UNIT – I

CASTING

Module-I

Casting processes: Classification, Metal mould casting processes, advanced casting processes, investment casting, Rheocasting, mould and core making materials and their characteristics. Technology of Selected casting Processes: Clay bonded, synthetic resin bonded, inorganic material bonded mould and core making, sand additives, mould coating, continuous casting process, centrifugal casting process.

1. Introduction to Casting processes

Metal casting process begins by creating a mold, which is the ‘reverse’ shape of the part we need. The mould is made from a refractory material, for example, sand. The metal is heated in an oven until it melts, and the molten metal is poured into the mould cavity. The liquid takes the shape of cavity, which is the shape of the part. It is cooled until it solidifies. Finally, the solidified metal part is removed from the mould.

A large number of metal components in designs we use every day are made by casting. The reasons for this include:

(a) Casting can produce very complex geometry parts with internal cavities and hollow sections

(b) It can be used to make small (few hundred grams) to very large size parts (thousands of kilograms)

(c) It is economical, with very little wastage: the extra metal in each casting is re-melted and re-used

(d) Cast metal is isotropic – it has the same physical/mechanical properties along any direction

Common examples: door handles, locks, the outer casing or housing for motors, pumps, etc., wheels of many cars. Casting is also heavily used in the toy industry to make parts, e.g. toy cars, planes, and so on. Typical metal cast parts are shown in Fig.1

Fig.1: Typical metal cast parts

Table 1 summarizes different types of castings, their advantages, disadvantages and examples.

Table 1

Process	Advantages	Disadvantages	Examples
Sand	Wide range of metals, sizes, shapes, low cost	poor finish, wide tolerance	engine blocks, cylinder heads
Shell mold	better accuracy, finish, higher production rate	limited part size	connecting rods, gear housings
Expendable pattern	Wide range of metals, sizes, shapes	patterns have low strength	cylinder heads, brake components
Plaster mold	complex shapes, good surface finish	non-ferrous metals, low production rate	prototypes of mechanical parts
Ceramic mold	complex shapes, high accuracy, good finish	small sizes	impellers, injection mold tooling
Investment	complex shapes, excellent finish	small parts, expensive	jewellery
Permanent mold	good finish, low porosity, high production rate	Costly mold, simpler shapes only	gears, gear housings
Die	Excellent dimensional accuracy, high production rate	costly dies, small parts, non-ferrous metals	precision gears, camera bodies, car wheels
Centrifugal	Large cylindrical parts, good quality	Expensive, limited shapes	pipes, boilers, flywheels

1.1 *Sand Casting***:** Sand casting uses natural or synthetic sand (lake sand) which is mostly refractory material called silica (SiO_2). The sand grains must be small enough so that it can be packed densely; however, the grains must be large enough to allow gasses formed during the metal pouring to escape through the pores. Larger sized molds use green sand (mixture of sand, clay and some water). Sand can be re-used, and excess metal poured is cut-off and re-used also.

Typical sand molds have the following parts (Fig 2):

• The mold is made of two parts, the top half is called the **cope**, and bottom part is the **drag**.

• The liquid flows into the gap between the two parts, called the mold **cavity**. The geometry of the cavity is created by the use of a wooden shape, called the **pattern**. The shape of the patterns is (almost) identical to the shape of the part we need to make.

• A funnel shaped cavity; the top of the funnel is the **pouring cup**; the pipe-shaped neck of the funnel is the **sprue**– the liquid metal is poured into the pouring cup, and flows down the sprue.

• The **runners** are the horizontal hollow channels that connect the bottom of the sprue to the mould cavity. The region where any runner joins with the cavity is called the **gate**.

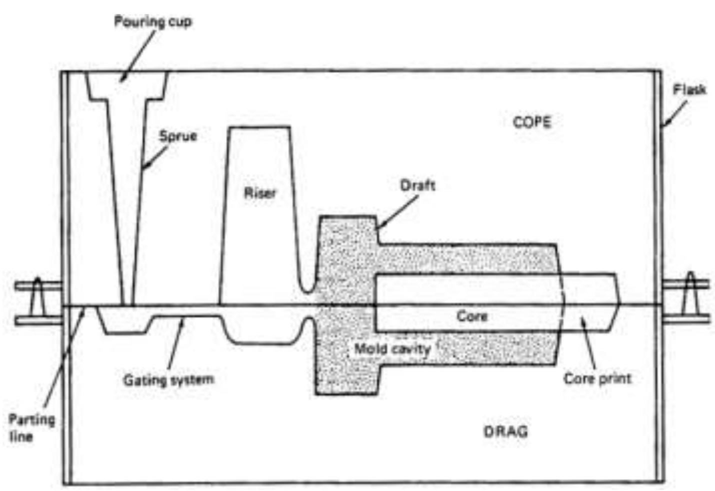


Fig 2: Schematic representation of a typical sand mould cross-section

Some extra cavities are made connecting to the top surface of the mold. Excess metal poured into the mould flows into these cavities, called **risers**. They act as reservoirs; as the metal solidifies inside the cavity, it shrinks, and the extra metal from the risers flows back down to avoid holes in the cast part.

- **Vents** are narrow holes connecting the cavity to the atmosphere to allow gasses and the air in the cavity to escape.
- **Cores**: Many cast parts have interior holes (hollow parts), or other cavities in their shape that are not directly accessible from either piece of the mold. Such interior surfaces are generated by inserts called **cores**. Cores are made by baking sand with some binder so that they can retain their shape when handled. The mold is assembled by placing the core into the cavity of the drag, and then placing the cope on top, and locking the mold. After the casting is done, the sand is shaken off, and the core is pulled away and usually broken off.

Gating System: Channel through which molten metal flows into cavity from outside of mold consists of a downsprue, through which metal enters a runner leading to the main cavity. At top of down-sprue, a pouring cup is often used to minimize splash and turbulence as the metal flows into down-sprue.

1.2 *Shell-mold Casting:*

In this process the moulds and cores are prepared by mixing the dry free flowing sand with thermosetting resins and then heating the aggregate (mixture of fine sand (100-150 mesh) and thermosetting resins) against a heated metal plate. Due to the heat, the resin cures, which causes the sand grains to get bonded with each other and it forms a hard shell around the metallic pattern. The inside portion of the shell is the exact replica of the pattern against which the sand aggregate is placed before heating. The shape and dimension of the inside portion of the shell thus formed is exactly the same as that of the pattern. If the pattern is of two pieces then the other half of the shell is also prepared the same way. Two halves of the shells prepared are placed together after inserting the core, if any, to make the assembly of the mould. The assembly of the shell is then placed in a molding flask and backing material is placed all around the shell mould assembly to give its assembly the sufficient strength. Now the shell mould is fully ready for pouring the liquid metal.

Sand

The dry free flowing sand used in the shell mould must be completely free of clay content. The grain size of the sand used in shell molding is generally in the range of 100150 meshes, as the shell casting process is recommended for castings that require good surface finish. However, depending on the requirement of surface finish of the final casting, the grain size of the sand can be ascertained. Also, if the grain size is very fine, it requires large amount of resins, making it expensive.

Resin and Catalyst

The resins most widely used, are the phenol formaldehyde resins, which are thermosetting in nature. Combined with sand, they give very high strength and resistance to heat. The resin initially has excess phenol and acts like a thermoplastic material. In order to develop the thermosetting properties of the resin, the coating of the sand is done with resin and a catalyst (Hexa-methylene-tetramine, known as Hexa). The measure of resin is 4-6% of sand by weight, the catalysts 14-16% of sand by weight. The curing temperature of the resin along with the catalysts is around 150o C and the time required for complete curing is 50 – 65 seconds. The sand composition to be used in making various casting of different materials can be seen from the relevant standards.

The resins available are of water-bourn, flake, or the granular types. The specifications of liquid, flakes or powder resins can be obtained from IS 8246-1976, IS 11266-1985, and IS 10979-1981 respectively.

Shell-mold casting yields better surface quality and tolerances. The process is described as follows:

- The 2-piece pattern is made of metal (e.g. aluminum or steel), it is heated to between 175°C-370°C, and coated with a lubricant, e.g. silicone spray.
- Each heated half-pattern is covered with a mixture of sand and a thermoset resin/epoxy binder. The binder glues a layer of sand to the pattern, forming a shell. The process may be repeated to get a thicker shell (Fig 3).
- The assembly is baked to cure it. 6

- The patterns are removed, and the two half-shells joined together to form the mold; metal is poured into the mold.
- When the metal solidifies, the shell is broken to get the part.

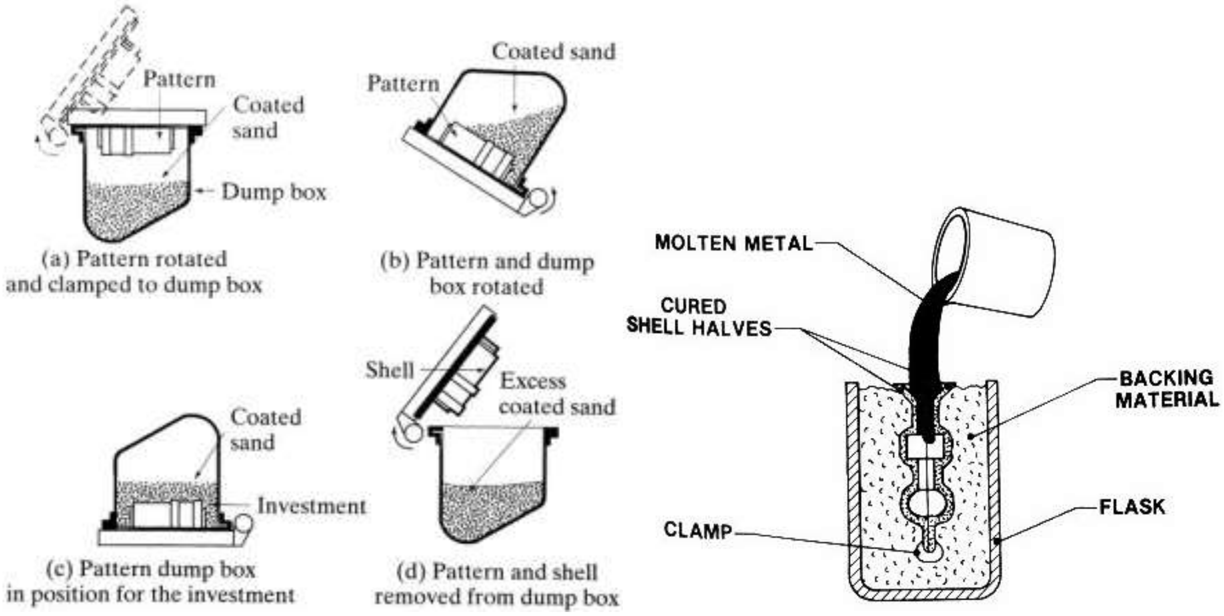


Fig 3: Making the shell-mold and Shell mold casting

1.3 *Expendable-pattern casting (lost foam process)*

The pattern used in this process is made from polystyrene (this is the light, white packaging material which is used to pack electronics inside the boxes). Polystyrene foam is 95% air bubbles, and the material itself evaporates when the liquid metal is poured on it.

