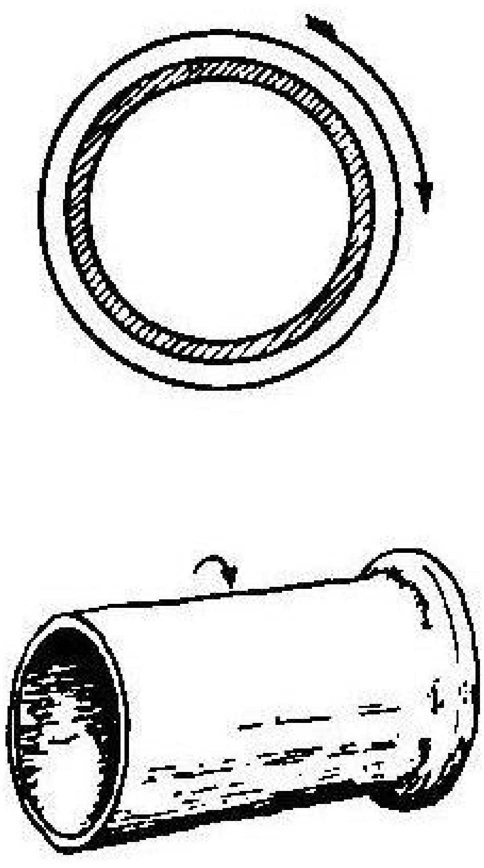
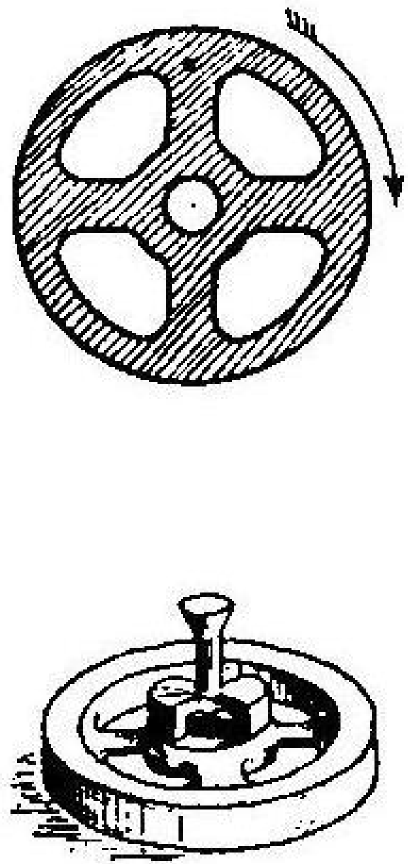
Centrifugal Casting

- The essential feature of centrifugal casting is the introduction of molten metal into a mold which is rotated during solidification of the casting. The centrifugal force is relied upon for shaping and feeding the molten metal with the utmost of detail as the liquid metal is thrown by the force of gravi-ty into the designed crevices and detail of the mold. (Fig. 70)
- The concept of centrifugal casting is by no means a modern process. This technique which lends clarity to detail was used by Benvenuto Cellini and others in the founding arts during the 16th century. The mention of actual centrifugal casting machines is first recorded when a British inventor, A.G. Eckhardt, was issued a patent in the year 1807. His method utilized the placing of the molds in an upright position on pivots or revolving bases (sometimes referred to today as a "vertical" centrifugal casting machine). In 1857 a U.S. patent described wheel molds which presumably were used for the centrifugal casting of railroad car wheels.

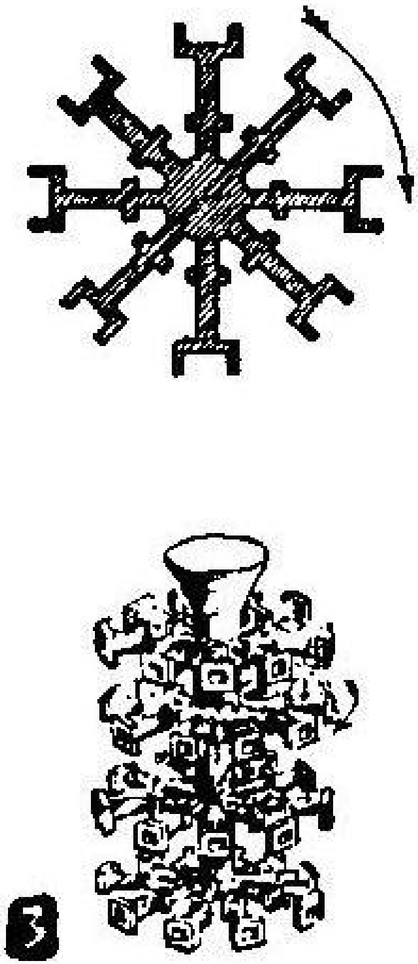
- The centrifugal casting of railroad car wheels was one of the first applica-tions involving controlled variations in chemical composition from the outside periphery of the car wheel as compared to the balance of the casting. As the casting was poured, a quantity of ferromanganese was introduced with the first metal to enter the mold. This formed a high manganese wear-resistant tread and car wheel flange, as compared to the softer second por-tion of the molten metal which became the center portion and the hub of the wheel. Although this practice is no longer used, similar applications do exist since, in principle, true solutions will not be separated in the centrifu-gal casting process.



