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Centrifugal Casting

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CENTRIFUGAL CASTING is one of the largest casting branches in the casting industry, accounting for 15% of the total casting output of the world in terms of tonnage. Centrifugal casting was invented in 1918 by the Brazilian Dimitri Sensaud deLavaud, after whom the process was named. DeLavaud's invention eliminated the need for a central core in the pipe mold, and the mold was water cooled, allowing for a high rate of repeated use. The technique uses the centrifugal force generated by a rotating cylindrical mold to throw molten metal against a mold wall to form the desired shape. Therefore, a centrifugal casting machine must be able to spin a mold, receive molten metal, and let the metal solidify and cool in the mold in a carefully controlled manner.

All metals that can be cast by static casting can be cast by the centrifugal casting process, including carbon and alloy steels, high-alloy corrosion- and heat-resistant steels, gray iron, ductile and nodular iron, high-alloy irons, stainless steels, nickel steels, aluminum alloys, copper alloys, magnesium alloys, nickel- and cobalt-base alloys, and titanium alloys. Nonmetals can also be cast by centrifugal casting, including ceramics, glasses, plastics, and virtually any material that can be made into liquid or pourable slurries. Centrifugal castings can be best described as isotropic, that is, having equal properties in all directions. This is not true of a forging, rolling, or extrusion.

The centrifugal technique is used primarily for the production of hollow components, but centrifugal casting is used to create solid parts. The centrifugal casting process is generally preferred for producing a superior-quality tubular or cylindrical casting, because the process is economical with regard to casting yield, cleaning room cost, and mold cost. The centrifugal force causes high pressures to develop in the metal, and it contributes to the feeding of the metal, with separation from nonmetallic inclusions and evolved gases. In centrifugal casting of hollow sections, nonmetallic inclusions and evolved gases tend toward the inner surface of the hollow casting. By using the outstanding advantage created by the centrifugal force of rotating molds, castings of high quality and integrity can be produced because of their high density and freedom from oxides, gases, and other nonmetallic inclusions. When casting solid parts, the pressure from rotation allows thinner details to be cast, making surface details of the metal-cast components more prominent. Another advantage of centrifugal casting is the elimination or minimization of gates and risers.

Centrifugal Casting Methods

Centrifugal casting machines are categorized into three basic types based on the direction of the spinning axis: horizontal, vertical, or inclined. Centrifugal casting processes also have three types (Fig. 1):

- True centrifugal casting (horizontal, vertical, or inclined)
- Semicentrifugal (centrifugal mold) casting
- Centrifuge mold (centrifugal die) casting

The latter two methods are only done with vertical spinning.

Horizontal centrifugal casting is mainly used to cast pieces with a high length-to-diameter ratio or with a uniform internal diameter. Products include pipe, tubes, bushings, cylinder sleeves (liners), and cylindrical or tubular castings that are simple in shape. On the other hand, vertical centrifugal casting is mainly for castings with a low length-to-diameter ratio (except vertically cast extralong rolls) or with a conical diameter. The product range for vertical centrifugal casting machines is wider, because noncylindrical (or even nonsymmetrical) parts can be made using vertical centrifugal casting. All vertical centrifugal castings have more or less taper on their inside diameters, depending on the gravitational (g) force applied to the mold and the casting size. The inclined centrifugal casting machine bears advantages and disadvantages of both horizontal and vertical castings and can be very useful in certain applications.

Although both vertical and horizontal methods employ centrifugal force, there are some differences in how the force is applied with respect to the axis of the mold rotation and the speed of the molten metal relative to the rotating mold. For example, with a vertical mold axis, the resultant force on the liquid is constant. This is not the case in a horizontal mold. The other difference between horizontal and vertical mold orientation is the speed obtained by the molten metal as it spins around the mold. When metal is poured into the horizontally rotating mold, considerable slip occurs between the metal and the mold such that the metal does not move as fast as the rotating mold. To overcome this inertia, the metal must be accelerated to reach the mold rotation speed. This is not a problem in the vertical centrifugal process, where the molten metal reaches the speed of the mold soon after pouring. However, with a vertical mold axis, there is a tendency for the molten metal to form a parabolic shape due to the competing gravitational and centrifugal forces.

True Centrifugal Casting

This method, also referred to as just centrifugal casting, is characterized by an outer cylindrical mold with no cores. The process can be vertical, horizontal, or inclined (Fig. 1). The permanent mold is rotated about its axis at high speeds (300 to 3000 rpm), so that the molten metal is forced to the inside mold wall, where it solidifies. The casting is usually very fine grained on the outer diameter, while the inside diameter has more impurities and inclusions that can be machined away.

Centrifugal casting is used to produce cylindrical, tubular, or ring-shaped castings. The need for a center core is completely eliminated. Castings produced by this method will always have a true cylindrical bore or inside diameter, regardless of shape or configuration. The bore of the casting will be straight or tapered, depending on the horizontal or vertical spinning axis used. Castings produced in metal molds by this method have true directional heat flow, facilitating a planar solidification front move from the outside of the casting toward the axis of rotation. This method results in the production of high-quality, defect-free castings without shrinkage, which is the largest single cause of defective sand castings.