The pattern itself is made by molding – the polystyrene beads and pentane are put inside an aluminum mold, and heated; it expands to fill the mold, and takes the shape of the cavity. The pattern is removed, and used for the casting process, as follows:

- The pattern is dipped in slurry of water and clay (or other refractory grains); it is dried to get a hard shell around the pattern.
- The shell-covered pattern is placed in a container with sand for support, and liquid metal is poured from a hole on top.
- The foam evaporates as the metal fills the shell; upon cooling and solidification, the part is removed by breaking the shell. 7

The process is useful since it is very cheap, and yields good surface finish and complex geometry. There are no runners, risers, gating or parting lines – thus the design process is simplified. The process is used to manufacture crank-shafts for engines, aluminum engine blocks, manifolds etc.

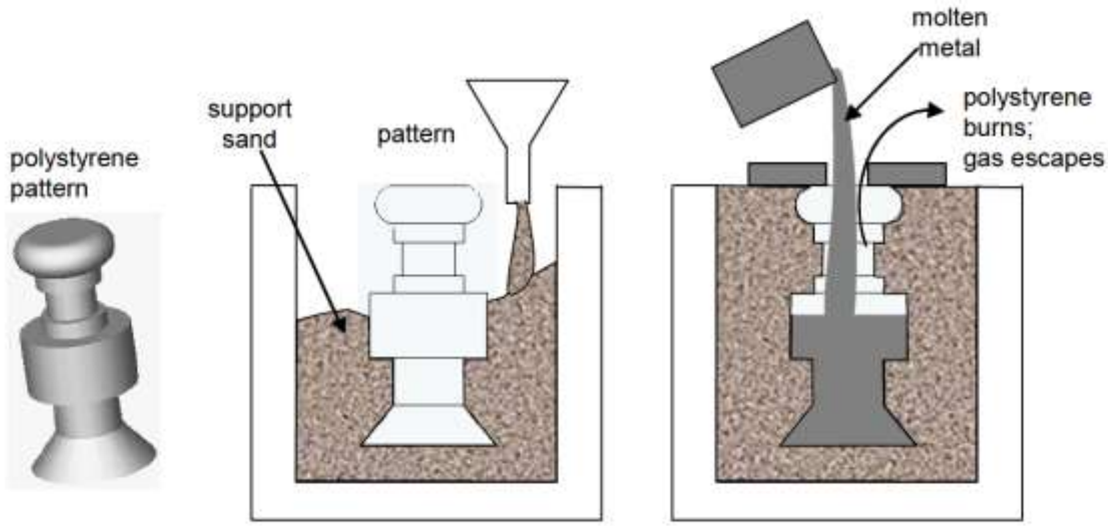


Fig 4: Expendable mold casting

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 is 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.

1.4 *Full Mold Process / Lost Foam Process / Evaporative Pattern Casting Process*

The use of foam patterns for metal casting was patented by H.F. Shroyer on April 15, 1958. In Shroyer's patent, a pattern was machined from a block of expanded polystyrene (EPS) and supported by bonded sand during pouring. This process is known as the full mold process. With the full mold process, the pattern is usually machined from an EPS block and is used to make primarily large, one-of-a kind castings. The full mold process was originally known as the lost foam process. However, current patents have required that the generic term for the process be full mold.

In 1964, M.C. Flemmings used unbounded sand with the process. This is known today as lost foam casting (LFC). With LFC, the foam pattern is molded from polystyrene beads. LFC is differentiated from full mold by the use of unbounded sand (LFC) as opposed to bonded sand (full mold process).

Foam casting techniques have been referred to by a variety of generic and proprietary names. Among these are lost foam, evaporative pattern casting, and cavity less casting, evaporative foam casting, and full mold casting.

In this method, the pattern, complete with gates and risers, is prepared from expanded polystyrene. This pattern is embedded in a no bake type of sand. While the pattern is inside the mold, molten metal is poured through the sprue. The heat of the metal is sufficient to gasify the pattern and progressive displacement of pattern material by the molten metal takes place.

The EPC process is an economical method for producing complex, close-tolerance castings using an expandable polystyrene pattern and unbonded sand. Expandable polystyrene is a thermoplastic material that can be molded into a variety of complex, rigid shapes. The EPC process involves attaching expandable polystyrene patterns to an expandable polystyrene gating system and applying a refractory coating to the entire assembly. After the coating has dried, the foam pattern assembly is positioned on loose dry sand in a vented flask. Additional sand is then added while the flask is vibrated until the pattern assembly is completely embedded in sand. Molten metal is poured into the sprue, vaporizing the foam polystyrene, perfectly reproducing the pattern.

1.5 *Plaster-mold casting*

The mold is made by mixing plaster of paris ($CaSO_4$) with talc and silica flour; this is a fine white powder, which, when mixed with water gets a clay-like consistency and can be shaped around the pattern (it is the same material used to make casts for people if they fracture a bone). The plaster cast can be finished to yield very good surface finish and dimensional accuracy. However, it is relatively soft and not strong enough at temperature above 1200°C, so this method is mainly used to make castings from non-ferrous metals, e.g. zinc, copper, aluminum, and magnesium.

Since plaster has lower thermal conductivity, the casting cools slowly, and therefore has more uniform grain structure (i.e. less warpage, less residual stresses).

1.6 *Ceramic mold casting*

Similar to plaster-mold casting, except that ceramic material is used (e.g. silica or powdered Zircon $ZrSiO_4$). Ceramics are refractory (e.g. the clay hotpot used in Chinese restaurants to cook some dishes), and also have higher strength that plaster.

- The ceramic slurry forms a shell over the pattern;
- It is dried in a low temperature oven, and the pattern is removed 8
- Then it is backed by clay for strength, and baked in a high temperature oven to burn off any volatile substances.
- The metal is cast same as in plaster casting.

This process can be used to make very good quality castings of steel or even stainless steel; it is used for parts such as impellor blades (for turbines, pumps, or rotors for motor-boats).

1.7 *Investment casting (lost wax process)*

The investment casting process, which is commonly referred to as the “lost wax method”, originated in and around the fourth millennium B.C. It is evidenced through the architectural works found in the form of idols, pectorals and jewelry in remains of the ancient Egypt and Mesopotamia. The investment casting process initiates with the production of wax replicas or patterns of the required shape of castings. Each and every casting requires a pattern to be produced. Wax or polystyrene is made used as the injecting material. The assembly of large number of patterns are made and attached to a wax sprue centrally. Metallic dies are used to prepare the patterns. The pattern is immersed in refractory slurry which completely surrounds it and gets set at room temperature forming the mold. The mold is further heated, so that the pattern melts and flows out, leaving the required cavity behind. After heating, the mold gets further hardened and molten metal is poured while it is still hot. After the casting gets solidified, the mold is broken and it is taken out.

The basic steps of the investment casting process are as shown in Fig 5:

1. Preparing the heat-disposable wax, plastic or polystyrene patterns in a die. 2. Assembly of the prepared patterns onto a gating system 3. “Investing,” (covering) the pattern assembly with a refractory slurry which builds the shell.

4. Melting the pattern assembly (burning out the wax) by firing, for removing the traces of the pattern material 5. The metal in molten state is poured into the formed mold. 6. Once the metal solidifies, the shell is removed (knocked out). 7. Fettling (cutting off) of the pouring basin and gates followed by finishing operations to get the desired dimensional tolerances and finish.

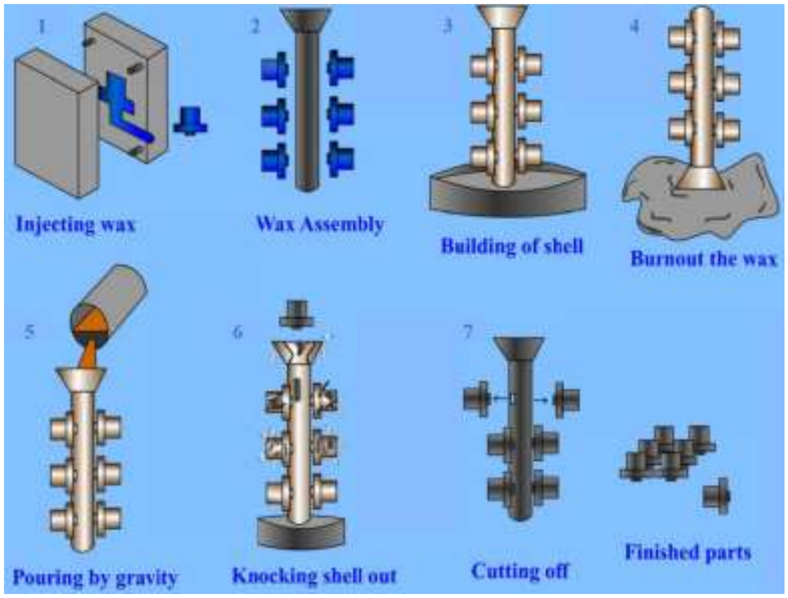


Fig 5: The Basic Steps of the Investment Casting Process

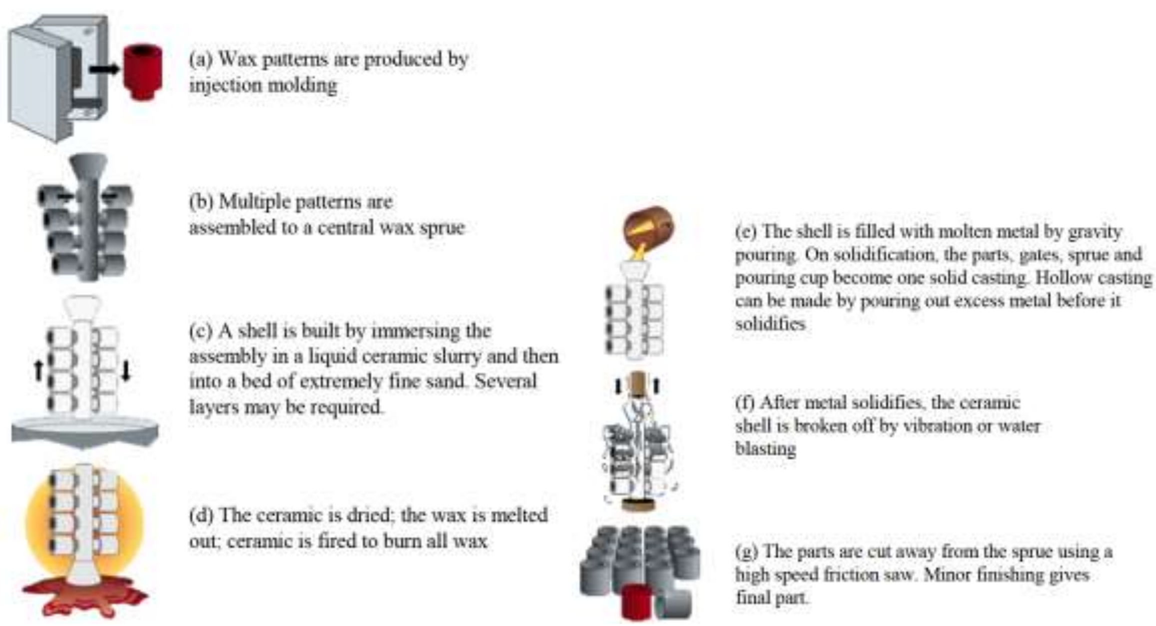


Fig 5a: Steps in the investment casting process

This is an old process, and has been used since ancient times to make jewellery – therefore it is of great importance to HK. It is also used to make other small (few grams, though it can be used for parts up to a few kilograms). The steps of this process are shown in the Fig 5a.

