LECTURE NOTES

ON

MANUFACTURING PROCESSES

B. Tech III Semester (R-18)

Prepared By

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SYLLABUS

Module-I	CASTING
Casting: Steps involved in making a casting, its applications, patterns and types of patterns, pattern allowances and their construction, types of casting processes, solidification of casting..	
Module-II	**WELDING**
Welding: Welding types, Oxy-fuel gas welding, cutting, standard time and cost calculations, arc welding Process, forge welding, resistance welding, thermit welding. Inert gas welding, TIG welding, MIG welding, friction welding, induction pressure welding, explosive welding, electron beam welding, laser welding, soldering and brazing. Heat affected zone in welding, welding defects, causes and remedies, destructive and non-destructive testing of welds.	
Module-III	**METAL FORMING**
Forming: Hot working, cold working, strain hardening, recovery, re-crystallization and grain growth, comparison of properties of cold and hot worked parts, rolling fundamentals, theory of rolling, types of rolling mills and products; Forces in rolling and power requirements, stamping, forming and other cold. Working processes: Blanking and piercing, bending and forming, drawing and its types, wire drawing and tube drawing; coining; hot and cold spinning, types of presses and press tools, forces and power requirements for the above operations.	
Module-IV	**EXTRUSION AND RAPID PROTOTYPING**
Extrusion of Metals: Basic extrusion process and its characteristics, hot extrusion and cold extrusion, forward extrusion and backward extrusion, impact extrusion, extruding equipment, tube extrusion and Pipe making, hydrostatic extrusion, forces in extrusion; Additive manufacturing: Rapid prototyping and rapid tooling.	
Module-V	**FORGING**
Forging processes: Forging operations and principles, tools, forging methods, Smith forging, drop forging, roll forging, forging hammers: Rotary forging, forging defects, cold forging, swaging, forces in forging operations.	
Text Books:	
1. Kalpakjian and Schmid, Manufacturing processes for engineering materials -Pearson India, 5 th Edition 2014.	
Reference Books:	
1. Mikell P. Groover, Fundamentals of Modern Manufacturing: Materials, Processes, and Systems John Wiley & Sons Inc., 4th Edition, 2008. 2. Degarmo, Black &Kohser, Materials and Processes in Manufacturing (9th Edition) John Wiley & Sons Inc., 7 th Edition, 2012.	

MODULE-I

CASTING

COURSE OUTCOMES (COs):

At the end of the course students are able to:		
	Course Outcomes	**Knowledge Level (Bloom's Taxonomy)**
CO1	**Outline** the steps involved in making a casting the desired pattern for automotive industry components cylinder heads, engine blocks etc.	Remember
CO2	**Design** the gating and riser system needed for casting requirements to achieve defect/error free components	Apply

PROGRAM OUTCOMES (POs):

Program Outcomes (POs)		Strength	Proficiency Assessed by
PO 1	**Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.	3	CIE/Quiz/AAT
PO 2	**Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.	3	CIE/Quiz/AAT

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

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

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

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.

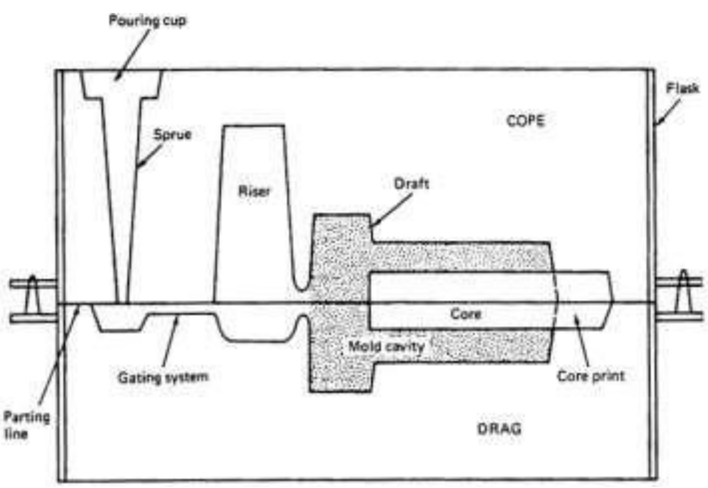
Typical sand molds have the following parts:

• 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**.



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 down sprue, 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.

