity can be increased by changing the chemical composition of the metal or by increasing the pouring temperature. Another possible cause is back pressure from improperly vented mold cavities.

Misruns and *cold shuts* are closely related and both involve the material freezing before it completely fills the mold cavity. The castability and viscosity of the material can be important factors with these problems. Fluidity affects the minimum section thickness that can be cast, the maximum length of thin sections, fineness of feasibly casted details, and the accuracy of filling mold extremities. There are various ways of measuring the fluidity of a material, although it usually involves using a standard mold shape and measuring the distance the material flows. Fluidity is affected by the composition of the material, freezing temperature or range, surface tension of oxide films, and, most importantly, the pouring temperature. The higher the pouring temperature, the greater the fluidity; however, excessive temperatures can be detrimental, leading to a reaction between the material and the mold; in casting processes that use a porous mold material the material may even penetrate the mold material.

The point at which the material cannot flow is called the *coherency point*. The point is difficult to predict in mold design because it is dependent on the solid fraction, the structure of the solidified particles, and the local shear strain rate of the fluid. Usually this value ranges from 0.4 to 0.8.

An inclusion is a metal contamination of dross, if solid, or slag, if liquid. These usually are metal oxides, nitrides, carbides, calcides, or sulfides; they can come from material that is eroded from furnace or ladle linings, or contaminates from the mold. In the specific case of aluminium alloys, it is important to control the concentration of inclusions by measuring them in the liquid aluminium and taking actions to keep them to the required level.

There are a number of ways to reduce the concentration of inclusions. In order to reduce oxide formation the metal can be melted with a flux, in a vacuum, or in an inert atmosphere. Other ingredients can be added to the mixture to cause the dross to float to the top where it can be skimmed off before the metal is poured into the mold. If this is not practical, then a special ladle that pours the metal from the bottom can be used. Another option is to install ceramic filters into the gating system. Otherwise swirl gates can be formed which swirl the liquid metal as it is poured in, forcing the lighter inclusions to the center and keeping them out of the casting. If some of the dross or slag is folded into the molten metal then it becomes an entrainment defect.

Metallurgical defects

There are two defects in this category: *hot tears* and *hot spots*. Hot tears, also known as hot cracking, are failures in the casting that occur as the casting cools. This happens because the metal is weak when it is hot and the residual stresses in the material can cause the casting to fail as it cools. Proper mold design prevents this type of defect.

Hot spots are areas on the surface of casting that become very hard because they cooled more quickly than the surrounding material. This type of defect can be avoided by proper cooling practices or by changing the chemical composition of the metal.

Process specific defects

Die casting

In die casting the most common defects are misruns and cold shuts. These defects can be caused by bold dies, low metal temperature, dirty metal, lack of venting, or too much lubricant. Other possible defects are gas porosity, shrinkage porosity, hot tears, and flow marks. *Flow marks* are marks left on the surface of the casting due to poor gating, sharp corners, or excessive lubricant.

Longitudinal facial crack

A *longitudinal facial crack* is a specialized type of defect that only occurs in continuous slab casting processes. This defect is caused by uneven cooling, both primary cooling and secondary cooling, and includes molten steel qualities, such as the chemical composition being out of specification, cleanliness of the material, and homogeneity.

Sand casting

Sand casting has many defects that can occur due to the mold failing. The mold usually fails because of one of two reasons: the wrong material is used or it is improperly rammed.

The first type is *mold erosion*, which is the wearing away of the mold as the liquid metal fills the mold. This type of defect usually only occurs in sand castings because most other casting processes have more robust molds. The castings produced have rough spots and excess material. The molding sand becomes incorporated into the casting metal and decreases the ductility, fatigue strength, and fracture toughness of the casting. This can be caused by a sand with too little strength or a pouring velocity that is too fast. The pouring velocity can be reduced by redesigning the gating system to use larger runners or multiple gates. A related source of defects are *drops*, in which part of the molding sand from the cope drops into the casting while it is still a liquid. This also occurs when the mold is not properly rammed.

The second type of defect is *metal penetration*, which is when the liquid metal penetrates into the molding sand. This causes a rough surface finish. This caused by sand particles that are too coarse, lack of mold wash, or pouring temperatures that are too high.

If the pouring temperature is too high or a sand of low melting point is used then the sand can fuse to the casting. When this happens the surface of the casting produced has a brittle, glassy appearance.

A *run out* is when the liquid metal leaks out of the mold because of a faulty mold or flask.

Scabs are a thin layer of metal that sits proud of the casting. They are easy to remove and always reveal a *buckle* underneath, which is an indentation in the casting surface. *Rattails* are similar to buckles, except they are thin line indentations and not associated with scabs. Another similar defect is a *pulldowns*, which are buckles that occur in the cope of sand castings. All of these defects are visual in nature and no reason to scrap the workpiece. These defects are caused by overly high pouring temperatures or deficiencies of carbonaceous material.

A *swell* occurs when the mold wall gives way across a whole face, and is caused by an improperly rammed mold.

Burn-on occurs when metallic oxides interact with impurities in silica sands. The result is sand particles embedded in the surface of the finished casting. This defect can be avoided by reducing the temperature of the liquid metal, by using a mold wash, and by using various additives in the sand mixture.