An advantage of this process is that the wax can carry very fine details – so the process not only gives good dimensional tolerances, but also excellent surface finish; in fact, almost any surface texture as well as logos etc. can be reproduced with very high level of detail.

1.8 *Vacuum casting*

This process is also called counter-gravity casting. It is basically the same process as investment casting, except for the step of filling the mold. In this case, the material is sucked upwards into the mould by a vacuum pump. The figure 6below shows the basic idea – notice how the mold appears in an inverted position from the usual casting process, and is lowered into the flask with the molten metal (Fig 6).

One advantage of vacuum casting is that by releasing the pressure a short time after the mold is filled, we can release the un-solidified metal back into the flask. This allows us to create hollow castings. Since most of the heat is conducted away from the surface between the mold and the metal, therefore the portion of the metal closest to the mold surface always solidifies first; the solid front travels inwards into the cavity. Thus, if the liquid is drained a very short time after the filling, then we get a very thin walled hollow object, etc. (Fig 7).

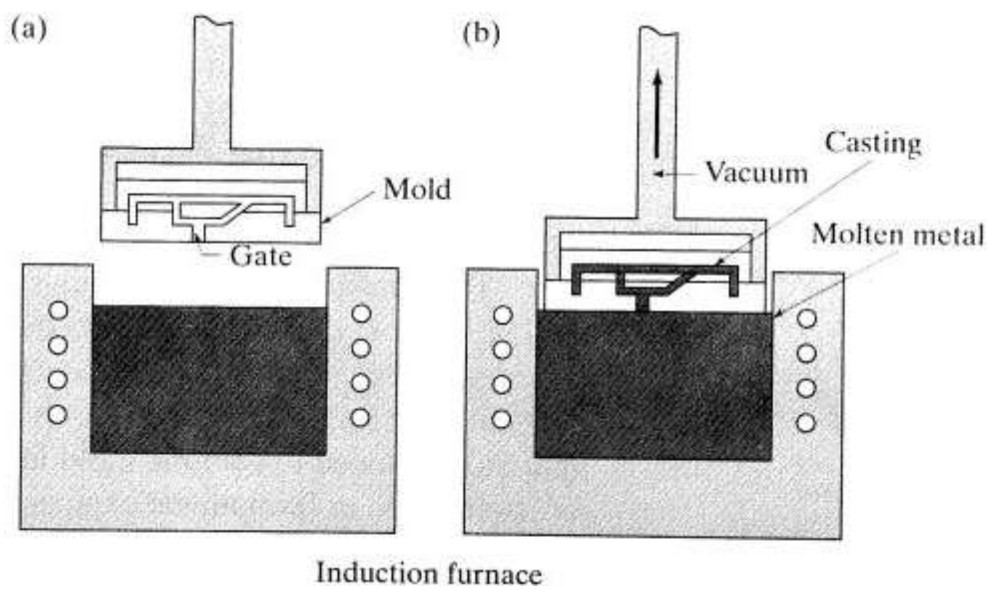


Fig 6: Vacuum casting

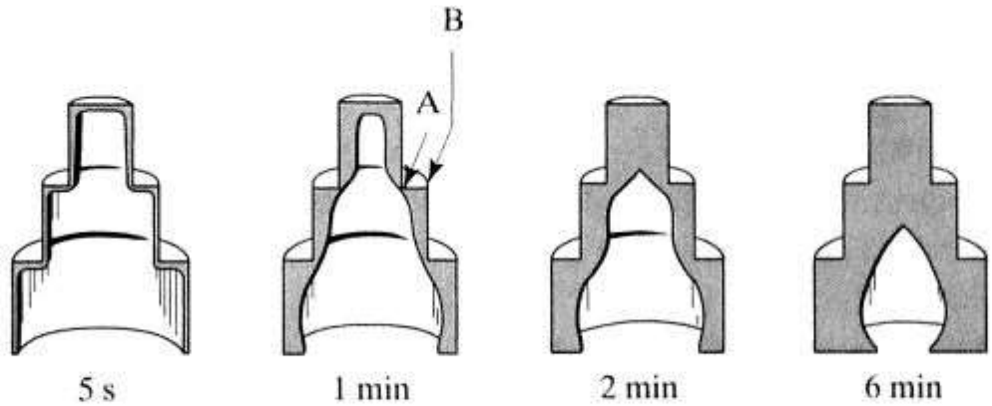


Fig 7: Draining out metal before solidification yields hollow castings

1.9 *Permanent mold casting*

Here, the two halves of the mold are made of metal, usually cast iron, steel, or refractory alloys. The cavity, including the runners and gating system are machined into the mold halves. For hollow parts, either permanent cores (made of metal) or sand-bonded ones may be used, depending on whether the core can be extracted from the part without damage after casting. The surface of the mold is coated with clay or other hard refractory material – this improves the life of the mold. Before molding, the surface is covered with a spray of graphite or silica, which acts as a lubricant. This has two purposes – it improves the flow of the liquid metal, and it allows the cast part to be withdrawn from the mold more easily. The process can be automated, and therefore yields high throughput rates. Also, it produces very good tolerance and surface finish. It is commonly used for producing pistons used in car engines, gear blanks, cylinder heads, and other parts made of low melting point metals, e.g. copper, bronze, aluminum, magnesium, etc.

In the **pressure casting process** the molten material is forced upward by gas pressure into a graphite mould or metallic mould Fig 8. The pressure is maintained until the melt has completely solidified in the mould. The molten material may also be forced upward by a vacuum, which also removes dissolved gases ahead of the rising melt and produces a casting with lower porosity.

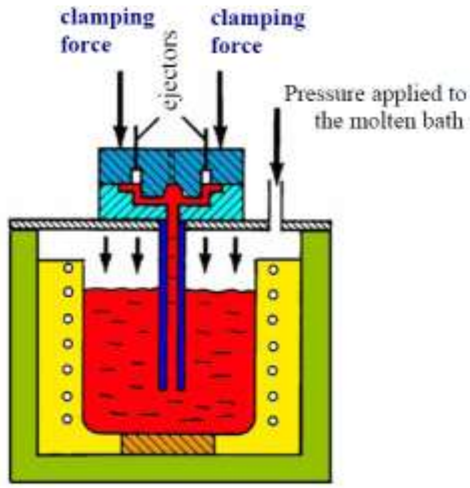


Fig 8: Pressure Casting Process

Variations of this method include Vacuum Riserless Casting (VRC) and Pressure Riserless Casting (PRC). These techniques are capable of producing a range of structural and high performance castings exhibiting excellent mechanical attributes and microstructure refinements in an economical manner. While VRC process uses vacuum to draw the liquid material up into a mould cavity, PRC uses pressure applied to a molten bath to force melt into a mould cavity. Yet another approach combines both techniques to achieve appropriate casting conditions.

Squeeze casting developed in the 1960s, involves solidification of the molten material under high pressure Fig 9. Thus it is a combination of casting and forging. The machinery includes a die, punch, and ejector pin.

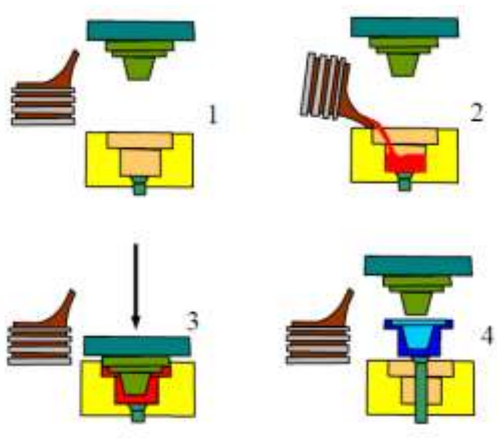


Fig 9: Sequence of operations in squeeze-casting:

1. Bring a ladle filled with liquid material close to the dies
2. Pour liquid in the bottom die cavity
3. Close dies and applies pressure
4. Open dies and ejects the solidified product

The pressure applied by the punch keeps the entrapped gases in solution, and the high-pressure contact at the die-product interface promotes rapid heat transfer, resulting in a fine microstructure with good mechanical properties. Parts can be made to near-net shape, with complex shapes and fine surface detail, from both nonferrous and ferrous alloys. Typical products: automotive wheels and mortar bodies (a short-barreled cannon). The pressures required in squeeze casting are lower than those for hot or cold forging.

Die casting

Die casting is a very commonly used type of permanent mold casting process. It is used for producing many components of home appliances (e.g rice cookers, stoves, fans, washing and drying machines, fridges), motors, toys and hand-tools – since Pearl river delta is a largest manufacturer of such products in the world, this technology is used by many HK-based companies. Surface finish and tolerance of die cast parts is so good that there is almost no post-processing required. Die casting molds are expensive, and require significant lead time to fabricate; they are commonly called dies. There are two common types of die casting: hot- and cold-chamber die casting.

• In a hot chamber process (used for Zinc alloys, magnesium) the pressure chamber connected to the die cavity is filled permanently in the molten metal. The basic cycle of operation is as follows: (i) die is closed and gooseneck cylinder is filled with molten metal; (ii) plunger pushes molten metal through gooseneck passage and nozzle and into the die cavity; metal is held under pressure until it solidifies; (iii) die opens and cores, if any, are retracted; casting stays in ejector die; plunger returns, pulling molten metal back through nozzle and gooseneck; (iv) ejector pins push casting out of ejector die. As plunger uncovers inlet hole, molten metal refills gooseneck cylinder. The hot chamber process is used for metals that (a) have low melting points and (b) do not alloy with the die material, steel; common examples are tin, zinc, and lead (Fig 10a).

• In a cold chamber process, the molten metal is poured into the cold chamber in each cycle. The operating cycle is (i) Die is closed and molten metal is ladled into the cold chamber cylinder; (ii) plunger pushes molten metal into die cavity; the metal is held under high pressure until it solidifies; (iii) die opens and plunger follows to push the solidified slug from the cylinder, if there are cores, they are retracted away; (iv) ejector pins push casting off ejector die and plunger returns to original position. This process is particularly useful for high melting point metals such as Aluminum, and Copper (and its alloys) (Fig 10b).

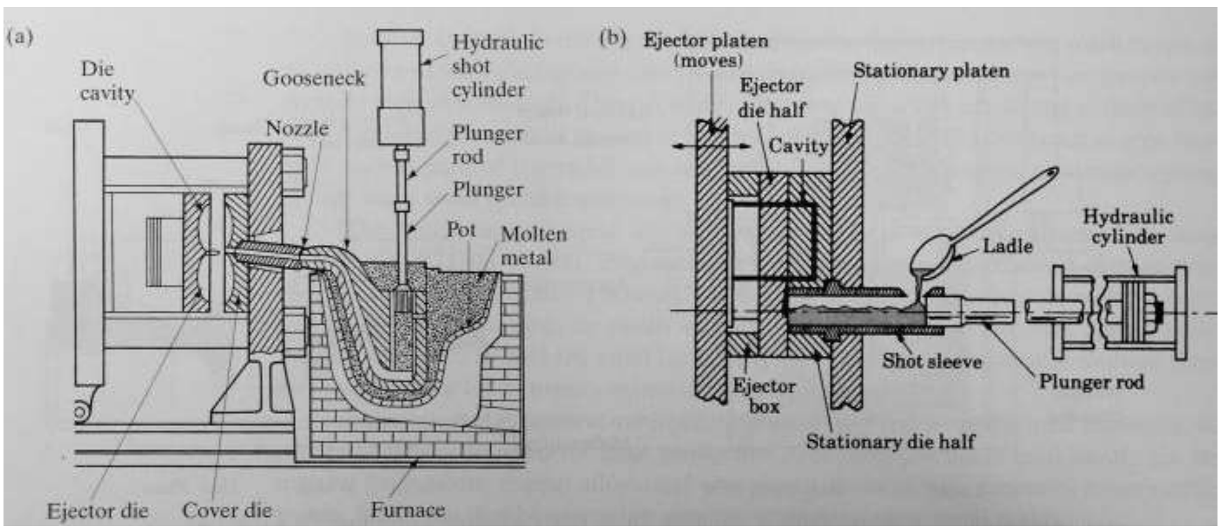


Fig. 10: (a) Hot chamber die casting (b) Cold chamber die casting

The **Die-casting** process is a typical example of permanent-mould casting. The molten material is forced into the die cavity at pressures ranging from 0.7 to 700 MPa. Typical products are carburettors, motor housings, business machine and appliance components, hand tools and toys. The weight of most castings ranges from less than 90 g to about 25 kg.