1
True centrifugal



2
Semi-centrifugal



3
Centrifuged

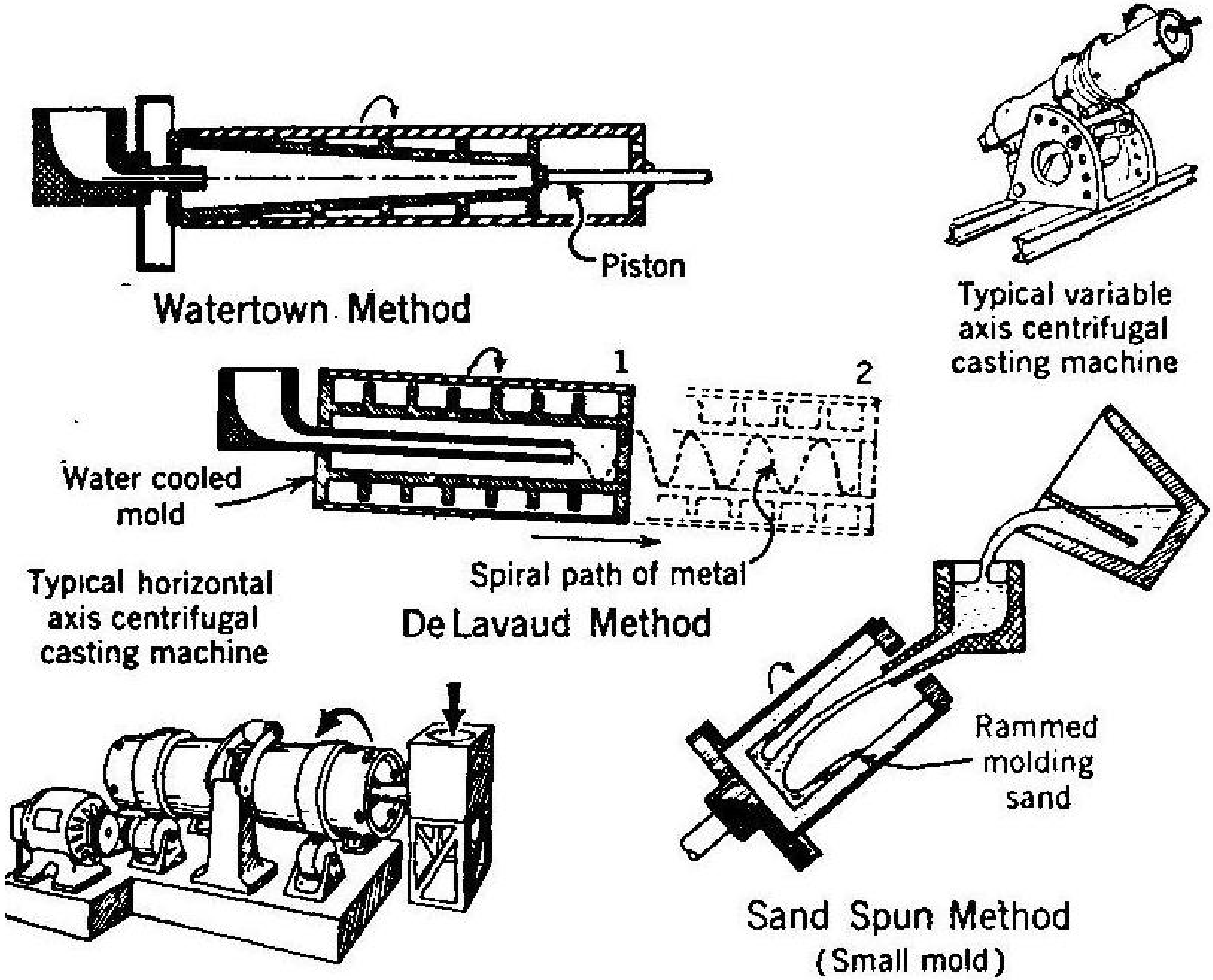


Fig. 70—Centrifugal casting methods.

- It is important to remember, however, that materials such as iron or copper that are immiscible in certain ranges are apt to segre-gate badly, such as lead in certain bronzes. Tubing with alloy modifications on the inside diameter which are designed to meet specific corrosion-resist-ant characteristics have been successfully produced using the centrifugal casting technique.

- Centrifugal casting remained a casting method for large objects until 1907 when Dr. Taggart, a dentist, introduced it to other dentists who experi-mented with the method hoping to perfect cast inlays for teeth that would replace malleting flake gold into prepared cavities. A Dr. Campbell in Mis-souri used a Hoosier cowbell as a casting flask. A wire loop such-as an extra long bucket bail was added to the bell, the clapper was removed, and the model and its sprues were embedded in the investment plaster.

- After the mold had been heated, the prepared molten metal was poured into the sprue and the bell swung first in pendulum style, then in a circular motion, to force the metal into all areas of the pattern chamber. This action re-sembled the old trick of swinging a bucketful of water over one's head in a circular motion. After 1920, the process began to be used for the manufac-turing of cast iron water pressure pipe, and use of the process has been ex-tended to a much wider range of shapes and alloys.

- In 1940, centrifugal casting methods were adopted for manufacturing jewelry and soon they became available to the nonprofessionai craftsman. Prior to its use in the jewelry trade, vacuum action was combined with the investing procedures of mold making to produce an air-free mold which was patented in 1935. Vacuum casting, combined with centrifugal casting was also attempted in 1935, and patents on this method were finally issued in 1940-42. However, successful vacuum-centrifugal casting was not ac-complished until 1948 by A.L. Englehardt. Continuous improvements in all the various machines, including large production models employing this centrifugal casting method, continued to make this form of casting ex-tremely popular and versatile for both the professional and the novice craftsman.

- In centrifugal casting, the mold may spin about a horizontal, inclined or vertical axis. The outside shape of the casting is determined by the shape of the mold. The inside contour is determined by the free surface of the liquid metal during solidification. The centrifugal force produced by rotation is large compared with normal hydrostatic forces and is utilized in two ways.
- The first of these is seen in pouring, where the force can be used to distrib-ute liquid metal over the outer surfaces of a mold. This provides a means of forming hollow cylinders and other annular shapes. The second is the development of high pressure in the casting during freezing. This, in con-junction with directional solidification, assists feeding and accelerates the separation of nonmetallrc inclusions and precipitated gases. The advan-tages of the process are therefore twofold: suitability for casting cylindrical forms and high metallurgical quality of the product,

- The effectiveness of centrifugal force in promoting a high standard of soundness and metallurgical quality depends above all on achieving a con-trolled pattern of solidification, this being governed by the process used and by the shape and dimensions of the casting. High feeding pressure is no substitute for directional freezing, which remains a primary aim of casting technique.

- Considering first the casting of a plain cylinder, conditions can be seen to be highly favorable to directional solidification owing to the marked radial temperature gradient extending from the mold wall. Under these con-ditions the central mass of liquid metal, under high pressure, has ready ac-cess to the zone of crystallization and fulfills the function of the feeder head used in static casting. The steepest gradients and the best conditions of all occur in the outermost zone of the casting, especially when a metal mold is employed.

- Another important factor is the length to diameter ratio of the casting, a high ratio minimizing heat losses from the bore through radiation and convection. Under these conditions, heat is dissipated almost entirely through the mold wall and freezing is virtually unidirectional until the cast-ing is completely solid; the wall of the casting is then sound throughout.

- The casting of a plain pipe or tube is accomplished by rotation of a mold about its own axis—the bore shape being produced by centrifugal force alone, and the wall thickness determined by the volume of metal intro-duced. This practice is widely referred to as "true centrifugal casting." (Fig. 71)

- In the case of a component of varying internal diameter or irregu-lar wall thickness, a central core may be used to form the internal contours, feeder heads then being introduced to compensate for solidification shrinkage.
- A further step away from the original concept is the spacing of separate shaped castings about a central downsprue which forms the axis of rotation. These variations are referred to respectively as "semicentrifugal casting and centrtfuging or pressure casting." (Fig. 72) In both cases, since the castings are shaped entirely by the mold and cores, centrifugal force is used primarily as a source of pressure for feeding.

Semicentrifugal Casting

- Such items as wheels and pulleys are occasionally cast in a semicentrifugal setup as illustrated in (Fig. 73). This type of mold need not be rotated as fast as in the case of a true centrifugal casting for only enough force is needed to cause the metal to first flow to the outer rim. As the wheel ro-tates around its hub core, the mold cavity is filled from rim-to-hub-not from bottom-to-top as is the case of common gravity pouring. This action promotes the direction of solidification from rim-to-hub and provides the required feeding by using only one central reservoir. Pouring and feeding on the center hub increases the yield-especially when casting high shrinkage alloys. Here, as in other centrifugal setups, the centrifugal force helps force lightweight nonmetalhc inclusions and trapped gas toward the center and into the feeder for elimination.