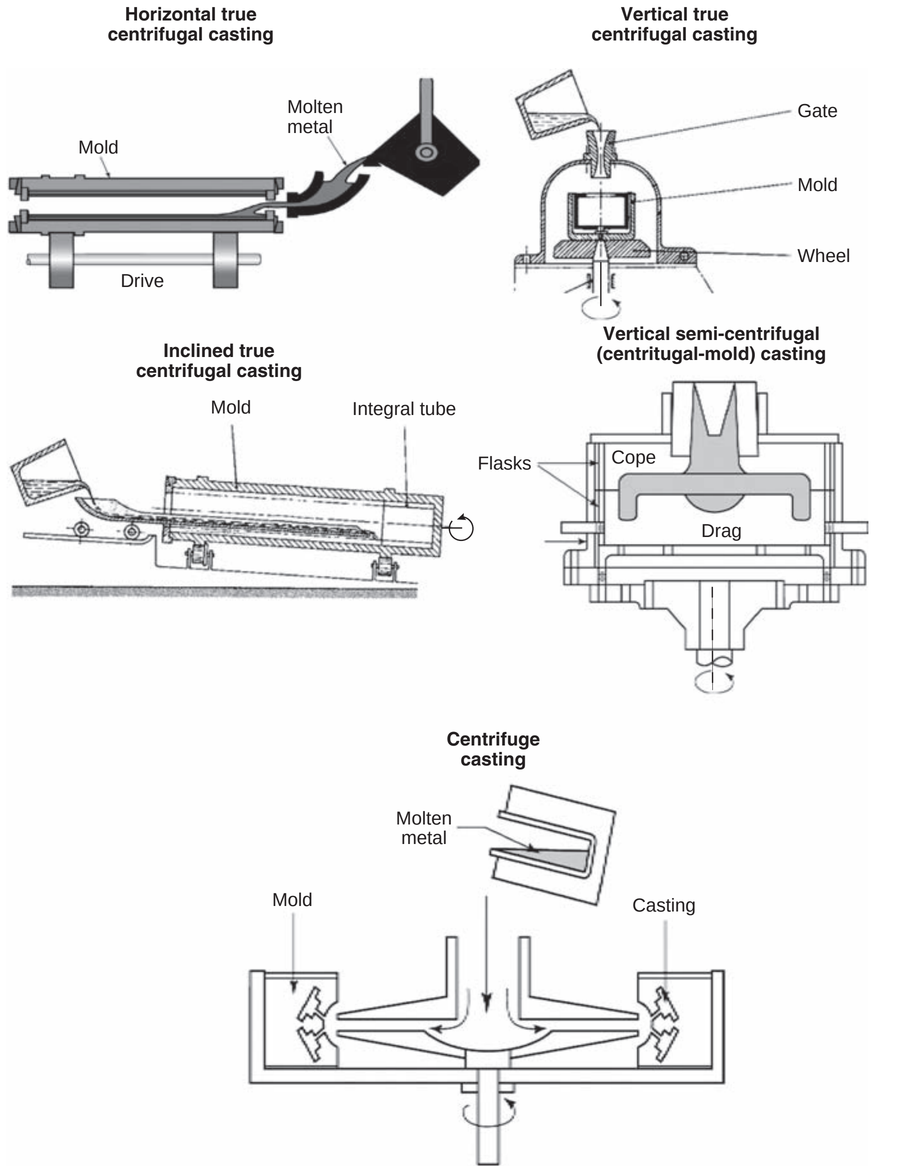

Fig. 1 Methods of casting with rotating molds. True centrifugal casting (top row) can be horizontal, vertical, or at an incline. Semicentrifugal and centrifuge die casting are vertical methods with molds that can be designed to produce solid parts.

Centrifugal casting is also the preferred method for Babbitting medium- and thick-wall, half-shell or full-round (nonsplit) journal bearings, because it virtually eliminates porosity and allows close control of the cooling process to promote a strong bond. A disadvantage is the need for more extensive equipment and tooling than for static casting. Minor segregation of the intermetallics can occur across the thickness of the Babbitt, but segregation along the axial length of a statically cast bearing can be more serious and is more difficult to detect. The spinning axis is usually horizontal, but vertical orientation is sometimes employed for unusual sizes (e.g., large diameters or short lengths).

Advantages of centrifugal casting include:

- *Flexibility in casting composition:* Centrifugal casting is applicable to nearly all compositions, with the exception of high-carbon steels (0.40 to 0.85% C). Carbon segregation can be a problem in this composition range.
- *Wide range of available product characteristics:* The metallurgical characteristics of a tubular product are mainly characterized by its soundness, texture, structure, and mechanical properties. Centrifugal castings can be manufactured with a wide range of microstructures tailored to meet the demands of specific applications.
- *Dimensional flexibility:* Horizontal centrifugal casting allows the manufacture of pipes with maximum outside diameters close to 1.6 m (63 in.) and wall thicknesses to 200 mm (8 in.). Tolerances depend on part size and the type of mold used.
- *Quality:* The centrifugal action removes unwanted inclusions, dross, cleaner casting, and material that contains shrinkage, which can be machined away. Class I castings can be produced without the need for upgrading and costly weld repairs.
- *Properties:* Mechanical properties are often superior to those of static castings due to the finer grains resulting from the process, which are of constant size in circumferential and axial directions. Due to cleanliness and finer grain size, good weldability is achieved.