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:

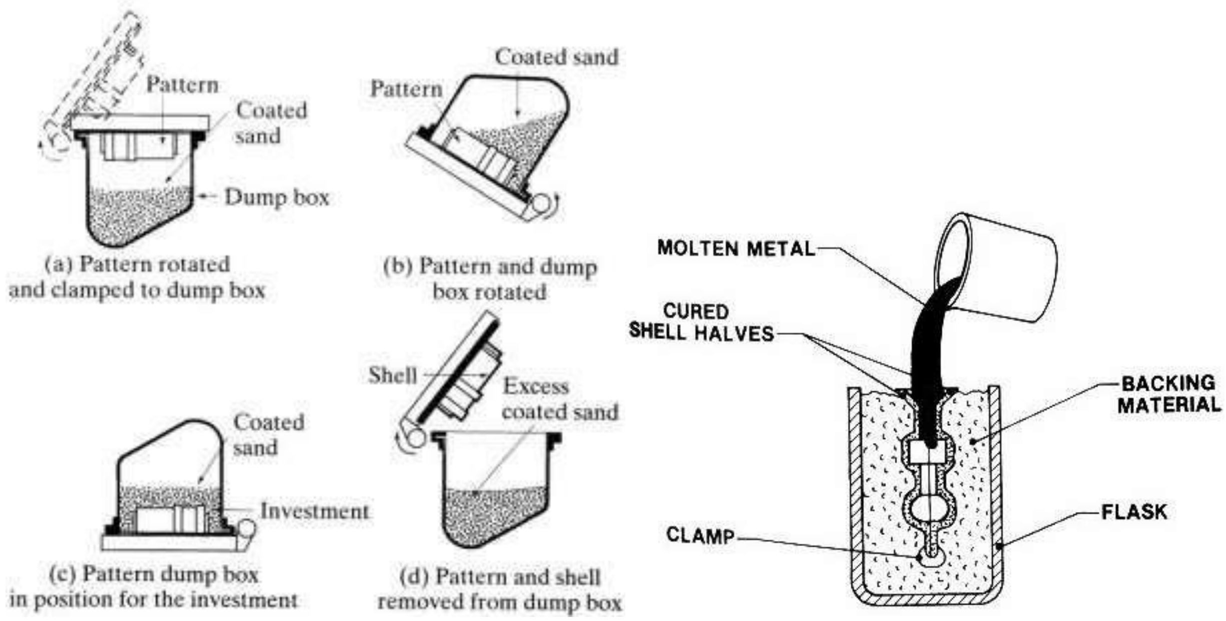
The dry free flowing sand used in the shell mould must be completely free of clay content. The grain size of the sand used in shell molding is generally in the range of 100150 meshes, as the shell casting process is recommended for castings that require good surface finish. However, depending on the 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.
- 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.



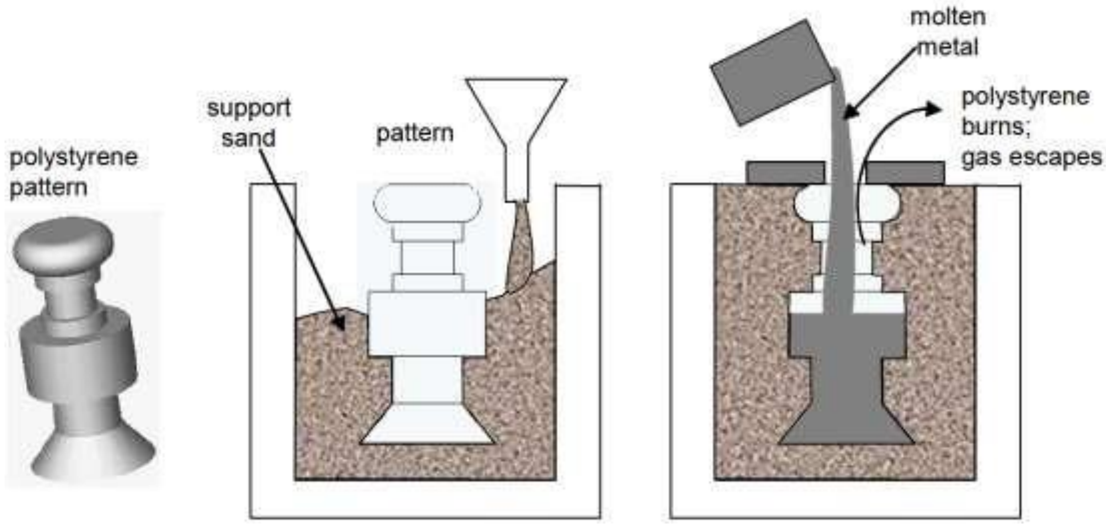
Making the shell-mold and Shell mold casting

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.
- 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.



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.

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.

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).

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 .
- 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).