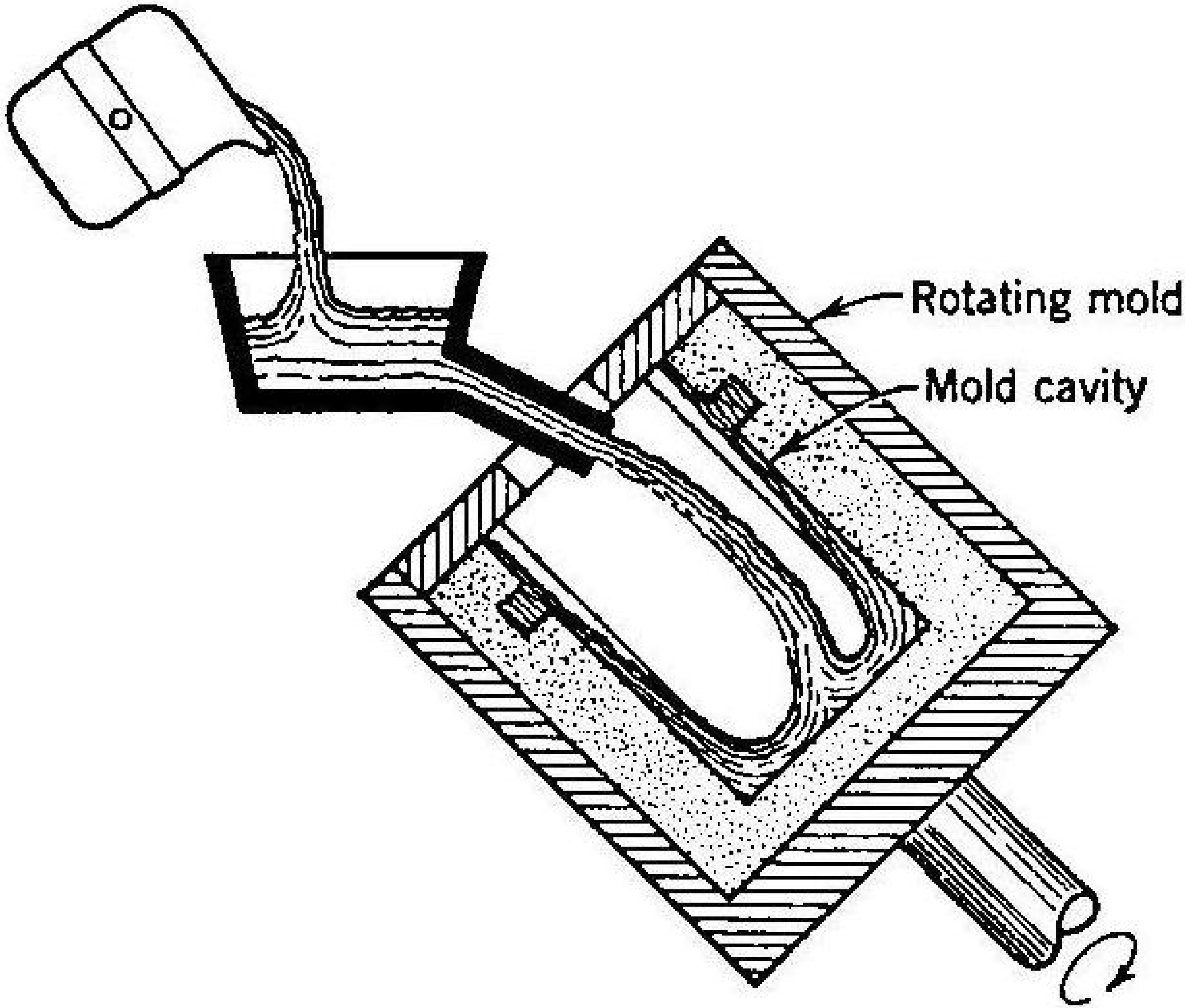


Fig. 71—True centrifugal casting process.

- In true or open bore casting, circumferential velocity is imparted from mold to metal by frictional forces at the mold surface and within the liquid. In horizontal axis casting, the metal entering the mold must rapidly acquire sufficient velocity to prevent instability and "raining" as it passes over the upper half of its circular path, because of slip, the generation of the neces-sary minimum force of 1G in the metal requires a much greater peripheral mold velocity than would be the case if metal and mold were moving to-gether. (Fig. 74)