The **Hot-chamber process** involves the use of a piston, which traps a certain volume of melt and forces it into the die cavity through a gooseneck and nozzle Fig 10c.

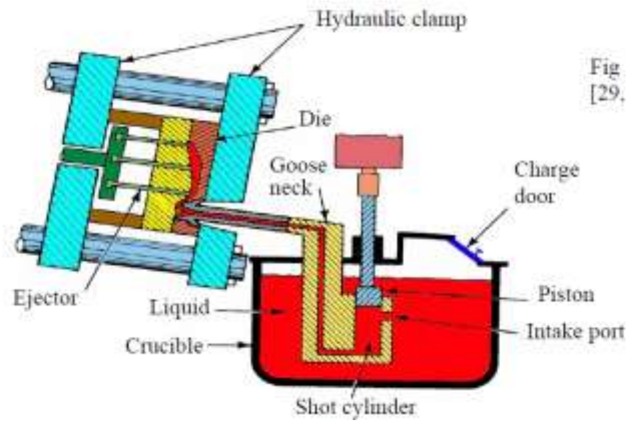


Fig 10c: Hot-chamber process

The pressures range up to 35 MPa. The melt is held under pressure until it solidifies. To improve die life and to aid in rapid heat transfer, thus reducing the cycle time, dies are cooled by circulating water or oil through passageways in the die block. Cycle times usually range up to 900 shots per hour for zinc, (very small components such as zipper teeth can be cast at 18,000 shots per hour). This process commonly casts low-melting-point alloys of metals such as zinc, tin, and lead.

In the **Cold-chamber process** molten metal is poured into the injection cylinder with a ladle Fig 10d. The shot chamber is not heated. The melt is forced into the die cavity at pressures ranging from 20 MPa to 70 MPa, (in extremes 150 MPa). The machines may be horizontal or vertical.

Process capabilities and machine selection: High-melting-point alloys of Al, Mg, and Cu are cast by this method; ferrous alloys can also be cast in this manner. The dies have a tendency to part unless clamped together tightly. Die casting machines are rated according to the clamping force and range from 25 t to 3000 t. A further factor in the selection of die-casting machines is the piston stroke which delimits the volume of fluid injected into die cavity.

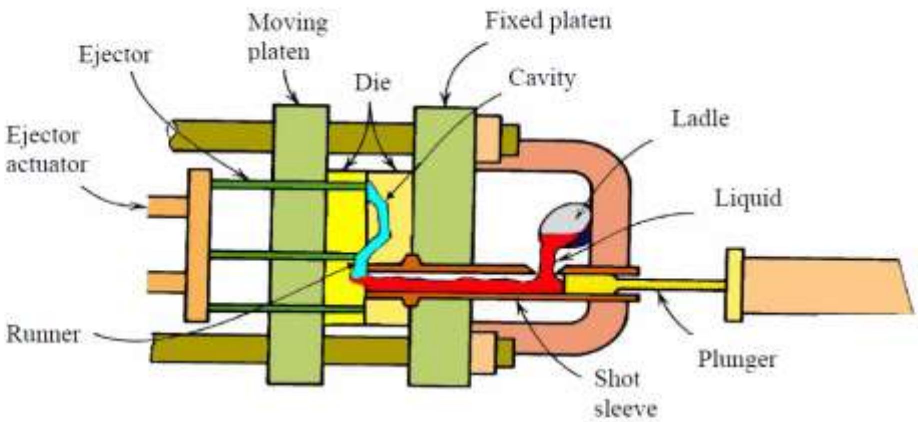


Fig 10d: Cold-chamber process

Dies may be made for single or multiple cavities. Dies wear increases with the temperature of the fluid. **Heat cracking** of the die surface from repeated heating and cooling can be a problem. However dies may last more than half a million shots before die wear becomes significant.

The entire die-casting and finishing process can be highly automated. Lubricants are applied, as parting agents on die surfaces. Alloys (except Mg alloys) generally require lubricants. Die-casting has the capability for high production rates with good strength, high-quality parts with complex shapes, good dimensional accuracy and surface detail, thus requiring little or no subsequent machining or finishing operations. Components such as pins, shafts, and fasteners can be cast integrally. Ejector marks remain, as do small amounts of **flash** (thin material squeezed out between the dies) at the die parting line.

Die-casting can compete favourably in some products with other manufacturing methods, such as metallic-sheet stamping or forging. Because the molten material chills rapidly at the die walls, the casting has a fine-grain, hard skin with higher strength than in the centre. The strength-to-weight ratio of die-cast parts increases with decreasing wall thickness. With good surface finish and dimensional accuracy, die-casting can produce bearing surfaces that would normally be machined. The cost of dies is somewhat high, but die-casting is economical for large production runs.

1.10 Centrifugal casting

Centrifugal casting uses a permanent mold that is rotated about its axis at a speed between 300 to 3000 rpm as the molten metal is poured. Centrifugal forces cause the metal to be pushed out towards the mold walls, where it solidifies after cooling. Parts cast in this method have a fine grain microstructure, which is resistant to atmospheric corrosion; hence this method has been used to manufacture pipes. Since metal is heavier than impurities, most of the impurities and inclusions are closer to the inner diameter and can be machined away. The surface finish along the inner diameter is also much worse than along the outer surface.

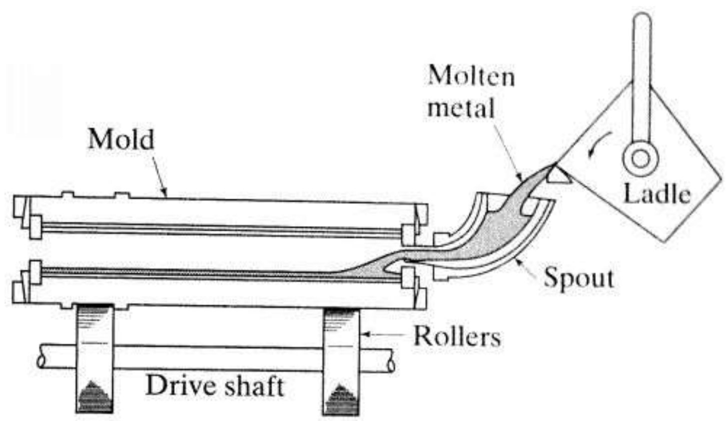


Fig 11: Centrifugal casting schematic

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 gravity into the designed crevices and detail of the mold. (Fig. 11)

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.

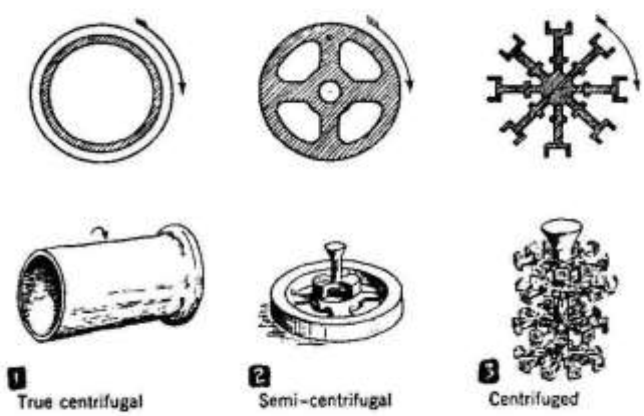
The centrifugal casting of railroad car wheels was one of the first applications involving controlled variations in chemical composition from the outside periphery of the car wheel as compared to the balance of the casting. As the casting was poured, a quantity of ferromanganese was introduced with the first metal to enter the mold. This formed a high manganese wear resistant tread and car wheel flange, as compared to the softer second portion 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 centrifugal casting process.

Centrifugal casting utilizes inertial forces caused by rotation to distribute the molten material into mould cavities. Variations of this manufacturing method include:

True centrifugal casting,

Semi-centrifugal casting, and

Centrifuging (also called **centrifuged** or **spin casting**).



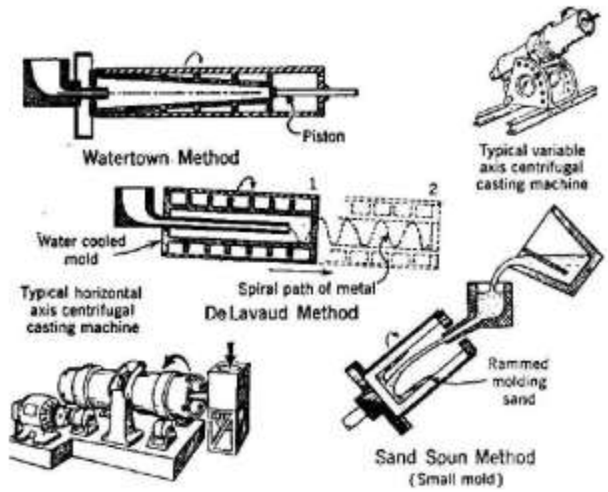


Fig 11a: Centrifugal Casting Methods

It is important to remember, however, that materials such as iron or copper that are immiscible in certain ranges are apt to segregate badly, such as lead in certain bronzes. Tubing with alloy modifications on the inside diameter which are designed to meet specific corrosion resistant 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 experimented with the method hoping to perfect cast inlays for teeth that would replace malleting flake gold into prepared cavities. A Dr. Campbell in Missouri 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 resembled 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 manufacturing of cast iron water pressure pipe, and use of the process has been extended to a much wider range of shapes and alloys.