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 :

1. Preparing the heat-disposable wax, plastic or polystyrene patterns in a die.

2. Assembly of the prepared patterns onto a gating system

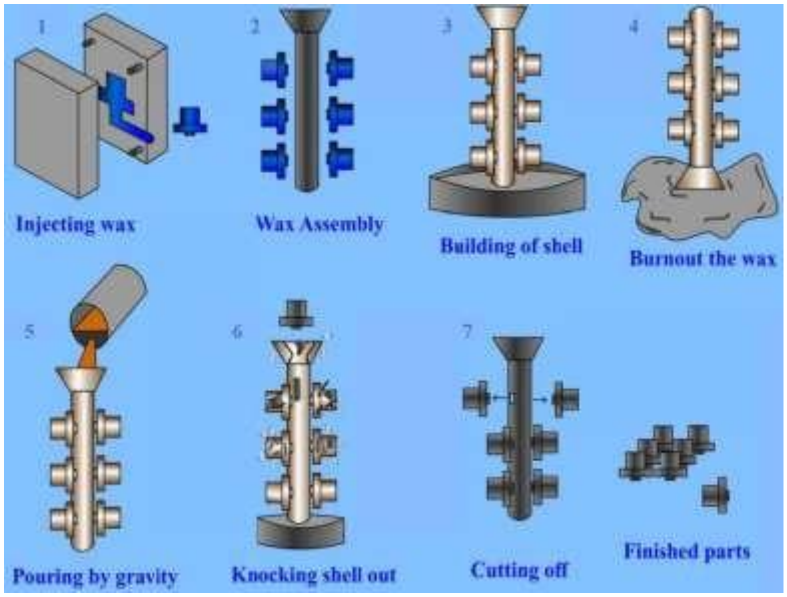
3. "Investing," (covering) the pattern assembly with a refractory slurry which builds the shell.

4. Melting the pattern assembly (burning out the wax) by firing, for removing the traces of the pattern material

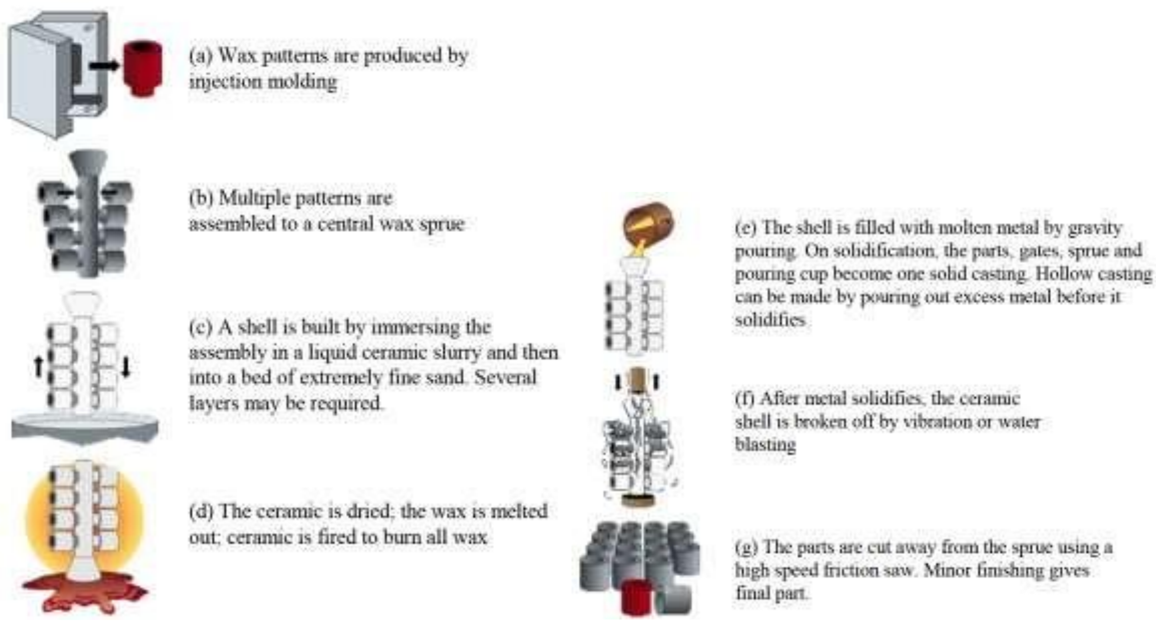
5. The metal in molten state is poured into the formed mold.

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.



The Basic Steps of the Investment Casting Process



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 Figure.