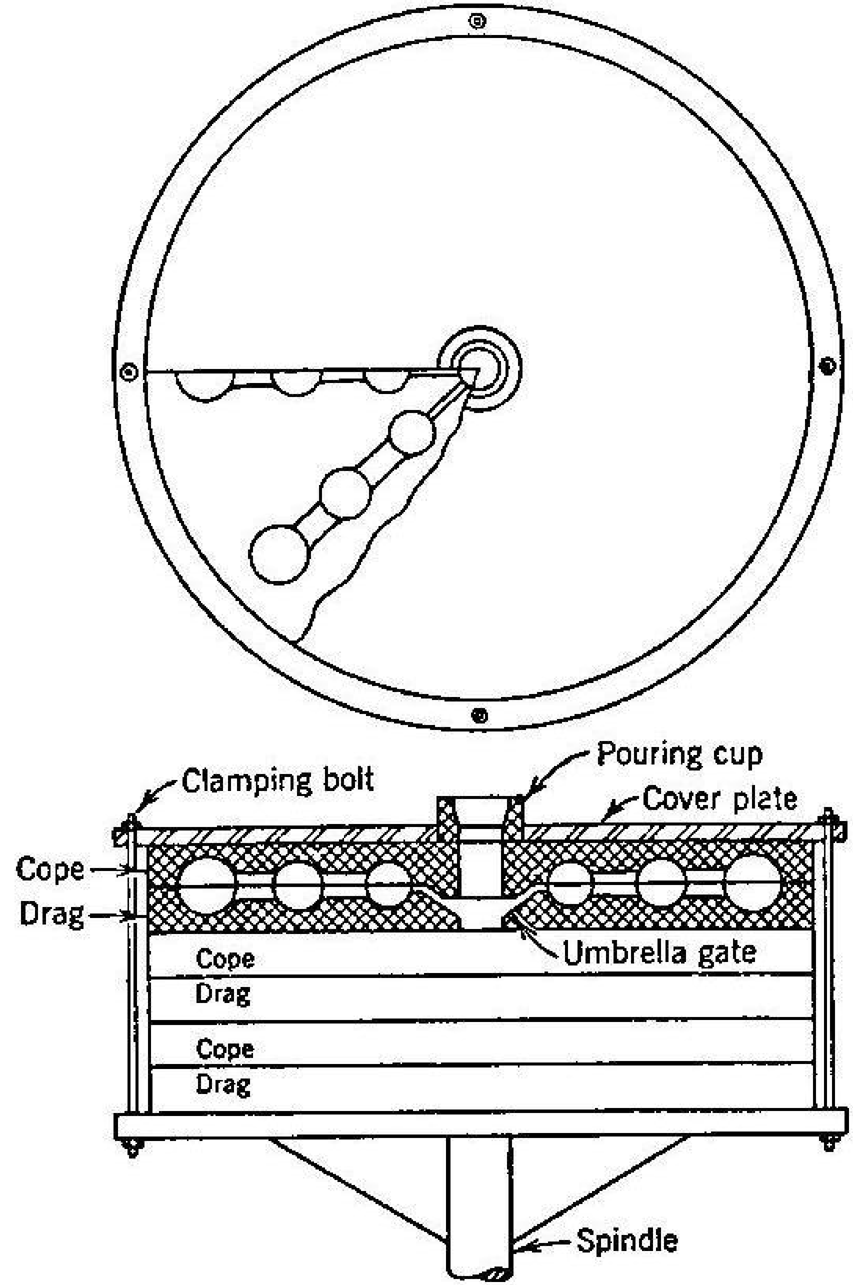


Fig. 72—Centrifuging process showing a dry sand stack of three molds

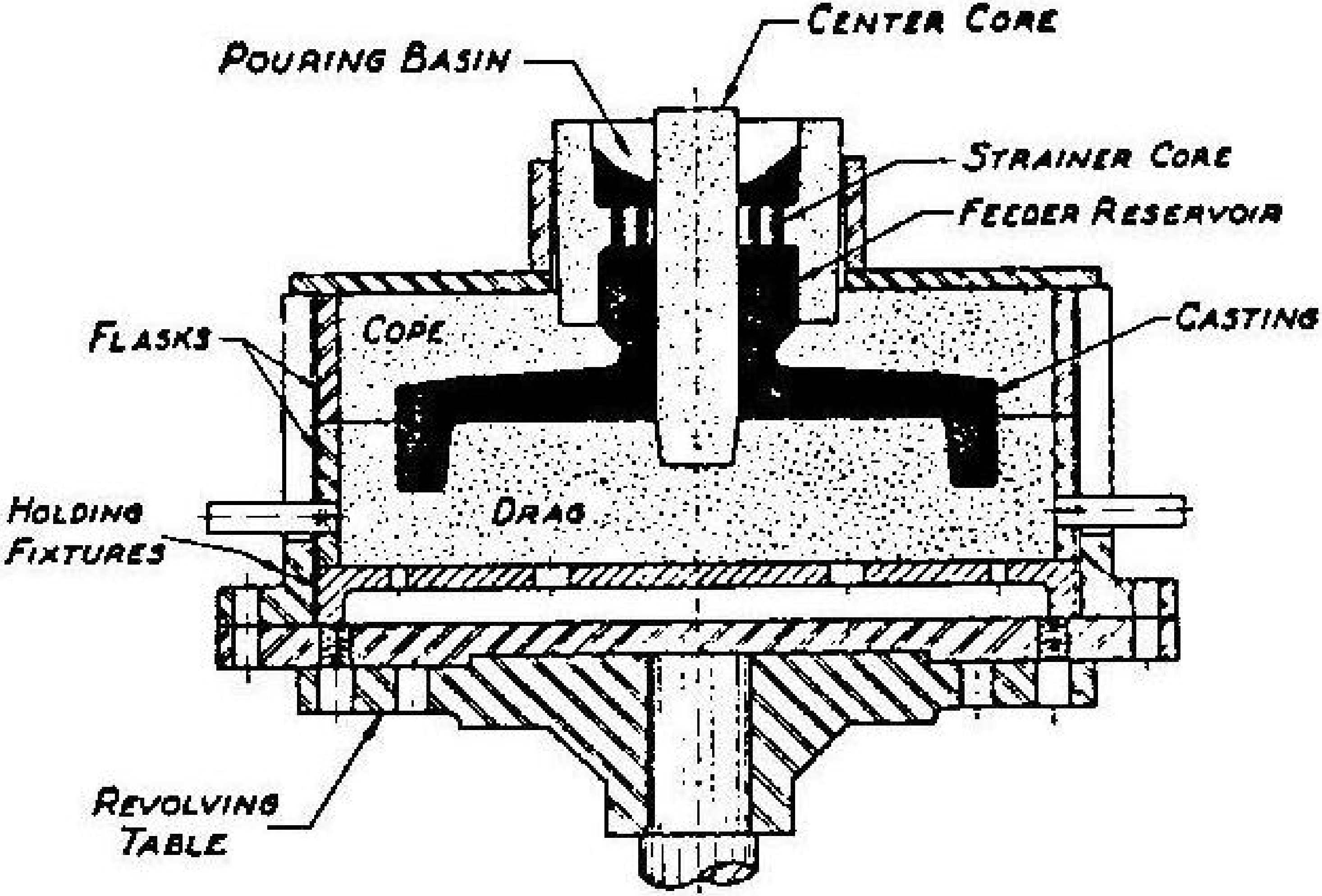


Fig. 73—Semicentrifugal casting process.

- Although centrifugal forces exceeding 200G are attained in some cases, most practice is empirically based within the range 10—150G, the highest values being used for open bore cylindrical components of small diameter and the lowest for semicentrifugal and pressure castings. Speeds generating forces of 60—80G are most commonly quoted for true centrifugal castings. As previously emphasized, however, the optimum value of centrifugal force diminishes with increasing diameter.
- Since the exactness of the science of centrifugal casting and the selection of mold speeds has been so well developed, it is suggested that the various manufacturers of centrifugal casting machines be consulted for copies of their charts and data.

- Each of the abovementioned centrifugal castings modes has certain inher-ent advantages and disadvantages. In many respects centrifugal casting might be termed a new and rapidly developing process. In the production of pressure pipe it is a highly developed process and has completely domi-nated this important industry. The use of this process for a wide variety of other end products has grown at a rapid rate.

- Except in iron, metal thicknesses vary from one-quarter of an inch and up. As metal sections increase, lengths and diameter may also be increased. The only limitation on the maximum size that can be cast is the economic demand for the product. Rough casting weights up to 100,000 lb have been poured.

- Pipe in nonstandard sizes can be produced in less time and at lower cost than the comparable wrought product. However, the process would not be competitive with off-the-shelf wrought material. In many instances the high integrity required in such applications as nuclear and aircraft parts lends itself to centrifugal production. Centrifugally produced castings offer better quality assurance than static castings and are more economical than the competitive forged part.

- Both ferrous and nonferrous materials are readily cast by the centrifugal process. Any air-melted material is readily castable by this method. Super-alloys that must be melted and poured in a vacuum are also cast centrifugally.

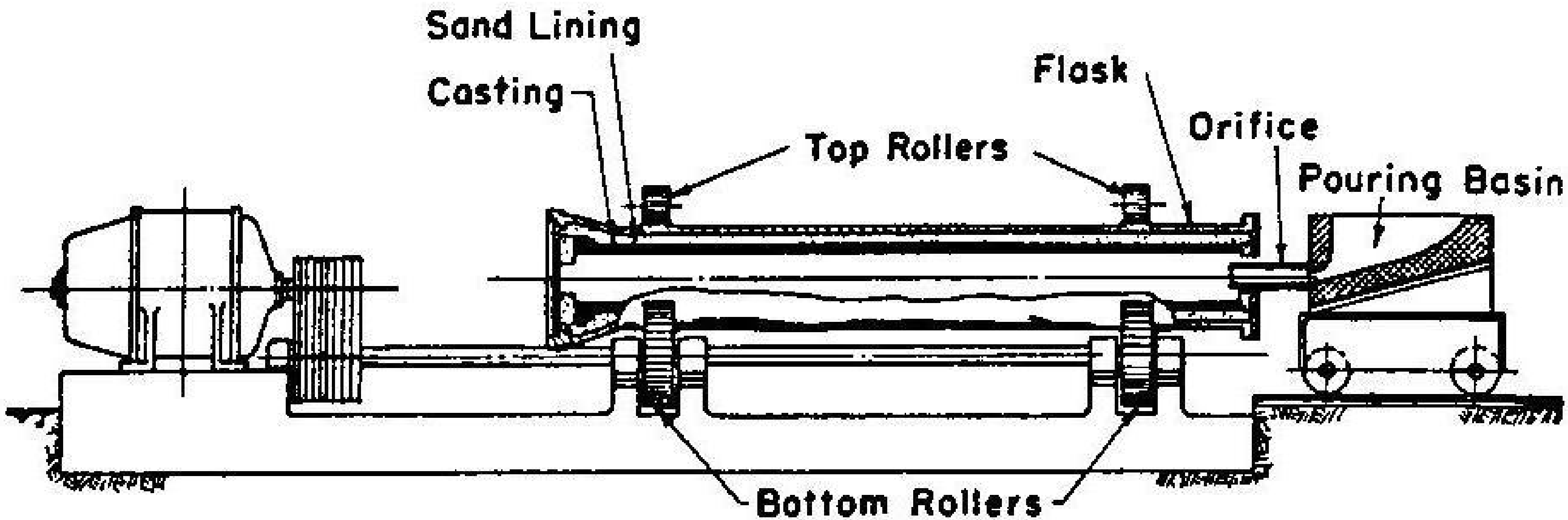


Fig. 74—Schematic representation of the true horizontal centrifugal casting machine.