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 distribute 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 conjunction with directional solidification, assists feeding and accelerates the separation of non-metallic inclusions and precipitated gases. The advantages 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 controlled 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 conditions the central mass of liquid metal, under high pressure, has ready access 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 casting 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 introduced. This practice is widely referred to as "true centrifugal casting." (Fig. 11b)

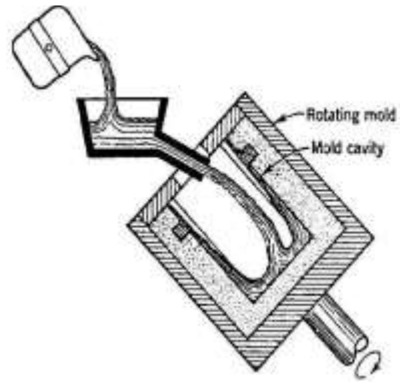


Fig 11b: True Centrifugal Casting

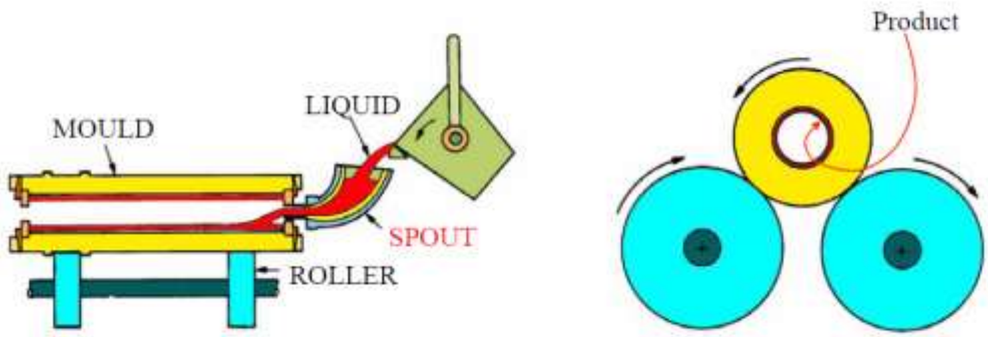


Fig 11c: True Centrifugal Casting

In **true centrifugal casting**, Fig 11c, hollow cylindrical parts, e.g. pipes and lampposts, are produced by pouring liquid into a rotating mould. The axis of rotation is usually horizontal but can also be vertical. Moulds are made of steel, cast iron, or graphite and may be coated with a refractory lining to increase mould life. Pipes with various outer shapes, (including polygonal) can be cast. The inner surface of the casting remains cylindrical because the molten material is uniformly distributed by centrifugal forces. Because of density differences, lighter particles such as dross and impurities tend to collect on the inner surface of the casting.

Cylindrical parts ranging from ∅13 mm to 3 m in diameter and 16 m long can be produced with wall thickness ranging from 6 mm to 125 mm. The acceleration generated by the centrifugal force is high, as much as 150 g, and is necessary for casting thick-walled parts. This process enables good dimensional accuracy, and external surface detail. Typical products are pipes, bushings, engine cylinder liners, and bearing rings with or without flanges. Apart from metallic products some glass and ceramic products_(e.g. TV picture tubes and ceramic membrane tubes) are also manufactured using this technique.

In the case of a component of varying internal diameter or irregular 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 "semi-centrifugal casting and centrifuging or pressure casting." 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.

Semi-Centrifugal Casting

Such items as wheels and pulleys are occasionally cast in a semi-centrifugal setup as illustrated in (Fig. 11d). 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 rotates 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.

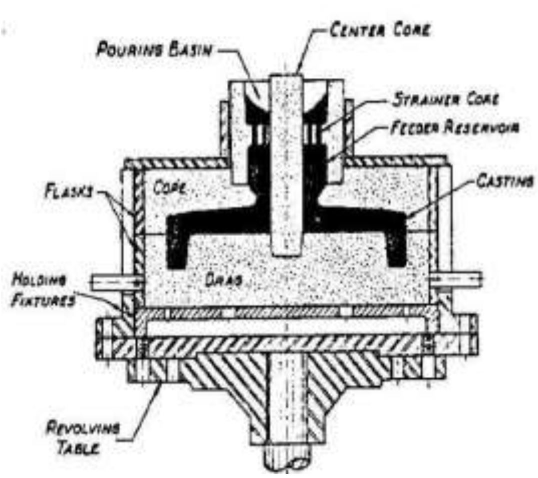


Fig. 11d Semi-Centrifugal Casting

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 necessary 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 together. (Fig. 11e)

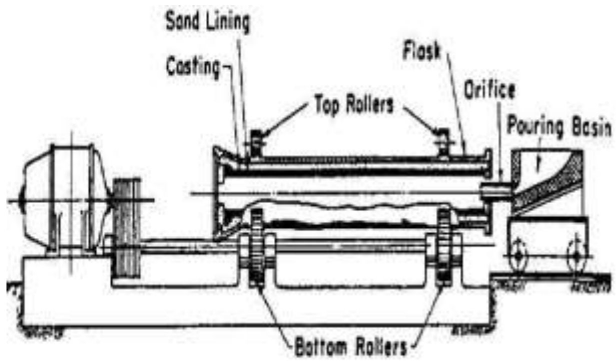


Fig 11e: Schematic representation of True Centrifugal Casting Machine

Semi-centrifugal casting is used to cast parts with rotational symmetry, such as wheels with spokes and central hub. This technique can be applied to most expendable and permanent moulds.

In **Centrifuging** mould cavities of odd shape are placed at a certain distance from the axis of rotation. The molten material is forced into the mould by centrifugal forces. The attributes within the castings vary with the distance from the axis of rotation, Fig 11f.

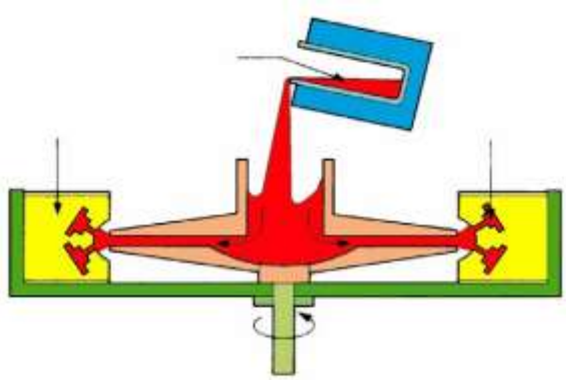


Fig 11f: Centrifuging

Vertical Centrifugal Casting

Vertical castings are produced by pouring a given weight of metal into a mold that rotates about a vertical axis. The metal is picked up and distributed on the inside surface of the mold. Dross, slag and other nonmetallics are centrifuged to the inside. Unlike the horizontal casting, it is not possible 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 revolution. The paraboloid "A" in Fig. 11g shows the shape of the cavity formed by a relatively high rotational speed and paraboloid "B" shows the approximate 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.

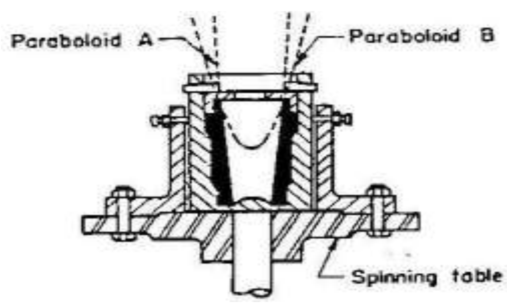


Fig 11g: Vertical Centrifugal Casting

The vertical axis centrifugal casting method is not suited to the production of pipelike 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 application in the production of ringlike 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 outside shape.

Vertical casting machines consist of a rotating table on which a mold is centered 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 machine failure.

1.11 Rheocasting processes

Semi-solid metal casting 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 process of thixocasting offers a number of advantages, such as improved mechanical properties, good surface finish, near net shape and so on. However, the thixocastingprocess has also a number of disadvantages, such as the need for special feedstock with near spherical primary crystals. In order to cast such special billets for thixocasting one has to pay a more expensive premium than normal. Eliminating this additional specialized casting step leads to savings in both costs and time. A product can be cast into a near net shape part directly from the molten metal state as in rheocasting, where the need of special billet is removed. Therefore, rheocasting is advantageous from an energy and cost saving point of view when compared to thixocasting. In the early days of semisolid casting research, mechanical stirring was used in order to achieve the right microstructures. More recently, electric stirring has used. There are two kinds of rheocasting process using a cooling slope and a process using low superheat casting, respectively. In the process using the cooling slope, the metal is in the semisolid condition when it flows into the die. In the low superheat casting process, the seed of the crystals are generated at the die surface. The casting is carried out before the crystal seeds could be re-melted. The crystal seeds could then grow to become spherical primary crystals. In the processes described only pouring of the molten metal into the die has been needed for the semisolid casting to take place. In conventional semisolid casting, the solid metal fraction content is usually 50%, however, in this process; casting has been tried at lower than 50% fraction solids.The primary crystal size becomes smaller as the solid rate becomes lower. In thixocasting, metal handling is difficult at fraction solids lower than 50%. However, in rheocasting, casting metal with lower fraction solids is easy because the product, which is thin, can be cast at low fraction solids. Fig. 10 shows the two rheocasting processes devised in this discussion.

The molten metal was poured into the lower die half via the cooling slope. The molten metal became semisolid slurry on the cooling slope. The cooling slope, which is very compact and simple, is made from mild steel, it is water-cooled and as a package offers both low equipment costs and low running costs. Thecooling slope can be easily mounted as part of any conventional casting machine. In conventional semisolid casting process, a typical fraction solid of about 50% is required, however, the present study aimed at fraction solids lower than 50%. The primary crystal size in the product becomes smaller as the fraction solid is reduced. The solidification rate of the semisolid slurry after flowing through on the cooling slope was about 10%. Casting was done immediately after pouring without holding the slurry in order not to increase the solidification rate. Therefore, there was no need of a system that controls the rate of solidification; this simplified the processes investigated in the present study. Fig. 10(b) shows the rheocasting process that used low superheat casting. The superheat of the molten metal was 10 ^{0}C. The crystal seeds are generated at the lower die surface, and the upper die is inserted into the lower die before the metal solidifies. When the superheat of the molten metal is low, the crystal seeds do not melt and if sufficient crystal seeds remain, they can grow into spheroidal primary crystals. The low superheat casting is simpler than the cooling slope process.

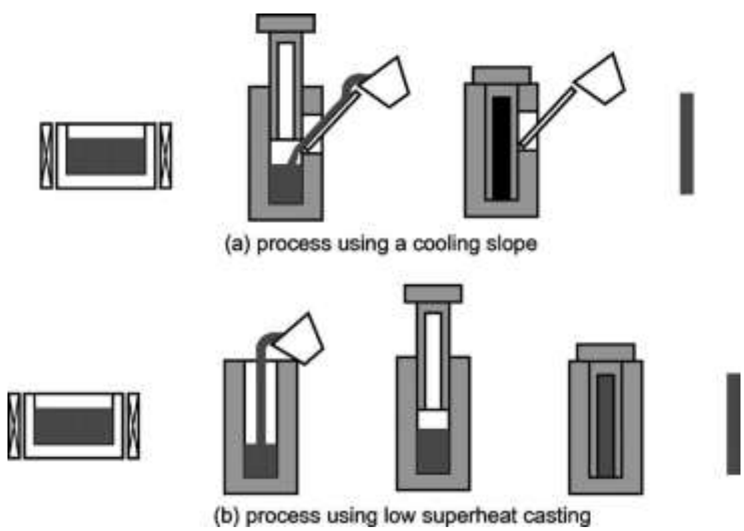


Fig. 12 Two kinds of Rheocasting process

1.12 Continuous Casting

Continuous casting transforms molten metal into solid on a continuous basis and includes a variety of important commercial processes. These processes are the most efficient way to solidify large volumes of metal into simple shapes for subsequent processing. Most basic metals are mass-produced using a continuous casting process, including over 500 million tons of steel, 20 million tons of aluminum, and 1 million tons of copper, nickel, and other metals in the world each year. Continuous casting is distinguished from other solidification processes by its steady state nature, relative to an outside observer in a laboratory frame of reference. The molten metal solidifies against the mold walls while it is simultaneously withdrawn from the bottom of the mold at a rate which maintains the solid / liquid interface at a constant position with time. The process works best when all of its aspects operate in this steady-state manner. Relative to other casting processes, continuous casting generally has a higher capital cost, but lower operating cost. It is the most cost- and energy- efficient method to mass-produce semifinished metal products with consistent quality in a variety of sizes and shapes. Cross-sections can be rectangular, for subsequent rolling into plate or sheet, square or circular for long products, and even "dog-bone" shapes, for rolling into I or H beams.