Semicentrifugal (Centrifugal Mold) Casting

In semicentrifugal casting (Fig. 1), a mold is rotated around its axis of symmetry. Cast configurations may be complex, determined by the shape of the mold. Molds for semicentrifugal casting often contain cores for production of internal surfaces. Directional solidification is obtained only by proper gating, as in static casting. Castings that are difficult to produce statically can often be economically produced by this method, because centrifugal force feeds the molten metal under pressure many times higher than that in static casting. This improves casting yield significantly (85 to 95%), completely fills mold cavities, and results in a high-quality casting free of voids and porosity. Thinner casting sections can be produced with this method than with static casting. Typical castings of this type include gear blanks, pulley sheaves, wheels, impellers, cogwheels, and electric motor rotors. The centrifugal force is used for slag separation and refilling of melt.

Centrifuge (Centrifugal Die) Casting

Centrifugal mold or die casting, also referred to as centrifuge casting, has the widest field of application. This casting method is typically used to produce valve bodies and bonnets, plugs, yokes, brackets, and a wide variety of various industrial castings.

In this method (Fig. 1), the casting cavities are arranged about the center axis of rotation like the spokes of a wheel, thus permitting the production of multiple castings. Centrifugal force provides the necessary pressure on the molten metal in the same manner as in semicentrifugal casting. The centrifugal force contributes to metal feed for casting thinner sections and making surface details.

Centrifuge casting is often used in conjunction with investment casting. It is also used with rubber molds made of silicone rubber with sufficiently higher temperature resistance for repeated use in casting without mold deterioration. Centrifuge casting with rubber molds is also referred to as spin casting. Suitable materials for spin casting include zinc-base alloys, lead-base alloys, tin-base alloys, aluminum, and plastics.

Equipment

A centrifugal casting machine must be able to perform six operations accurately and with repeatability:

- The machine must be able to accelerate the mold to a predetermined speed, maintain smooth spinning, and decelerate to a stop in a reasonable time frame. The machine also should be able to change speeds during pour and solidification for some special applications.
- There must be a way to heat and coat the mold before pouring the molten metal (except the cold mold method for ductile iron pipe).
- There must be a means to pour the molten metal safely into the rotating mold at a controlled rate, position, and orientation.
- Once the metal is poured, a proper solidification and cooling rate must be established in the mold to obtain a desired casting microstructure, protect the mold, and achieve required productivity.
- There must be a means of adding inoculants or fluxes for some special applications.
- There must be a means of extracting the solidified casting quickly from the mold at elevated temperatures without deforming the casting.

Centrifugal casting machines have realized mechanization and automation basically in all of the aforementioned six tooling areas in many applications. An example of an automated horizontal machine and extractor is shown in Fig. 2. New casting and machine products are still evolving, such as metal-matrix composite castings and magnetic stirring solidification. Centrifugal casting and equipment engineers continue to use computers to collect, store, and process the key production, equipment, and product information for high-tech products, so that the production parameters can be optimized and automatically set up in production. Centrifugal casting will continue to be prosperous in the casting industry.

Spinners. Spinning of the mold is realized by spinners. The achievable spinning speed and, sometimes, the ability to change speeds during the pour and solidification process is an important consideration for determining whether a casting geometry or a casting microstructure can be achieved. Spinning speeds are chosen based on the centrifugal force requirement, which is measured by the multiple of the gravitational force (called *g* force). Horizontal casting machines are typically spun at 45 to 60 *g* force on the casting inside diameter, and vertical casting machines are typically spun at 75 *g* force. For some special applications, the spinning speed can be as high as 100 to 200 *g* force (e.g., horizontal roll castings and heat-resistant steel tube castings); in other cases, it can be as low as a fraction of a *g* to a few *g*'s (e.g., when vertically pouring a roll core, vertically pouring solid bars, or horizontal two-speed pouring). Figure 6 in the article "Vertical Centrifugal Casting" in this Volume provides a convenient chart to check the centrifugal force against casting diameters and spinning speeds.

In order to achieve the correct *g* force, the proper motor size is required. Too small a motor cannot meet process requirements for the spinning speed, and too big a motor can have an excessive acceleration rate that may cause machine vibration. For large horizontal machines, hydraulic motors are preferred over electric motors, because the former offer smoother spinning. Vibration monitors are installed for some large spinners to ensure smooth spinning. The spinners also need to be stopped at a predetermined time, which can be realized by the proper electric, hydraulic, or mechanical means. Most vertical machines use a single spinner, and the mold is spun on top of the spinner. These vertical machines will have less stability than horizontal machines when the mold length-to-diameter ratio is greater than 1. Vertical machines with a long mold need trunnion wheels to support the mold around the circumference at the upper section. Small spinners and molds can be clustered to form a turntable, an over-and-under, or a Ferris wheel-type casting machine, which shares the same pouring, heating, coating, and extracting systems, forming a very efficient production cell.

Pour equipment and pour rate can be essential pieces of the process for successful production of certain types of castings. Pouring is a critical factor in the following applications, to name a few. The centrifugal ductile iron pipe casting process requires a long, moving trough and quadrant pour ladle to deliver the molten iron along the mold to make 6 to 8 m (20 to 26 ft) long pipe. The centrifugal soil pipe casting process needs a proper chute that can be cleaned and coated in a few seconds after each pour and a consistent pour rate to dash the molten metal to the far end of the mold to form 3 m (10 ft) long pipes with even thickness. Centrifugal heat-resistant steel tube castings rely on a fast pour rate and sufficient pour height to help form the long thin-wall tube before the molten metal gets too cold. Vertical roll casting uses a special-shaped down sprue to prevent the metal flow from whirling.