- Both vertical and horizontal castings are used to produce high integrity ma-terial for further processing. In the production of thin-walled tubing it is customary to cast an ingot, forge, pierce and then draw the tubing; by start-ing with a centrifugal tube ingot casting, forging and piercing operations can be eliminated. Likewise, ring shapes are frequently more economically produced from centrifugal castings. These can be cast and/or processed di-rectly by ring rolling or other forging operations.
- To generalize, the type of product which lends itself to centrifugal produc-tion will have one or more of the following characteristics:

- It will be essentially cylindrical with a hole in the center.
- The shape and size of the part will not be readily available by other manufacturing methods.
- The cost of production by the centrifugal process will be less than by the competitive method.
- The quality and reliability of the part will be superior to that of the competitive product.
- The material will be difficult or impractical to form by other methods.

- The end products which fulfill these requirements and are thus produced commercially by centrifugal casting techniques are quite numerous but defy easy categorization. Perhaps the best separation may be made by con-sidering in one category those products which are generally tubular in shape and are therefore cast horizontally (or on a slight incline) as opposed to those products which are essentially ring shape in nature and therefore usually cast vertically.

- A special category includes those products which are not basically hollow but which are arranged treelike about a central sprue and cast centrifugally in order to facilitate feeding. This type is often referred to as centrifuge type casting as opposed to true centrifugal casting (where the approximate centerline of the hollow casting corresponds to the axis of rotation). The centrifuge type of casting is often used in the precision ceramic lost wax process and is commonly used in dental castings. Since these are special ap-plications, they will be discussed later.

Horizontal and Inclined

- There is an extremely wide diversity of tubular objects which are centrifu-gally cast horizontally. These range from the low production jobbing type of casting to the highly repetitive items. Mold materials vary from nearly bare steel to sand-lined molds and those lined with thick ceramics. Metals that can be cast include almost any conceivable alloy of iron and nearly ev-ery nonferrous metal. To gain an understanding of these diverse yet related processes, one must study some of the individual processes of the field in some detail so that the differences will become apparent.

Inclined-Retractive

- The casting process producing the largest tonnage of centrifugally cast product is the deLavaud system, widely employed in the gray and ductile iron pressure pipe industry. The method is named for Dmitri deLavaud, a Brazilian who developed the process in the 1920s. It is an inclined retrac-tive process in which a hollow steel mold is fitted inside a water cooling jacket and is mounted on tracks fastened to a heavy steel bed, inclined to a slope of perhaps 1/2 in. per foot. The water box and mold assembly are ar-ranged for movement back and forth on the sloped bed and fitted with suit-able pouring troughs and pipe pulling devices. (Fig. 75)

- In operation, the mold is moved down the slope where it is rapidly fitted with a sand core to form the required inside contour of the enlarged bell end of the pipe. Then the mold in its water box is moved up the slope and envelopes a cantilevered pouring trough so that as the mold comes to rest at its farthest point up the slope, the trough, with a curved spout at its end is in position to pour iron into the space between the bell core and the steel mold. As mold revolution begins iron is caused to flow down the trough from a special ladle designed to provide a consistent and controllable flow rate. As sufficient iron is poured into the bell cavity to form that bell the machine is caused to move down the slope at a controlled rate-usually by means of a large hydraulic cylinder. One can thus visualize a helix of molten iron being deposited on the face of the mold, held there by the cen-trifugal force.