In the continuous casting, molten steel is poured from the tundish in the water cooled mold and partially solidified bloom/billet or slab (hereafter called strand) is withdrawn from the bottom of the mold into water spray so that solidified bloom/billet or slab is produced constantly and continuously. Continuous casting is widely adopted by steelmakers. The advantages of continuous casting over ingot casting are

- Quality of the cast product is better
- No need to have slabbing / blooming or billet mill as required when ingot casting is used.
- Higher extent of automation is possible
- Width of the slab can be adjusted with the downstream strip mill.
- Continuously cast products show less segregation.
- Hot direct charging of the cast product for rolling is possible which leads to energy saving.

The essential components of a continuous casting machine are tundish, water cooled mold, water spray and torch cutters. Tundish, mold and water spray are arranged such that molten stream is poured from tundish to mold and solidified strand (billet/bloom/billet) is produced continuously. The required length of the strand is cut by torch cutter. In Fig. 13, the arrangement of tundish, mold and water spray is shown. Various continuous casting processes are shown in Fig 13a.

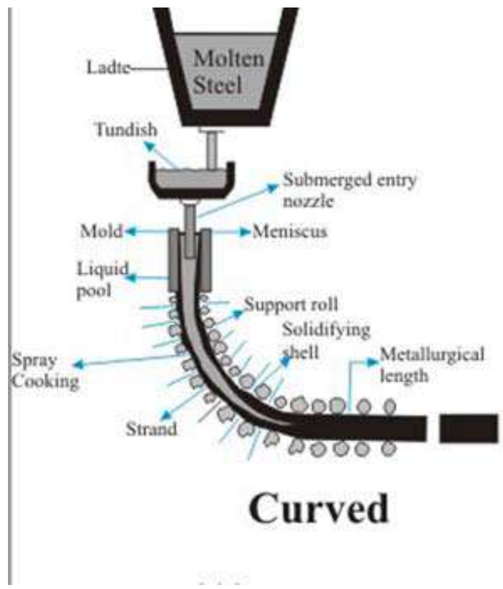


Fig 13: Arrangement of tundish, mold and water spray in a curved mold machine

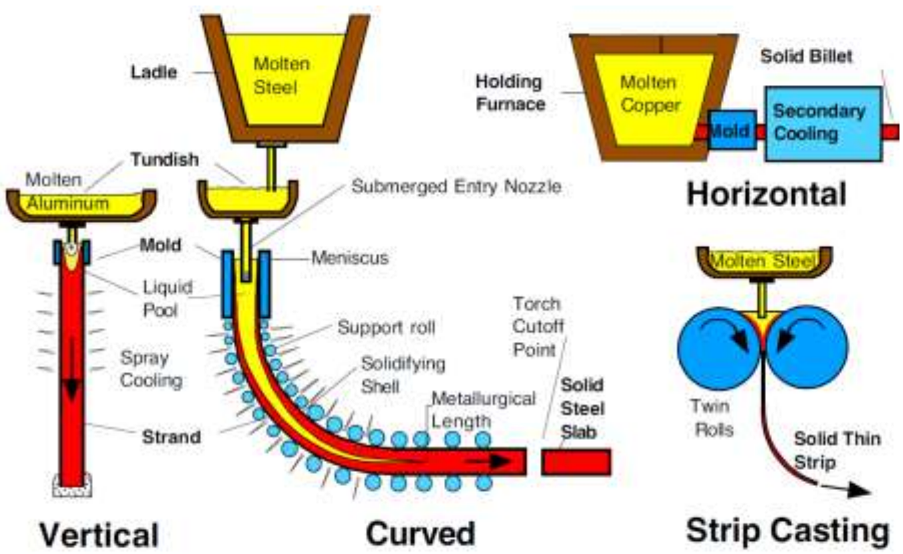


Fig. 13a Various continuous casting processes

Tundish

Tundish is a refractory lined vessel. Liquid steel is usually tapped from ladle into tundish. The stream is shrouded as it enters from ladle to tundish. The functions of the tundish are:

Reservoir of molten steel

Tundish acts as a reservoir for molten steel. It supplies molten steel in presence of a slag cover to all continuous casting molds constantly and continuously at constant steel flow rate. The flow rate is maintained constant by maintaining a constant steel bath height in the tundish through teeming of molten steel from the ladle. The number of mold is either one or more than one. Normally bloom and billet casting machines are multi strand i.e. number of molds are either 4 or 6 or 8. Slab casters usually have either single or two molds. During sequence casting and ladle change over periods, tundish supplies molten steel to the molds.

Distributor

Tundish distributes molten steel to different molds of the continuous casting machine at constant flow rant and superheat which is required for stand similarly with reference to solidification microstructure. Control of superheat is required in all the moulds to reduce break out. Location of ladles stream in the tundish is important. It may be located symmetric or asymmetric to the centre of the tundish depending on the number of mold. For single strand machines, molten stream enters from one side and exits the other side of the tundish. In multi strand tundishes, ladle stream is either at the centre of the tundish or displaced to the width side of the tundish.

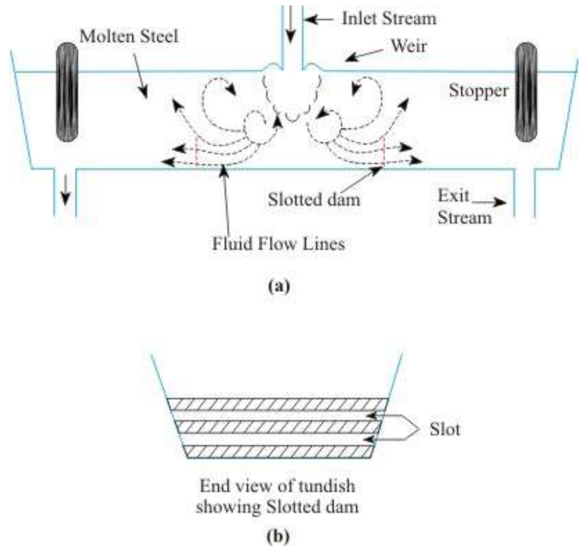


Fig. 13b: Tundish with flow control device, namely weir and slotted dam

Inclusion removal

Tundish helps to remove inclusions during the process of continuous casting. For this purpose liquid steel flow in the tundish is modified by inserting dams, weirs, slotted dams etc. The whole idea is to utilize the residence time available before steel leaves the tundish. For example, if capacity of tundish is 40 tons and casting speed is 5 tons/min, then the average residence time of molten steel in the tundish is 8 minutes. During this average residence time, inclusion removal can be exercised .For this purpose flow of steel melt in the tundish has to be modified so as to accelerate the inclusion removal. The Inclusion removal is a two-step step unit operation, namely floatation and absorption by a flux added on the surface of the tundish. Flux is usually rice husk, or fly ash or some synthetic powder.

Mold:

Mold is the heart of continuous casting. In the water cooled mold, molten stream enters from the tundish into mold in presence of flux through the submerged nozzle immersed in the liquid steel. Solidification of steel begins in the mold. The casting powder is added onto the top of molten steel in the mold. It melts and penetrates between the surface of mold and the solidifying strand to minimize friction as shown in Fig 13c. Control of height of molten steel in the mould is crucial for the success of the continuous casting machine. The solidification begins from the meniscus of steel level in the mould. Mold level sensors are used to control the meniscus level in the mould.

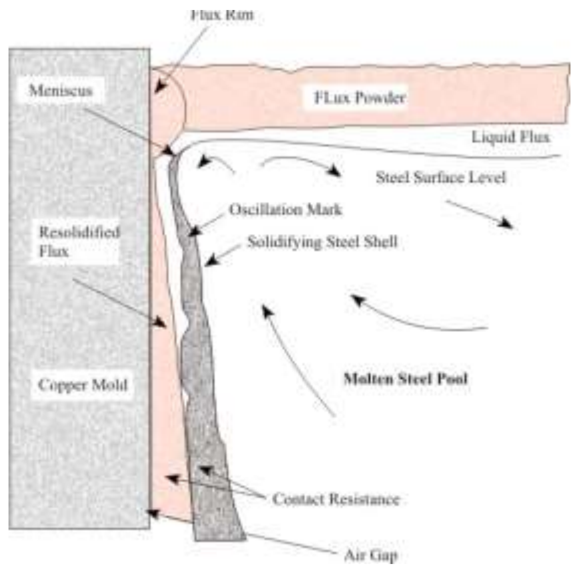


Fig13c: Role of flux in continuous casting mold

As seen in the figure, flux melts and enters into the gap between mold surface and solidified strand. Molds are made of copper alloys. Small amounts of alloying elements are added to increase the strength. Mold is tapered to reduce the air gap formation. Taper is typically 1% of the mold length. For cross section of mold the taper is about 1mm for 1m long mold. The cross section of the mold is the cross section of the slab/bloom/billet. Length of the mold is around 0.7 and is more for large cross sections. Mold cross section decreases gradually from top to bottom. Mould extracts around 10% of the total heat.

The mold is oscillated up and down to withdraw the partially solidified strand (strand is either billet or bloom or slab).The oscillated frequency can be varied. At Tata steel slab caster frequency is varied in between 0 and 250cycles/min and the stroke length from 0 to 12mm.

Steel level in mould is controlled, that is the meniscus for smooth caster operation. Sensors are used to control the meniscus level.

The functions of mold flux are.

- Inclusion absorption capability
- Prevention of oxidation
- Minimization of heat losses
- Flux on melting enters into the air gap and provides lubrication

For the above functions the flux should have the following properties.

- Low viscosity
- Low liquidus temperature
- Melting rate of flux must match with the speed of the continuous casting.

2. The Capabilities of major casting processes are compared in Table 2.

Table 2: Capabilities of major casting processes

Attribute \ Process	Sand	Investment	Gravity Die	Pressure Die
Maximum size	several tons	up to 20 kg	up to 50 kg	up to 8 kg
Dimensional tolerance	> 0.6 mm	> 0.1 mm	> 0.4 mm	> 0.05 mm
Surface finish	> 200 RMS	> 60 RMS	> 150 RMS	> 30 RMS
Minimum thickness	> 6 mm	> 1.5 mm	> 4.5 mm	> 0.8 mm
Economic quantity	any number	> 100	> 500	> 2500
Sample lead time	2-10 weeks	8-10 weeks	8-20 weeks	12-24 weeks

The hierarchical classification of various casting processes are summarized in Fig. 14.