Casting Cooling. Centrifugal castings should be cooled unidirectionally from outside to inside. Any two-way solidification will increase the chance of shrinkage porosity and machining allowance, which should be avoided or minimized in thick-wall castings. Cooling rate can affect the microstructure, casting hardness, circumferential and axial cracks, machine productivity, as well as mold life. In most cases, the early cooling rate of the castings is mainly controlled by the coating thickness, coating texture, coating materials, as well as mold thickness and mold materials; however, the later cooling rate is mainly controlled by water cooling (unless the mold is not cooled by water). Water-cooling methods include water submerge, waterjet spray, and water sleeve. Ductile iron pipe production uses all three water-cooling methods mentioned previously, but other centrifugal castings mainly require waterjet spray, because of its simple setup and easy control of mold temperature. Roll production usually does not require water cooling, because the chill wall thickness is sufficient to absorb heat from the molten metal. Water cooling needs to be consistent, but sometimes, it needs intensity variation along the casting length. For example, the middle section of a long tube mold usually needs more water for cooling.

As far as the grain structure of centrifugal castings (e.g., columnar versus equiaxed) is concerned, the pour temperature or the variable spinning speed plays a much more important role in obtaining the equiaxed grains than the water-cooling rate or mold temperature. Water cooling can be critical in certain products, such as high leaded bronze bushings and Babbitt bearings, where intensive water cooling assures that the lead segregation is suppressed.

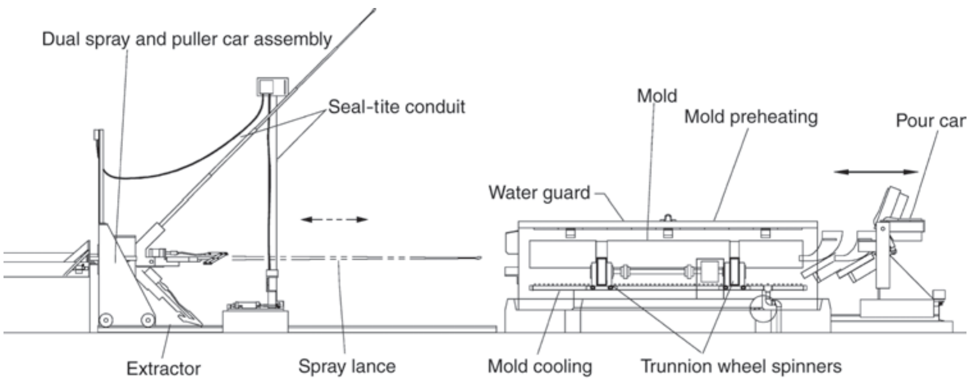

Fig. 2 Automated horizontal casting machine. Courtesy of the Centrifugal Casting Machine Company

Some applications require continuous monitoring of casting and mold temperatures by a thermal couple probe inserted into the mold cavity or infrared sensors aimed at the casting inside diameter and mold outside diameter, so that the current process can be stopped and the next process can be started. This is critical, for example, to obtain a good bimetal bonding for roll production.

Casting Inoculation and Fluxing. Some castings necessitate the use of inoculants to obtain the desired microstructure (such as ductile iron and gray iron) or grain sizes (such as thick-wall chilled iron or steel tubes). In some applications, fluxes are needed to protect the casting inside diameter in order to obtain a sound metallurgical bimetal bonding (such as in the production of rolls and brake drums) or to prevent premature solidification or oxidation (such as in thick-wall steel castings) of the casting inside diameter. Still others may use fluxes to purify the molten metal during pouring and solidification. All of these would require some means to deliver the inoculants or fluxes into the metal stream during pouring or into the mold cavity before or during solidification.

Casting Extraction. Castings need to be extracted from the permanent mold. Small and low-production machines use manual extractors and manpower to extract. Large castings, however, rely on mechanized extractors to do the job. In extracting from horizontal machines, the extractor must overcome the friction acting on the whole interface between the casting and the mold. For vertical machines, the extractor must overcome friction plus casting weight. For some applications, the castings are kept rotating during and/or after extraction to prevent the casting from warping.

Molds

Sand molds, semipermanent molds, and permanent molds can be used for the centrifugal casting process. Centrifugal action can also be combined with other molding methods such as investment casting. Selection of the type of mold is determined by the shape of the casting, the degree of quality needed, material to be cast, and the production (number of castings) required. In addition to the processing parameters, proper mold design and selection is vital to producing quality castings. More details on mold design are provided in the articles "Horizontal Centrifugal Casting" and Vertical Centrifugal Casting" in this Volume.

Molds consist basically of four parts: the mold body, track grooves or roller tracks on the body (these can be absent if the machine has thrust wheels to hold the mold axially), endplates attached to the mold body, and endplate swing locks or taper pins/wedges. A vertical mold needs fixtures to fasten it onto the adapter table, and the table is bolted onto the spinner shaft. A mold used on a dual-faceplate horizontal machine can have a mold body without other mold parts.

Mold materials include metallic permanent molds, refractory-lined metal molds, sand-lined metal molds, and other materials such as graphite and rubbers. The metallic permanent molds are most widely used because of their reusability, accurate casting geometry, and high productivity. Mold inside diameters are subject to thermal fatigue no matter what mold material is used. The low-carbon and low-alloyed forged steel molds have much longer fatigue lives than cast steel or cast iron molds, and they are also safer to use. However, forged steel molds are more expensive to make than molds made of cast steel and iron. Copper alloys, tool steels, and superalloys are sometimes used for small castings that require high pour temperatures or high cooling rates. Hardened rubber molds are used for some metal jewelry with low melting points.