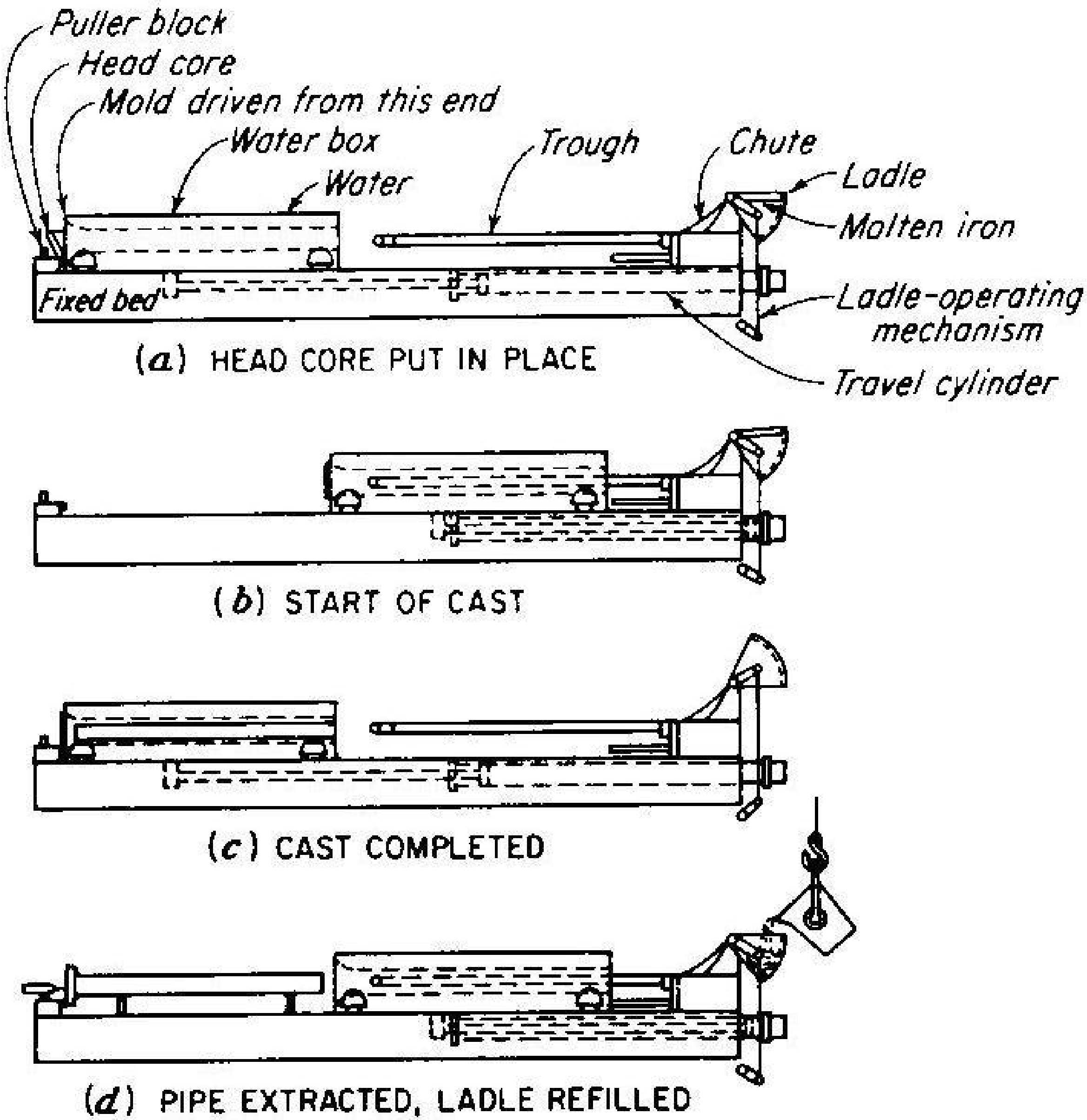


Fig. 75—Schematic diagram of DeLavaud pipecasting machine and casting operations.

- Although the solidification rate is quite high, it is delayed enough that the helix disappears as the casting becomes a homogeneous unit. After solidification the pipe can be easily extracted from the mold and the process repeated.

- By adjusting the speed of lateral movement of the mold and the rate of iron delivery, nearly any desired thickness of metal can be provided. Pressure pipes are produced by the deLavaud method in lengths from 18-20 ft and in nominal diameters from 2 to 54 in-. Casting rates from a single machine can be quite high, with 40-50 pipe per hour not being unusual for a 6 in. diame-ter pipe 18 ft long and 15-20 pipe per hour not uncommon in the 24-in. size.

- The mold material used almost universally in the deLavaud system of cen-trifugal casting is a forged, quenched and tempered SAE 4130 steel with the tubular shape trepanned from a solid forging. These molds are usually 1 to 1-1/2 in. in thickness and are provided with a relatively rough interior surface to provide pickup of the molten metal and avoid metal slippage in the mold. The mold is often sprayed with a refractory slurry when hot, to aid in providing tooth and to delay solidification slightly to improve the pipe surface and for metallurgical reasons. Additionally, a very fine ferro-silicon powder is sometimes applied to the mold surface to provide an inoc-ulating effect on the outer portions of the pipe.

- The service life of such a water cooled mold is important to the economic success of the process. As the hot iron strikes the inner surface its tempera-ture rises to about 1200F (648C). The expanding hot inner fibers of the mold are restricted by the outer layers in contact with water and are thus forced to upset inwardly. As the pipe is subsequently extracted these upset fibers cool, try to contract and set up tensile stresses which eventually re-sult in rupture of the inner surface. Peening is said to improve mold life and is often accomplished along the full length of the mold.

- It is quite common to repair the inner surface of a mold by welding, usually using a submerged arc method. A typical mold might be used to cast 2000-6-in. pipes before repairing becomes necessary but could finally produce a total of 6000 pipes utilizing a dozen separate repairs.

Horizontal-Nonretractive

- By far the greatest variety of horizontal centrifugal castings are made on molds rotated perfectly horizontally and without lateral movement. If the product is relatively long, the metal introduced at one end must travel the full length of the mold before it begins to solidify and thus the mold must be much more heavily insulated than in the case of the deLavaud process which depends upon rapid solidification.

- A wide variety of insulating materials is used. The most insulative and re-fractory of the mold (or flask) linings is the ceramic lining in which a true ceramic bond is developed to withstand the erosion and deterioration which can develop with very thick and/or very hot centrifugal castings.

- Such linings are not applicable to high production operations since solidifi-cation time is so protracted, but are often used for the production of very thick steel or alloy rolls or cylinders where special care must be taken to withstand the eroding effect of the molten metal. Single castings of this kind might well weigh many tons and a thinly coated mold would deterio-rate rapidly.
- Another process using a mold with a very insulative lining is known as the sand-spun process. Many thousands of tons of pressure pipe have been produced by horizontal centrifugal casting into molds heavily lined with molding sand. In this process the sand is rammed between a pattern and a cylindrical steel flask. After pattern removal, the sand is coated and dried, and after fitting with end cores is placed in a casting machine for suitable rotation and iron delivery. Pipe made by this method are commonly 16-20 ft long and made in a wide range of diameters.

- A similar method is used by some producers of soil pipe in which the sand is introduced into the mold, then compacted against the flask wall first simply by centrifugal force and finally by the action of a revolving mandrel moved laterally toward the flask wall. These castings are nominally much shorter than pressure pipe, limited no doubt by the deflection in a long mandrel.

- Still another, and newer, horizontal process in use for production of pres-sure pipe is the resin sand system in which a suitably sized and vented flask is heated to the proper temperature for an application of a relatively thin layer of resin coated sand. Upon curing at the proper temperature, this lay-er of "shell'[1] sand becomes the effective inside surface of the mold and pro-vides a somewhat slower solidification rate than the metal mold process, but faster than the ceramic or molding sand system.

- These lined flasks, fit-ted with end closures, are rotated in a horizontal mode with iron poured in from one end, often by means of a short movable trough to keep the metal from all-impinging on one spot in the mold. Because of the slower solidifi-cation of this process compared to the deLavaud system, the casting rate is somewhat slower and so this system is usually reserved for the larger di-ameters of pressure pipe.
- The widest variety of horizontal centrifugal casting is made on molds coat-ed with one or more layers of a refractory slurry, bonded with clay or or-ganic binders and dried prior to pouring. In the case of thin linings, drying is often accomplished by the residual heat left in the mold from the previous cast.

- In the case of thicker washes applied by multiple passes of the spraying equipment, the mold heat must often be supplemented. By con-trolling the thickness and character of this refractory, the operator can in-fluence the structure of the metal being cast, the surface smoothness of the casting and the cycle time for the operation. In many cases water sprays are applied to the exterior surface of the mold to speed solidification, prolong mold life and prepare the mold for another cast as quickiy as possible.
- One interesting variation of the usual horizontally cast tube is the produc-tion of dual metal tubes or cylinders. In this process, the metal desired on the outside surface is first poured and allowed to just solidify. At precisely the proper time, the core or backup metal is introduced, forming the inner layer. A special flux is sometimes interposed between the layers to aid in achieving the proper interfacial bond between the two metals.

Vertical Centrifugal Casting

- Vertical castings are produced by pouring a given weight of metal into a moid that rotates about a vertical axis. The metal is picked up and distrib-uted on the inside surface of the mold. Dross, slag and other nonmetallics are centrifuged to the inside. Unlike the horizontal casting, it is not possi-ble to obtain a uniform bore.

- Depending on the rotational speed of the mold, the inside will have varying amounts of taper. The inside surface will be that of the parabola of revolu-tion. The paraboloid "A" in Fig. 76 shows the shape of the cavity formed by a relatively high rotational speed and paraboloid "B" shows the approx-imate shape of the cavity that would be formed at a lower speed. This fact can be utilized advantageously in the production of certain conically-shaped parts.