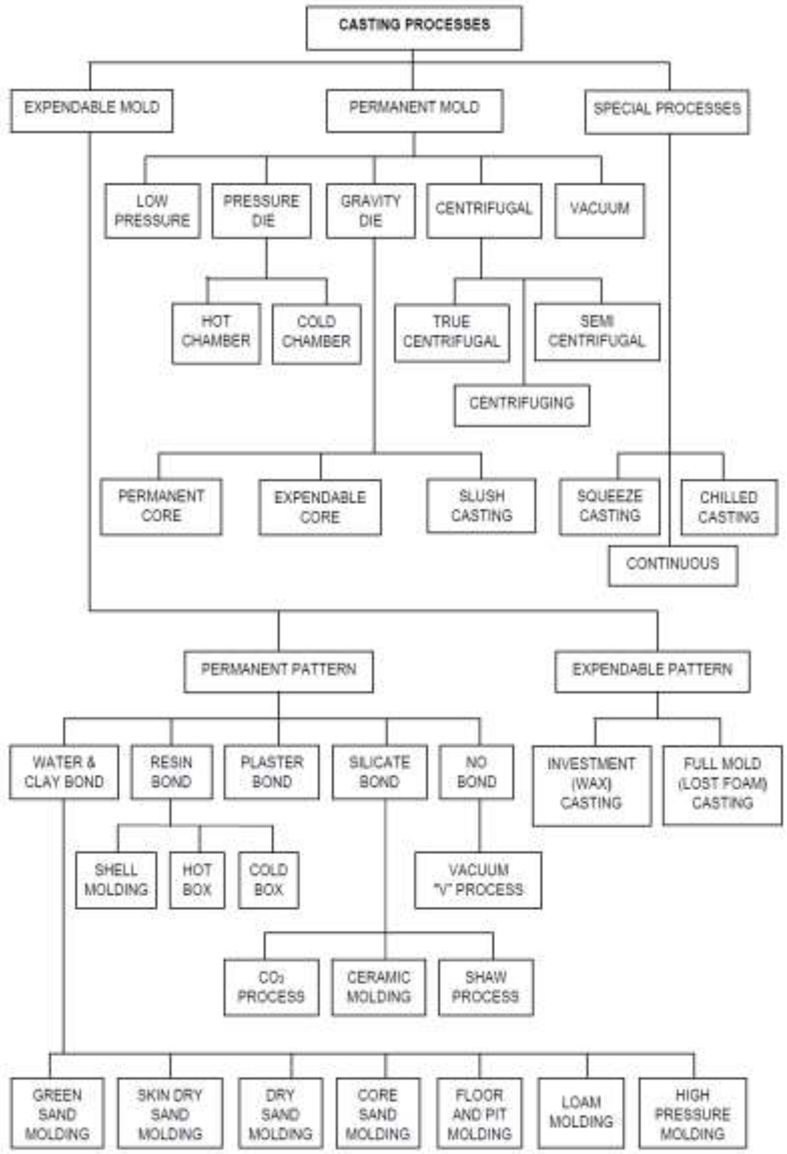


Fig.14 Hierarchical classification of various casting processes

2.1 Sand mould and core making

Sand casting is the most common productiontechnique, especially for ferrous castings. Sand ismixed with clay and water or with chemical binders and then packed or rammed around the pattern to form a mould half. The two halves are joined together to make the mould - a rigid cavity that provides the required shape for the casting, as shown in Fig. 15 below. Variations on this technique include the use of plaster in place of sand and the recently invented Pattern less process, where the mould is machined directly out of a sand block without the need for a pattern.

Cores are produced by blowing, ramming or in heated processes, investing sand into a core box. The finished cores, which can be solid or hollow, are inserted into the mould to provide the internal cavities of the casting before the mould halves are joined. Sand cores are also widely used in die-casting, where permanent metal moulds are employed.

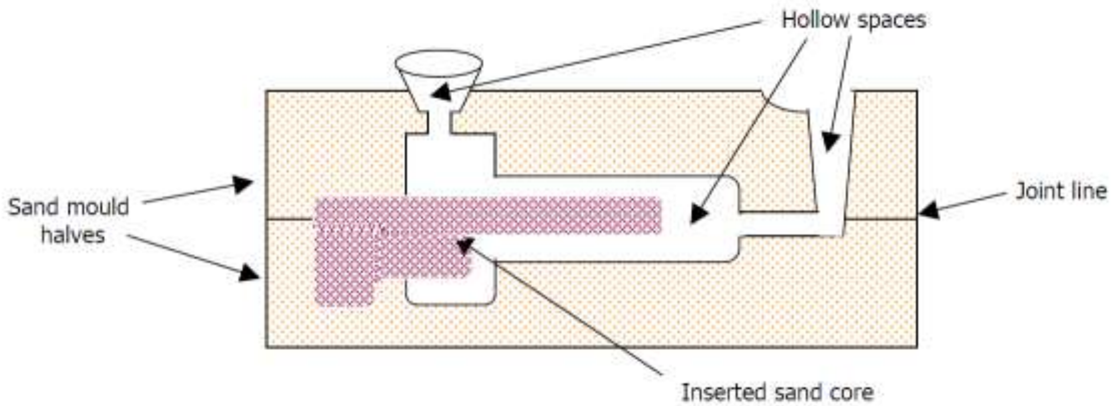


Fig 15: Assembled Mould with Core Inserted Ready for Casting

Sand Preparation: Moulding sand should have good flowability (for better reproduction of pattern details), adequate green strength (to prevent its collapse during moulding), dry strength (to prevent its collapse during mould filling), sufficient refractoriness (to withstand molten metal temperature), enough permeability (to allow entrapped air and gases generated inside the mould to escape) and collapsibility (for ease of shakeout).

These are achieved by a suitable composition of sand, binders, additives and moisture. Silica sand is the most widely available and economical. Special sands include zirconsand (lower thermal expansion, higher refractoriness and higher thermal conductivity, butmore expensive), olivine sand (with properties in between silica and zircon sand) and chromite/magnesite sand (high thermal conductivity). The most widely used binder is bentonite clay (sodium or calcium bentonite), which imparts strength and plasticity tosilica sand with the addition of water. Additives include coal dust (to improve surfacefinish by gas evolution at metal-mould interface), iron oxide (for high temperatureresistance), dextrin (for improved toughness and collapsibility) and molasses (for highstrength and collapsibility). Modern sand plants automatically carry out mulling, mixing, aeration and testing of the sand. They also reclaim used sand through magnetic separation(to remove metal particles), crushing of lumps and finally removal of excess fines andbond (usually by washing in hot water or by mechanical impact).

Core Making: Cores are surrounded by molten metal, and have higher requirement compared to mould sand in terms of strength (to support their own weight and the buoyancy force of metal), permeability and collapsibility (especially for curved holes, otherwise they will be difficult to clean out). The most widely used binder for core sands is vegetable oil (linseed and corn oil, sometimes mixed with mineral oils), which is economical, but requires heating in an oven to about 240 C for 2-3 hours to develop sufficient strength. Another widely used process uses sodium silicate binder mixed in dry sand free of clay; the sand mixture hardens immediately when CO2 gas is passed through it. The process is highly productive. The core develops high compressive strength but has poor collapsibility. Other processes are based on organic binders; mainly thermosetting resins such as phenol, urea and furan. This includes *hot box* and *cold box* processes. The core sand mixed with binder is filled into a core box either manually or using a sand slinger. For higher productivity core blowing machines are used, in which core boxes are mounted in the machine and sand is forced and pressed into the core box under a stream of high velocity air. This is followed by appropriate heating of the core box to impart the desired properties to the core.

Moulding: This involves packing the moulding sand uniformly around a pattern placed in a moulding box (or flask). Most foundries are equipped with jolt-squeeze machines operated by compressed air. The combination of jolting and squeezing action gives good compaction of sand near the pattern (by jolting the sand into crevices) as well as the top where the squeeze plate comes in contact with the mould. Many modern foundries have high pressure moulding equipment, which use air impulse or gas injection to impact the sand on the pattern. These machines produce relatively less noise and dust compared to jolt and squeeze machines and has much higher productivity (several moulds per minute). A special type of high pressure moulding machine is the flask less moulding machine pioneered by Disamatic, in which the parting plane is vertical and the mouldcavity is formed between consecutive blocks of mould.

2.2 Heating the Metal

• Heating furnaces are used to heat the metal to molten temperature sufficient for casting

• The heat required is the sum of:

1. Heat to raise temperature to melting point
2. Heat of fusion to convert from solid to liquid
3. Heat to raise molten metal to desired temperature for pouring

Pouring the Molten Metal

•For this step to be successful, metal must flow into all regions of the mold, most importantly the main cavity, before solidifying

•Factors that determine success: Pouring temperature, pouring rate, Turbulence

2.3 Solidification of Metals

Transformation of molten metal back into solid state •Solidification differs depending on whether the metal is a pure element or an alloy

A pure metal solidifies at a constant temperature equal to its freezing point (same as melting point)

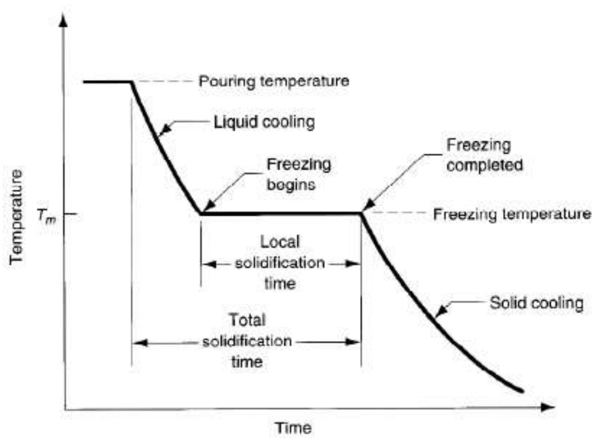


Fig 16 - Cooling curve for a pure metal during casting

Solidification of Pure Metals

•Due to chilling action of mold wall, a thin skin of solid metal is formed at the interface immediately after pouring

•Skin thickness increases to form a shell around the molten metal as solidification progresses

•Rate of freezing depends on heat transfer into mold, as well as thermal properties of the metal

Figure 16a - Characteristic grain structure in a casting of a pure metal, showing randomly oriented grains of small size near the mold wall, and large columnar grains oriented toward the center of the casting

Most alloys freeze over a temperature range rather than at a single temperature

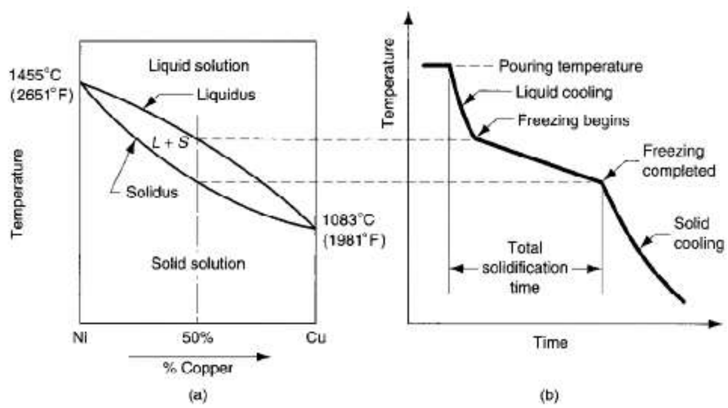


Figure 17 - (a) Phase diagram for a copper-nickel alloy system and (b) associated cooling curve for a 50%Ni-50%Cu composition during casting

Figure 18 - Characteristic grain structure in an alloy casting, showing segregation of alloying components in center of casting

Solidification Time

• Solidification takes time

• Total solidification time *TST* = time required for casting to solidify after pouring

•*TST* depends on size and shape of casting by relationship known as *Chvorinov's Rule*

$$TST = C_m \left(\frac{V}{A} \right)^n$$

where *TST* = total solidification time; *V* = volume of the casting; *A* = surface area of casting; *n* = exponent usually taken to have a value = 2; and *Cm* is *mold constant*