Both horizontal and vertical molds must meet certain geometrical precisions (straightness, smoothness, roundness, concentricity, freedom from internal pores) to minimize machine vibration, which can be critical to safety, bearing life, machine life, and product quality. The mold should also be maintained or repaired during the life of its service. For example, the inside diameter of a ductile iron pipe mold is periodically peened to eliminate tensile stress caused by thermal fatigue. Large grooves or cracks on the mold inside diameter can be repaired by subarc welding and grinding. The mold geometric accuracy can be maintained through remachining and grinding.

Mold endplates should be properly designed to prevent molten metal leakage. It cannot be overemphasized that the mold endplate locks and mold fasteners are designed with a safety factor greater than 10 to prevent the endplates from coming off the mold or the molds from coming off the machine, which can cause catastrophic molten metal spilling. The push force (F) on the endplates generated by the spinning metal is expressed by the following equation:

$$F = 5.375\rho\left(\frac{N}{100}\right)^2\left(d_o^2 - d_i^2\right)^2$$

where ρ is the molten metal density (kg/m^3), N is the mold spinning speed (rpm), d_o is the casting outside diameter (m), and d_i is the casting inside diameter (m).

This equation illustrates that the pushing force increases rapidly with the spinning speed (squared), casting diameter (squared), casting thickness (squared), as well as the metal density. Therefore, whenever a large or thick casting is to be poured, the pushing force on the endplates must be calculated so that the stresses of the endplate locks, bolts, pins, and fasteners can be calculated and properly designed.

Mold Heating and Coating Techniques. The centrifugal casting mold must be heated and coated with ceramic mold wash, mold powder, sand, resin sand, or graphite. The most widely used mold coating is water-based mold wash, which is consistently replacing the other coating materials. Sand and resin sand linings are quickly fading out, and graphite coating is mainly used for small nonferrous castings. The dominance of water-based mold wash is established on the fact that it offers significant advantages over the other types. Some of these advantages are:

- Water-based mold wash is insulating enough for almost all applications.
- It allows immediate metal pouring as soon as the coating application is finished, which greatly increases the casting productivity.
- It offers a better surface finish to the castings.
- Coating thickness can be easily used to control the microstructure.
- It greatly reduces the friction between the casting and the mold.
- It can be easily cleaned off the casting and mold.
- Its consumption is very small compared to sand linings.
- The mold has a long life under its protection.

The mold can be heated from the outside or inside diameter on the machine with the mold spinning slowly by a row, or rows, of gas burners or off the machine in an oven at 180 to 320 °C (355 to 610 °F). The mold temperature can be critical for the coating adhesion to the mold, coating strength, as well as casting surface quality. Once the mold is heated sufficiently, mold wash is applied on the mold inside diameter by spraying or flooding. The mold wash thickness is usually between 0.5 and 3 mm (0.02 and 0.12 in.), depending on the application. The spraying method is preferred for most processes because it gives more uniform coating thickness, smoother coating finish, and more consistent coating quality. Spraying can also reach the areas that flooding cannot. The spraying method works for both horizontal and vertical molds, but the flooding method works only for horizontal molds. Figure 3 shows a patented automatic spray lance system that offers automatic control of the forward and backward movement, moving velocity, and spray on and off operations of the spray lance. It can also adjust height and tilt angle to align the lance with all customer mold sizes.

Defects in Centrifugal Castings

The three most common defects observed in centrifugal castings are segregation banding, raining, and vibration defects.

Segregation banding occurs only in true centrifugal casting, generally where the casting wall thickness exceeds 50 to 75 mm (2 to 3 in.). It rarely occurs in thinner-wall castings. Banding can occur in both horizontal and vertical centrifugal castings. Banding is more prevalent in alloys with a wide solidification range and greater solidification shrinkage.

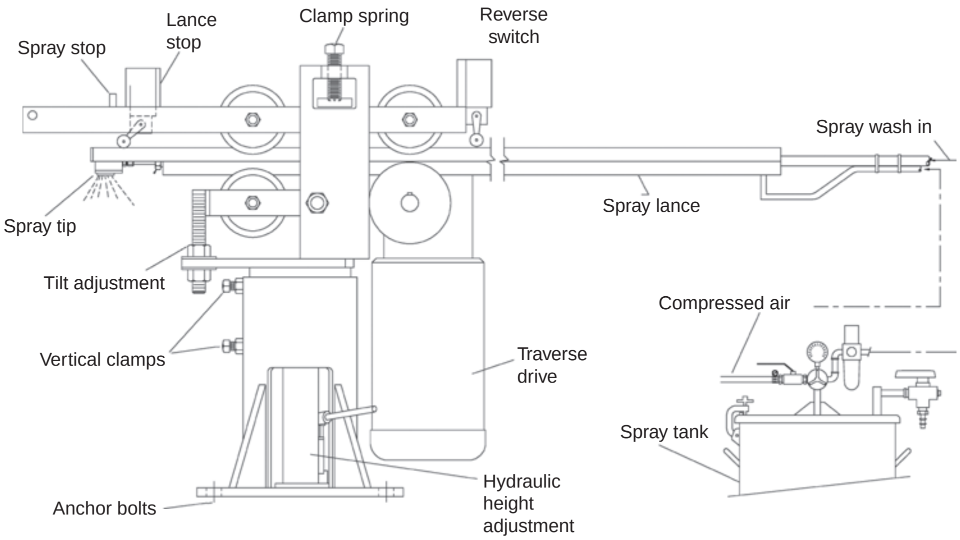

Fig. 3 Patented automatic mold wash spray assembly. Courtesy of the Centrifugal Casting Machine Company

Bands are annular segregated zones of low-melting constituents, such as eutectic phases and oxide or sulfide inclusions. They are characterized by a hard demarcation line at the outside edge of the band that usually merges into the base metal of the casting.