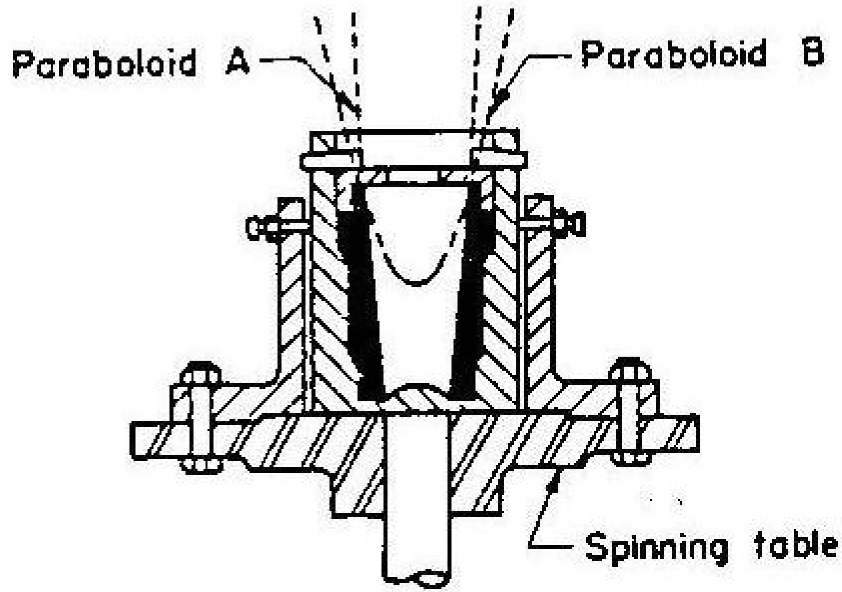


Fig. 76—Vertical centrifugal casting, showing the effect of rotational speed on the shape of the inner surface.

- The vertical-axis centrifugal casting method is not suited to the production of pipe-like shapes because of the inherent taper on the inside. Likewise, it is not suited to the production of very long parts. It finds its greatest appli-cation in the production of ring-like shapes. Because the inside contour can be controlled to some extent, the method is particularly useful in producing tapered sections. Also, because the rotational speeds can be lower than in the horizontal-axis machine, there is greater latitude in modifying the out-side shape.

- Vertical casting machines consist of a rotating table on which a mold is cen-tered and fastened. The machine must be constructed to withstand static and dynamic loads imposed on it. The dynamic loading is the most critical. Speed controls are infinitely variable and speed regulation should be good. For safety's sake the machines are often mounted below floor level. They are provided with adequate shields for protection in case of runout or ma-chine failure.

- Molds may be produced with any material capable of containing the metal during the casting process. In many instances this may be dictated by the metal being poured. Permanent molds made of cast iron, steel, graphite or other suitable materials are commonly used. In the case of steel or cast iron, these are fastened directly to the rotating table. In the case of graphite dies with sand cores, these require a die holder in which they are positioned.

- The type of metal being poured, casting design and the properties required often dictate the mold material for a given job. Also, as with static castings, the mold material may be varied in a manner to control the solidification rate at various sections in the casting. Sand cores for molding sand may be used. This facilitates the production of complex shapes on the outside of the casting. The disadvantage is that the mold may not be reused.

- It should be noted at this point that adequate care in the form of guards at the machine location must be considered, and properly engineered founda-tions be established upon which the horizontal centrifugal machines are mounted. When a large centrifugal mold (die) is achieving its full centrifu-gal speed, all mold components must be firmly in place and bolted assem-bly secured, because the slightest tendency toward eccentricity (a bolt shearing or an out-of-balance "whip") may cause much damage or even in-jury to personnel in the area should the mold or one of its components tear loose from its assembly or even from its foundation.

- In casting ferrous materials, the molds must be coated with a "wash" or re-fractory coating. On sand molds the wash acts to prevent metal penetra-tion. On metal molds it prevents burn-in or fusion of the metal to the mold and acts as an insulator to control the solidification rate. If graphite molds are used a wash is absolutely essential to prevent the graphite from being eroded and dissolving in the metal.

- In casting nonferrous materials, both metal molds and sand molds are coated with" wash to prevent sticking and penetration into the sand. If graphite molds are used a wash may or may not be required.

- On smaller castings where the mold temperature remains relatively low, and after successive castings are poured, a wash may not be required. On large castings and on those where the mold temperature becomes exces-sive, excessive oxidation and wear of the die surface may be encountered if wash is not used.

Some Specialized Centrifugal Applications

- Simple shapes may be cast centrifugally out of most metals. There are sev-eral highly specialized applications that are worthy of note.

- Dual metal castings are produced by pouring two different metals into the same mold in the following manner. The metal that is to form the outside is poured first. This is allowed to cool until the inside surface is at the correct temperature to form a metallurgical bond with the second metal. When this temperature is reached, the second metal forming the inside is then

- While it is usually desirable that the first metal poured have the higher melting point, this is not absolutely necessary. Typical applications involve rolls with stainless steel outside and cast iron centers. Such rolls find appli-cation in the printing and process industries where a stainless outside sur-face is required for its corrosion-resistant properties and the cast iron fur-nishes the needed mass on the inside at a much reduced material cost.

- Similarly, very abrasive-resistant material may be cast on either the outside or the inside of the part. Since most highly abrasive-resistant materials do not have good impact properties, it is desirable to back these up with mate-rials being of the desired toughness. A typical application involves dual-metal pipe cast with a carbon or low alloy steel on the outside and a hard (HC250) 27% Cr, 2.5% C material on the inside.

- Grinding rolls made with very hard materials such as HC200 have been cast with softer materials on the inside in order to facilitate the machining and mounting of the roll on the shaft. Similarly, it is possible to cast hard-sur-faced rolls for many applications. However, considerable knowhow is re-quired for each type and combination of materials. Unless the potential quantities are large it may not be economically practical to develop the knowhow for a specific new application.

- The practice of bonding molten metal to the inside of a revolving metal tube or band has been successfully developed for special applications. However, in order for a good metallurgical bond to occur it is necessary that the rotating tube be close to or above the melting point of the inside material. In addition, it is also necessary that the surfaces be free of oxide and, preferably, coated with a suitable flux. An example of this procedure is the centrifugal casting of iron into revolving steel bands in the production of the so-called "centrifused" type of automotive brake drums. Prior to spinning, the steel bands are cleaned, flux-coated and preheated to assure a good bond between the iron and steel during the spin-pour operation. Centrifused drums are unique in that they have a wear-resistant, anti-galling gray iron braking surface on the inside and a tough shock-resistant steel band on the outside.

- Another procedure used for bonding a metal to the inside of a tube is to first introduce the metal into the tube coid with a suitable flux. The ends are sealed and the tube is heated in a furnace until the metal on the inside is molten. The tube is then taken out and spun to centrifuge the desired metal lining. This process has wide application in the lining of cylinders with cor-rosion and abrasive-resistant materials.

- Vacuum-melted and vacuum-centrifugally cast materials frequently differ materially from the vacuum static-cast and air-melted static or centrifugal-ly-cast materials. The improvement in properties is usually significant and the cleanliness and uniformity of the vacuum centrifugal material is exceptional.

- A properly made vacuum-melted and vacuum-centrifugally cast material represents the ultimate in cleanliness that can presently be obtained in a cast product. Not only are the metal impurities reduced to a minimum by the vacuum-melting, but those that remain are effectively reduced by the centrifugal process. As pointed out above, these materials may have some unexpected properties.