Mold Constant in Chvorinov's Rule

•*Cm* depends on mold material, thermal properties of casting metal, and pouring temperature relative to melting point

•Value of *Cm* for a given casting operation can be based on experimental data from previous operations carried out using same mold material, metal, and pouring temperature, even though the shape of the part may be quite different

A casting with a higher volume-to-surface area ratio cools and solidifies more slowly than one with a lower ratio

- To feed molten metal to main cavity, *TST* for riser must greater than *TST* for main casting

• Since riser and casting mold constants will be equal, design the riser to have a larger volume-to-area ratio so that the main casting solidifies first

- This minimizes the effects of shrinkage

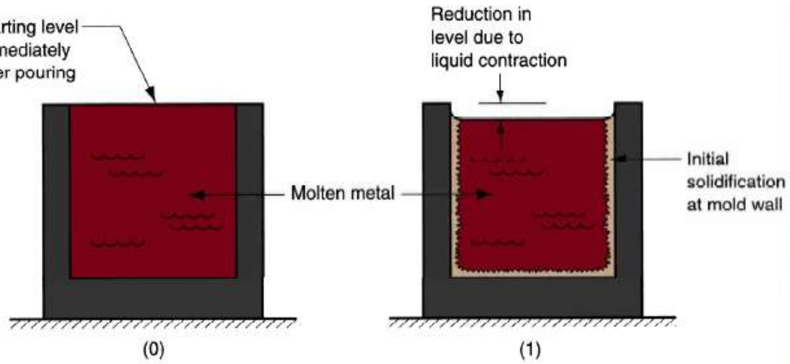


Figure 19 - Shrinkage of a cylindrical casting during solidification and cooling: (0) starting level of molten metal immediately after pouring; (1) reduction in level caused by liquid contraction during cooling (dimensional reductions are exaggerated for clarity in sketches)

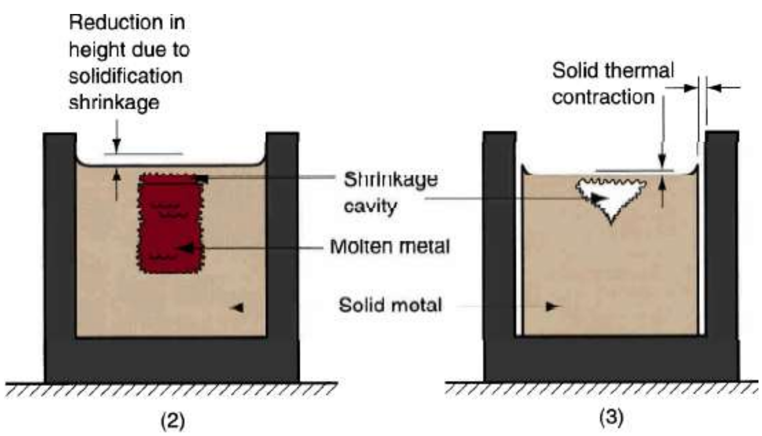


Figure 20 - (2) reduction in height and formation of shrinkage cavity caused by solidification shrinkage; (3) further reduction in height and diameter due to thermal contraction during cooling of the solid metal (dimensional reductions are exaggerated for clarity in our sketches)

Solidification Shrinkage

•Occurs in nearly all metals because the solid phase has a higher density than the liquid phase

•Thus, solidification causes a reduction in volume per unit weight of metal

•Exception: cast iron with high C content

--Graphitization during final stages of freezing causes expansion that counteracts volumetric decrease associated with phase change

Shrinkage Allowance

•Patternmakers account for solidification shrinkage and thermal contraction by making mold cavity oversized

•Amount by which mold is made larger relative to final casting size is called *pattern shrinkage allowance*

•Casting dimensions are expressed linearly, so allowances are applied accordingly

Directional Solidification

•To minimize damaging effects of shrinkage, it is desirable for regions of the casting most distant from the liquid metal supply to freeze first and for solidification to progress from these remote regions toward the riser(s)

Thus, molten metal is continually available from risers to prevent shrinkage voids

The term *directional solidification* describes this aspect of freezing and methods by which it is controlled

Achieving Directional Solidification

•Desired directional solidification is achieved using Chvorinov's Rule to design the casting itself, its orientation in the mold, and the riser system that feeds it

•Locate sections of the casting with lower *V/A* ratios away from riser, so freezing occurs first in these regions, and the liquid metal supply for the rest of the casting remains open

•*Chills* - internal or external heat sinks that cause rapid freezing in certain regions of the casting

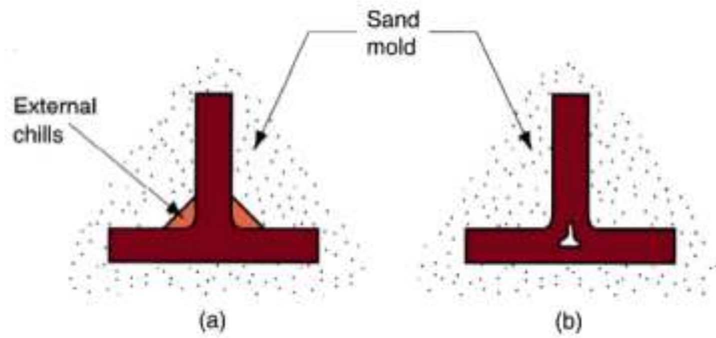


Figure 21 - (a) External chill to encourage rapid freezing of the molten metal in a thin section of the casting; and (b) the likely result if the external chill were not used

Riser Design

• Riser is waste metal that is separated from then casting and remelted to make more castings

• To minimize waste in the unit operation, it is desirable for the volume of metal in the riser to be a minimum

• Since the geometry of the riser is normally selected to maximize the *V*/*A* ratio, this allows reduction of riser volume as much as possible

Melting: Most widely used melting equipment include cupula, oil/gas fired furnaces (including crucible and rotary furnaces), direct arc furnace and induction furnace. The cupola is the simplest and the most economical, and most suited for grey iron. Layers of pig iron, coke and flux (limestone) are charged into the cupola; air for combustion is blown through several openings (tuyeres). Use of hot air blast and double row tuyeres improves cupola efficiency. Oil or gas fired crucible furnaces are suitable for melting small quantities of metal, usually non-ferrous. The crucible is usually made of graphite and clay. Rotary furnaces are made of steel shells lined with refractory, turning at a rate of 1-2 rpm. The charge is placed through a door in the middle; one end of the furnace is heated (by firing oil or gas) and the melt is taken out through the other end. Electric furnaces include direct arc and induction furnaces, which are more widely preferred by newer foundries owing to ease of control over temperature and composition, and high melting rate. In arc furnace, the heat is generated between the electrodes and transferred to the metal. In induction furnace, the heat is generated in the metal itself by eddy currents. Induction furnaces can be classified depending on the location of the induction coil (cored and coreless), and frequency of current (high or medium).

Molten metal is prepared in a variety of furnaces, the choice of which is determined by the quality, quantity and throughput required.

Electric induction furnaces are the most common type used for batch melting of ferrous, copper and super alloys. This method involves the use of an electrical current surrounding a crucible that holds the metal charge. Furnace sizes range from < 100 kg up to 15 tons. For production of super alloys and titanium, melting may be undertaken in a vacuum chamber to prevent oxidation.

Cupolas are used solely by iron foundries for continuous production of molten iron. The cupola consists of a shaft in which a coke bed is established. Metal, coke and limestone are alternately charged into the furnace from the top. Molten metal trickles through the coke bed picking up essential carbon, while impurities react with the limestone to form waste slag. Both metal and slag are continuously tapped out at the bottom. Metal throughputs of 1 to 45 tons per hour are achieved in the UK.

Electric arc furnaces are still used by a few ferrous foundries in the UK, mainly producing steel castings, although most have been replaced by induction furnaces. Furnaces of 3 to 100 tons capacity are in use in the UK. The design involves the use of a holding bath into which electrodes are inserted. The heat generated by creating a charge between the electrodes causes the metal to melt.

Rotary furnaces are relatively uncommon in the UK but are used in some iron foundries. The furnace consists of a horizontal cylindrical steel shell mounted on rollers and lined with refractory material. The furnace is fired using gas or oil from one end and the furnace body is slowly rotated during melting.

Gas-fired shaft and resistance furnaces are used for melting of aluminium. Shaft furnaces provide a continuous melting and tapping capability, useful at high production facilities. Resistance furnaces are employed for melting of small batches.

Gas and oil-fired crucible furnaces are used for small batch melting of copper and aluminium alloys, although oil-fired units are less common now and tend to be limited to smaller foundries. Unlike the larger furnaces where molten metal is tapped into a ladle for casting, the crucible is lifted out (or pops out) of the heating chamber and the molten metal can be poured directly into the mould.

2.4 Casting Applications

Castings can range in size: from a few grams (for example, watch case) to several tones (marine diesel engines), shape complexity: from simple (manhole cover) to intricate (6-cylinder engine block) and order size: one-off (paper mill crusher) to mass production (automobile pistons). The desired dimensional accuracy and surface finish can be achieved by the choice of process and its control. Castings enable many pieces to be combined into a single part, eliminating assembly and inventory and reducing costs by 50% or more compared to machined parts. Unlike plastics, castings can be completely recycled. Today, castings are used in virtually all walks of life. Major areas of applications are given below (see Fig. 1.3). The transport sector and heavy equipment (for construction, farming and mining) take up over 50% of castings produced.

Transport: automobile, aerospace, railways and shipping
Heavy equipment: construction, farming and mining
Machine tools: machining, casting, plastics moulding, forging, extrusion and forming
Plant machinery: chemical, petroleum, paper, sugar, textile, steel and thermal plants
Defense: vehicles, artillery, munitions, storage and supporting equipment
Electrical machines: motors, generators, pumps and compressors
Municipal castings: pipes, joints, valves and fittings
Household: appliances, kitchen and gardening equipment, furniture and fittings
Art objects: sculptures, idols, furniture, lamp stands and decorative items

Virtually any metal or alloy that can be melted can be cast. The most common ferrousmetals include grey iron, ductile iron, malleable iron and steel. Alloys of iron and steel are used for high performance applications, such as temperature, wear and corrosion resistance. The most common non-ferrous metals include aluminum, copper, zinc and magnesium based alloys. The production and application of ductile iron and aluminum castings are steadily increasing. Aluminum has overtaken steel in terms of production by weight. The consumption of magnesium alloys is rapidly increasing in automobile and other sectors, owing its high strength to weight ratio. Important and emerging metal titanium is stronger than steel, but has found limited applications owing to thedifficulty in casting and machining. Table 3 lists the major metals in use today (by weight) along with their main characteristics and typical applications.

Table 3: Major cast metals

METAL	USE	CHARACTERISTICS	APPLICATIONS
Grey Iron	54%	Heat resistance, damping, low cost, high fluidity, low shrinkage.	Automobile cylinder block, clutch plate, brake drum, machine tool beds, housings
Ductile Iron	20%	Strength, wear and shock resistance, dimensional stability, machinability.	Crank shafts, cam shafts, differential housing, valves, brackets, rollers.
Aluminum	12%	Strength to weight ratio, corrosion resistance.	Automobile pistons, oil and fuel pumps, connecting rod, clutch housings.
Steel	9%	Strength, machinability, weldability	Machine parts, gears, valves
Copper base	2%	High ductility, corrosion resistance.	Marine impellers, valves, hydraulic pump parts.
Zinc base	1%		