Most alloys are susceptible to banding, but the wider the solidification range and the greater the solidification shrinkage, the more pronounced the effects may be. Banding has been found when some critical level of rotational speed is attained, and it has been associated with very low speeds, which can produce sporadic surging of molten metal. Therefore, both mechanisms may be involved. Minor adjustments to casting operation variables, such as rotational speed, pouring rate, and metal and mold temperatures, will usually reduce or eliminate banding.

Raining is a phenomenon that occurs in horizontal centrifugal castings. If the mold is rotated at too low a speed or if the metal is poured into the mold too fast, the metal actually rains or falls from the top of the mold to the bottom. Proper process control can eliminate raining.

Vibration Defects. Vibration can cause a laminated casting. It can be held to a minimum by proper mounting, careful balancing of the molds, and frequent inspection of rollers, bearings, and other equipment.

Applications

Typical products produced by horizontal centrifugal casting machines include pipe and tubes of all different metals; alloyed iron, steel, and high-speed steel rolls for steel mills and the food-processing, papermaking, and printing industries; iron and steel cylinder liners, gray iron piston rings, gray iron brake drums, and alloy and superalloy seal rings and valve seats for the auto industry; heat-resistant steel cracking tubes for petroleum refinery and radiant heating tubes and furnace rolls for heat treatment furnaces; and copper alloys and Babbitt alloys for bimetal bearings and bushings. See the article "Horizontal Centrifugal Casting" in this Volume for more information.

Vertical machines are mainly used for shorter parts, such as bushings, gear blanks, rings, short rolls, wheels, aluminum and copper electric motor rotors, jewelries, and vacuum titanium alloy parts, and many different small round parts, such as balls, valve bodies, and rings for the machinery industry. With proper support, vertical casting machines can also produce extralong rolls. Slightly inclined machines are used for producing ductile iron pipe for water and gas mains, and other inclined machines are used for rolls and conical bushings. See the article "Vertical Centrifugal Casting" in this Volume for more information.

Centrifugal casting is also used to ensure good filling in investment casting, as described subsequently. Another related technique is spin casting, which uses rubber molds for casting of zinc, tin, and other alloys with low melting points. It is also used in conjunction with nonmetallic materials such as glass and plastics. A more advanced materials application is the combustion synthesis of functionally graded materials.

Investment Casting with Centrifugal Force (Ref 1). When the action of centrifugal force is combined with investment casting, the main benefit is an improvement in casting soundness with subsequent improvements in mechanical properties. The influence of centrifugal force in aluminum investment castings (Ref 2) found that:

- A down-tapered sprue was more effective in eliminating turbulence of the metal stream and nonmetallic incisions.
- Surface smoothness and dimensional accuracy of aluminum alloy centrifugal castings were much better than the gravity investment castings, but they were much more affected by the fineness of investment material than centrifugal force.
- The soundness and mechanical properties were improved with increased centrifugal force.

The liquidus-solidus interval is important in centrifugally cast investment mold castings, and final casting soundness depends on the gating system for castings of alloys with narrow and wide freezing ranges (Ref 3). Factors that influence soundness were identified to be (Ref 3):

- Ingate diameter
- Sprue diameter
- Metal pour temperature
- Mold temperature prior to pour
- Mold speed
- Spinning period
- Casting weight (expressed as a casting length, l)
- Number of castings in each ring on the sprue
- Distance (L) from the axis of rotation to the castings on the sprue (which characterizes the sprue length)
- Liquidus-solidus interval (freezing range)

For a wide freezing range (e.g., 100 K in bronze), the casting soundness was improved by increasing mold speed, ingate diameter, sprue diameter, and the product ($l \times L$) of specimen size and sprue length. Mold speed, n, was found to be the most significant variable.

For wide-interval alloys, optimal conditions (Ref 3) are "those under which each portion of molten metal newly arriving in the mold cavity should spread out at the appropriate level and freeze onto the solidification front without building up a substantial surplus of molten metal. Thus, the optimum conditions for pouring intricate castings in wide-interval alloys are those which produce layer-by-layer freezing."

"Casting soundness decreased as the number of castings at the same level on the sprue increased. Thus, as fewer castings are made, their density will increase. Increasing the number of ingates surrounding the sprue at the same level probably leads to the development of a hot spot, heat storage around the spot, and departure from conditions required for layer-wise solidification. It is therefore best to assemble the patterns in a helical array on the sprue for intricate castings in wide-interval alloys."

"Density comparisons between the centrifugal castings at the two extreme levels on the sprue have shown that the sprue length has no significant influence on density." For narrow-interval alloys, there is a sprue-length effect. Narrow-interval alloys require much greater ingate and sprue cross sections than wide-interval alloys, and narrow-interval alloy "castings should always be made on short sprues."

"Narrow-interval alloys require heat accumulation around the sprue and ingates. Sound castings can be made by accumulating surplus molten metal ahead of the solidification front. In this case, the optimum conditions correspond to wide-section ingates and sprues, mold preheating, the use of short sprues, and some reduction in the relative rate of molten metal supply to the mold cavities."