- In some instances, metal alloys that were con-sidered unmachinable become machinable; some alloys that were unforge-able or difficult to forge are made readily forgeable. Many of the super-alloys made in this manner are finding new applications in the aircraft jet engine field.

- Modifications and adaptations of the principle of centrifugal casting also exist under the various headings of centrifuge casting, semicentrifugal cast-ing and pressure casting. Today, the technique of centrifugal casting is used a great deal in combination with the famous and age-old lost-wax (cire perdue) process. Centrifugal casting as it is now done is more aptly called centrifuge casting. True centrifugal casting is used primarily for articles with hollow cores.

- This method is identical to other lost-wax modeling and molding procedures except that the mold-is attached to a revolving shaft which rotates the entire mold on an angle. The molten metal enters the mold from a stationary crucible position above the rotating mold, and flows down into the pattern chamber where it is forced centrifugally against the inner walls until it solidifies to the thickness desired for the finished hollow casting. (Fig. 77)

- Another modification of these various centrifugal casting processes and one which makes possible a greater degree of refinement in articles cast by the lost-wax process is the pressure casting technique. In this procedure, the upper portion of the machine is placed over the mold that is to receive the molten metal. As this is being done, a sufficient amount of air pressure is applied to the mold to force out the gases and allow the metal to flow in-to even the most intricate details incorporated in the'pattern chamber. The use of pressure casting machines using this technique successfully produces very intricate castings in precious metals.

Centrifugal Casting Process Variables and Casting Quality

- Once the particular process has been established, the main variables con-trolling casting quality are *speed of rotation, pouring temperature, pouring speed* and *mold temperature.* Their individual significance can be briefly summarized:

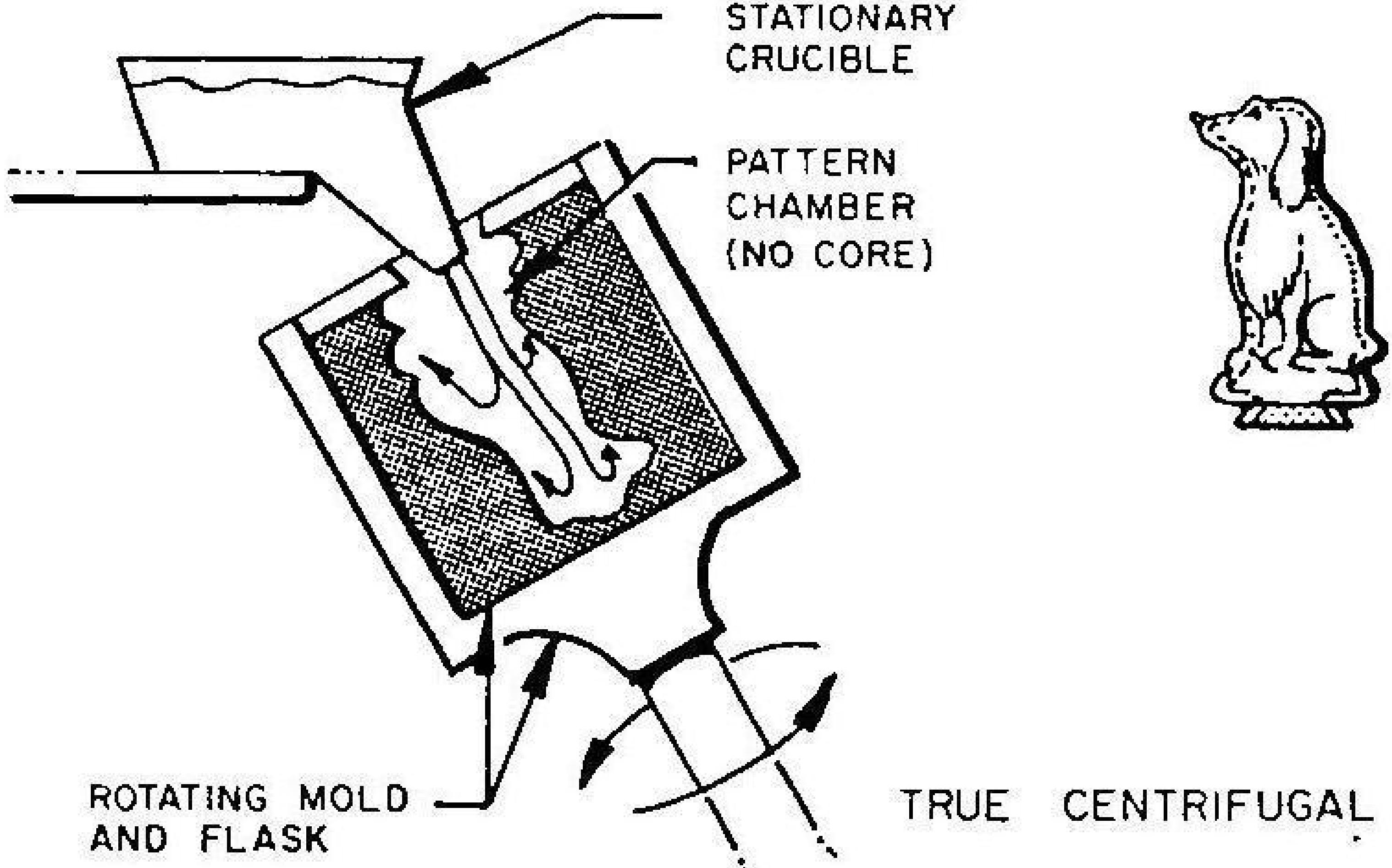


Fig. 77—Typical hollow core casting obtained from true centrifugal method.

- **Speed** of **Rolation-The** main factors influencing speed selection were dis-cussed in detail. However, the governing factor in true centrifugal casting is retention of the bore shape against gravity while still avoiding longitudi-nal tearing and stresses during the accelerated solidification of the molten metal against the mold face. Rotational speed also exerts a marked influ-ence upon metal structure, the most common effect of increased speed being to promote grain refinement although this can also be brought about from turbulence induced by instability of the liquid mass at very low speeds. A good judgment is to use the highest speed of rotation possible without encountering hot tearing.

- **Pouring Temperature-Pouring** temperature exerts a major influence on the mode of solidification. Low temperatures are associated with maxi-mum grain refinement and with equiaxed structures, while higher tempera-tures promote columnar growth in many alloys; however, practical consid-erations limit the available temperature range. The pouring temperature must be sufficiently high to ensure satisfactory metal flow and freedom from cold laps while still avoiding coarse structures and the increased risk of hot tearing due to excessive superheat.

- **Pouring** Speed-This is governed primarily by the characteristics of the par-ticular metal being poured and the need to finish the delivery of the molten metal before the metal becomes sluggish, although too high a rate of pour can cause excessive turbulence as well as "raining" and a potentially scrapped casting. In practice, slow pouring offers a number of advantages. Directional solidification and feeding are promoted while the slow devel-opment of full centrifugal pressure on the outer solidified skin of metal reduces the risk of hot tearing.

- **Mold Temperature-As** a general recommendation, molds for centrifugal casting should be maintained in the operating range of 500-550F (260-288C). Preheating of the mold to this approximate temperature range will also facilitate the application of the refractory mold coating. The principal significance of maintaining the mold (die) at a uniform operating tempera-ture will also serve to ensure uniformity of the cyclic pouring operation as well as casting quality.