"Intricate castings in wide-interval alloys must be made under conditions which will prevent excessive heat accumulation around the gating system and mold cavities, and minimize the volume of molten metal ahead of the solidification front. Sound metal can be ensured by directional solidification. In this case, mold preheating, commensurate metal weights and sprue lengths, helical mold assemblies around the sprue, and normal ingate and sprue cross sections should lead to a certain'freezing' action, while rapid mold cavity filling with metal in this condition should lead to layerwise solidification" (Ref 3).

Centrifugal Casting with Combustion Synthesis. Combustion synthesis (CS) is an attractive technique for synthesizing a wide variety of advanced materials, including powders and near-net-shape products of ceramics, intermetallics, composites, and functionally graded materials. One type of CS is self-propagating high-temperature synthesis (SHS), as described in Ref 4. Combustion synthesis of highly exothermic reactions (typically reduction type) often results in completely molten products, which may be processed using common metallurgical methods.

Casting of CS products under inert gas pressure or centrifugal casting has been used to synthesize cermet ingots, corrosion- and wear-resistant coatings, and ceramic-lined pipes. Casting under gas pressure is similar to the conventional SHS production, while centrifugal casting allows for greater control of the distribution of phases by controlling the time of separation. For radial centrifuges (Fig. 4a), the sample is placed at a fixed radial position from the axis of rotation, and the applied centrifugal force is parallel to the direction of propagation. The influence of centrifugal acceleration characterizes the phase distribution in the final product (Fig. 5).

The second type of centrifugal casting apparatus, called an axial centrifuge (Fig. 4b), is used for production of ceramic, cermet, or ceramic-lined pipes. The axial centrifuge casting method was developed further for production of long pipes with multilayer ceramic inner coatings. In this process, a thermite mixture (e.g., $Fe_2O_3/2Al$) is placed inside a rotating pipe and ignited locally. A reduction-type combustion reaction propagates through the mixture, and the centrifugal force results in separate layers of metal and ceramic oxide, with the latter forming the innermost layer (Fig. 6). The process is carried out in air under normal pressure, and pipes with diameters up to 30 cm (12 in.) and 5.5 m (18 ft) long have been obtained.

Spin casting typically refers to a special type of centrifuge casting with rubber molds. In the early 1970s, heat-cured silicone rubber (General Electric Silcast) was introduced with a sufficiently higher temperature resistance for molds in casting plastics and metals with low melting points, such as zinc alloys, tin alloys, and aluminum. Heat-cured silicone rubber molds can withstand temperatures up to approximately 550 °C (1020 °F) at a rate of 50 to 60 cycles per hour for hundreds of cycles. However, spin casting of metals with rubber molds is generally limited to the low-melting-point alloys (below 400 °C, or 750 °F), due to the degradation of the silicone rubber. Mold life is on the order of 200 to 250 shots at 400 °C (750 °F).

During pouring, the mold is placed on a centrifuge wheel to achieve adequate metal filling into intricate areas of the mold. Depending on the size of the mold and the material being cast, spinning speeds range from 100 to 900 rpm. Metal products can range from less than 100 g to 1.2 kg (3.5 oz to 2.6 lb). Maximum product size depends on mold diameter and thickness. Mold diameters can range up to approximately 60 cm (24 in.), with thicknesses of 10 cm (4 in.) or more. In mold making, metal patterns are laid on uncured silicone rubber sheets, which are packed into a circular metal frame. The circular metal frame is placed into a hydraulic vulcanizer press and electrically heated for curing.

The curing temperature and duration depends on the type of rubber and the mold thickness. Pattern materials, such as pewter, can be used as long as they can withstand a temperature of

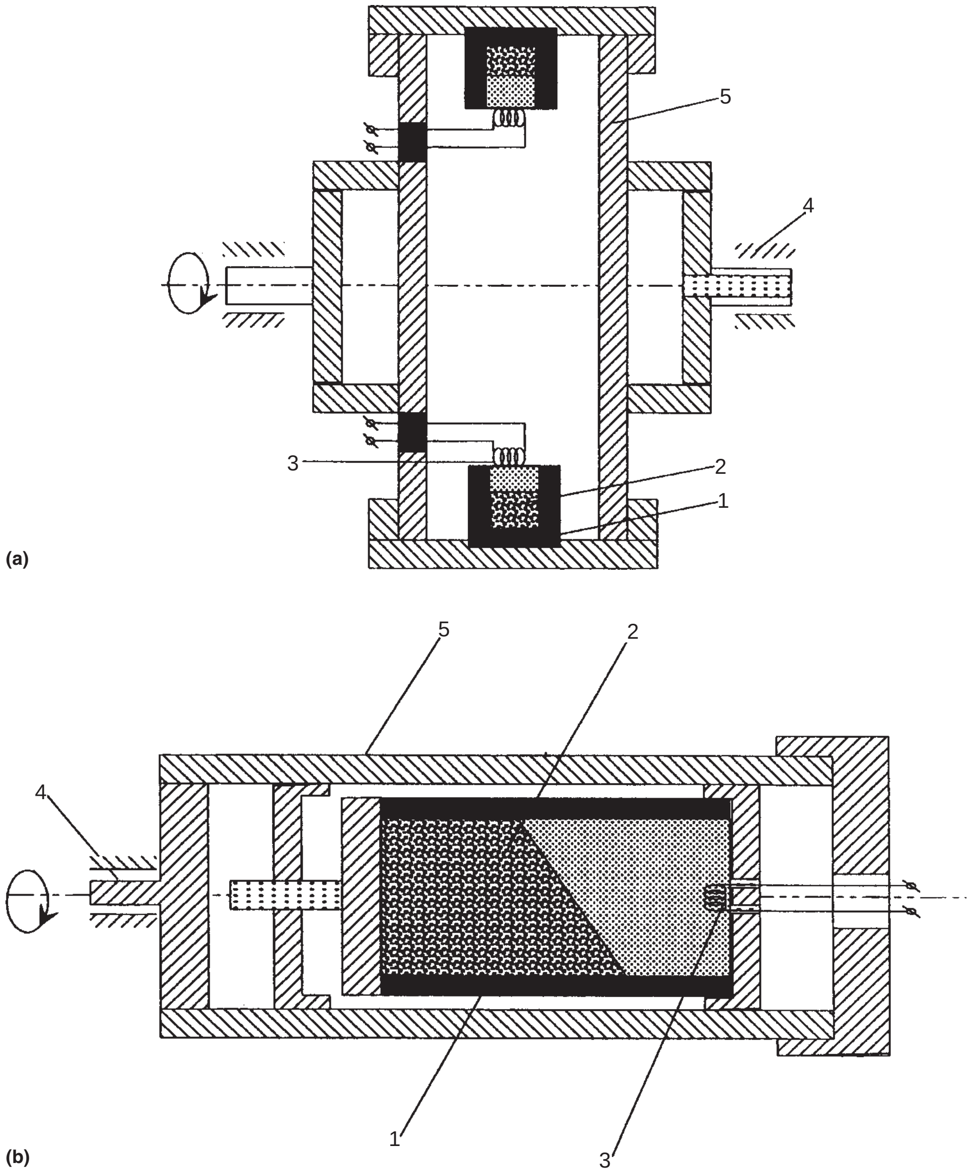

Fig. 4 Schematic of self-propagating high-temperature synthesis plus centrifugal casting. (a) Radial centrifuge. (b) Axial centrifuge. 1, sample container; 2, reactant mixture; 3, ignitor; 4, axle; 5, reactor

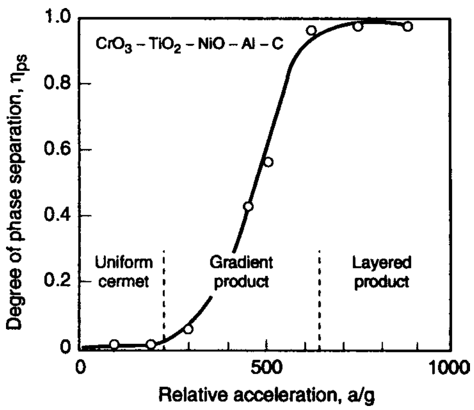

Fig. 5 Degree of phase separation as a function of centrifugal acceleration, *a*, where *g* is acceleration due to gravity. Source: Ref 5

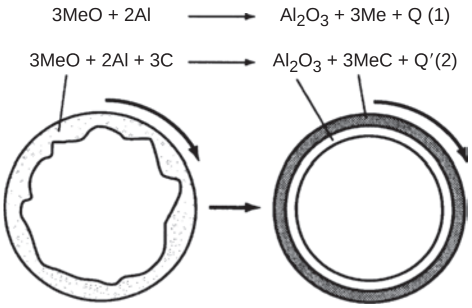

Fig. 6 Concept of centrifugal process for production of ceramic-lined steel pipes. Source: Ref 6

190 °C (375 °F) under several thousands of pounds pressure without distorting, melting, breaking, or outgassing. The heat melts the rubber, which is pressed against the surface of the pattern before the rubber sets. After vulcanization, the mold is separated from the metal, and the patterns are removed. Special-shaped tools are used to cut gates and runners on the rubber. Air vents are also cut for air to escape from the mold cavity. Modifications to gates and vents are usually required after a few shots to obtain the best results. Making of the mold takes approximately 1 to 3 days, depending on the complexity of the product shape.

While the mold is spinning, the liquid metal or plastic is melted in a suitable electric or gas-fired crucible furnace and then poured into the center sprue of the mold. After the metal solidifies (the plastic parts set up), the parts are quickly removed from the mold. With metal, 50 to 60 cycles per hour can readily be made; with plastic, 10 to 15 cycles are typical. Parts with undercuts can be demolded from the rubber mold with no difficulty. Thin-walled parts can be molded comparable to die casting. The rubber mold is not as precise as the metal mold, but the surface finish is generally good. However, blisters (very small pinpoint holes) were often found on the surface of the thick section due to the shrinkage of metals. The blisters are the defects for products with a plated glossy surface.

Metal Products. Spin casting has the capability to produce intricate designs for low- or high-volume quantities. Metal products include:

- Cams and levers in automotive control panels
- Bushings
- Hub, clamps, and screws
- Triggers, firing mechanisms, and cartridges
- Medals, pins, figurines, key chains, name plates, and costume jewelry
- Door hardware, locks, hooks, and rings
- Handles
- Belt buckles, buttons, and watch cases
- Gears, motor housings, and pump impellers

Plastic Products. Spin casting of thermoplastics and thermoset plastics includes:

- Plumbing fittings, valves, and couplings
- Electrical switch plates, condensers, and connector plugs
- Toy cars, wheels, and gears
- Pen holders, clips, and fasteners
- Electronic computer parts
- Calculator casing keys

Wax patterns for investment casting are also produced by spin casting.

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