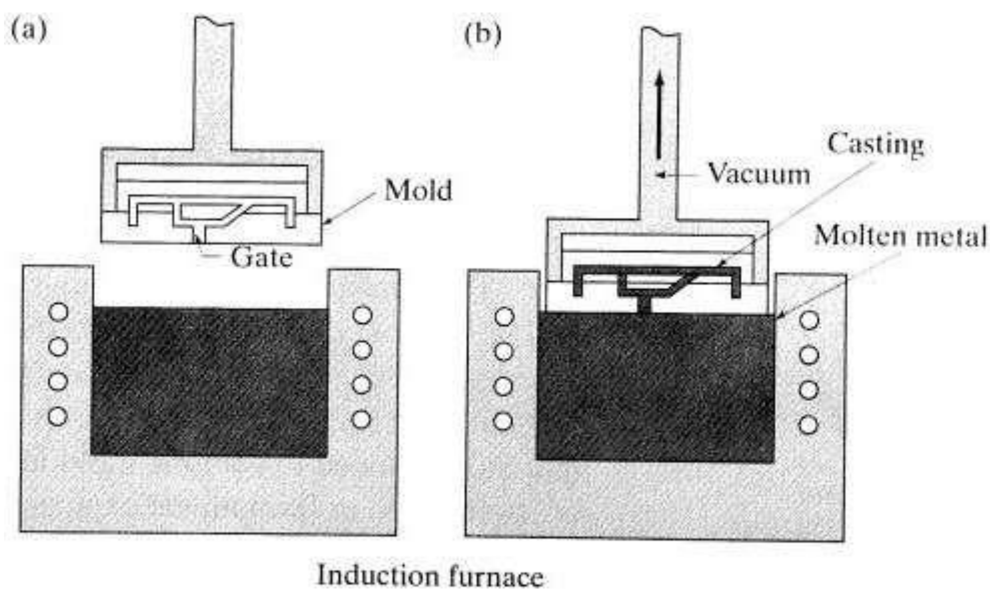
An advantage of this process is that the wax can carry very fine details – so the process not only gives good dimensional tolerances, but also excellent surface finish; in fact, almost any surface texture as well as logos etc. can be reproduced with very high level of detail.

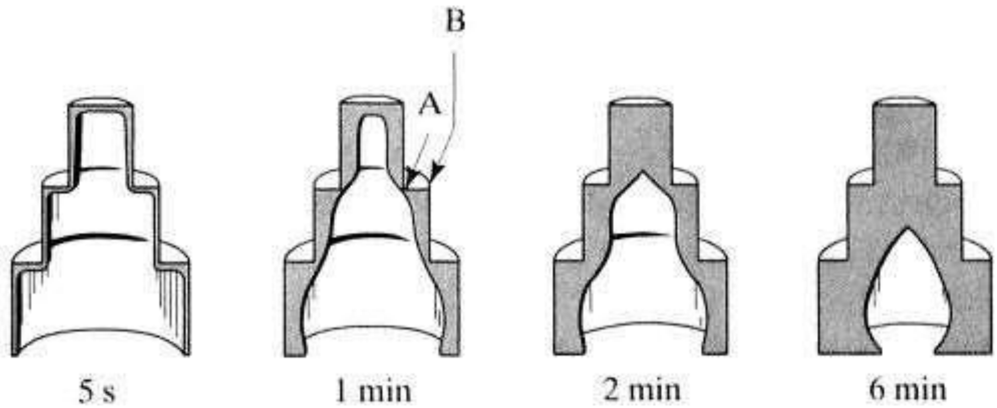
Vacuum casting

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 below 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 .

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.

Vacuum casting



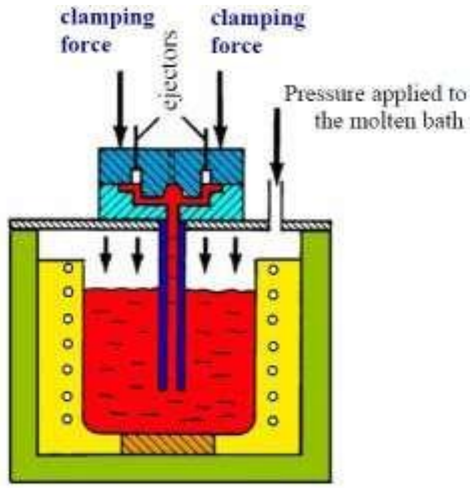


Draining out metal before solidification yields hollow castings

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.

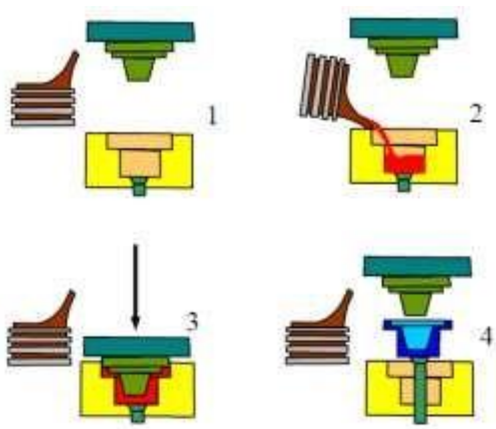
In the **pressure casting process** the molten material is forced upward by gas pressure into a graphite mould or metallic mould. The pressure is maintained until the melt has completely solidified in the mould. The molten material may also be forced upward by a vacuum, which also removes dissolved gases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



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. Thus it is a combination of casting and forging. The machinery includes a die, punch, and ejector pin.



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.

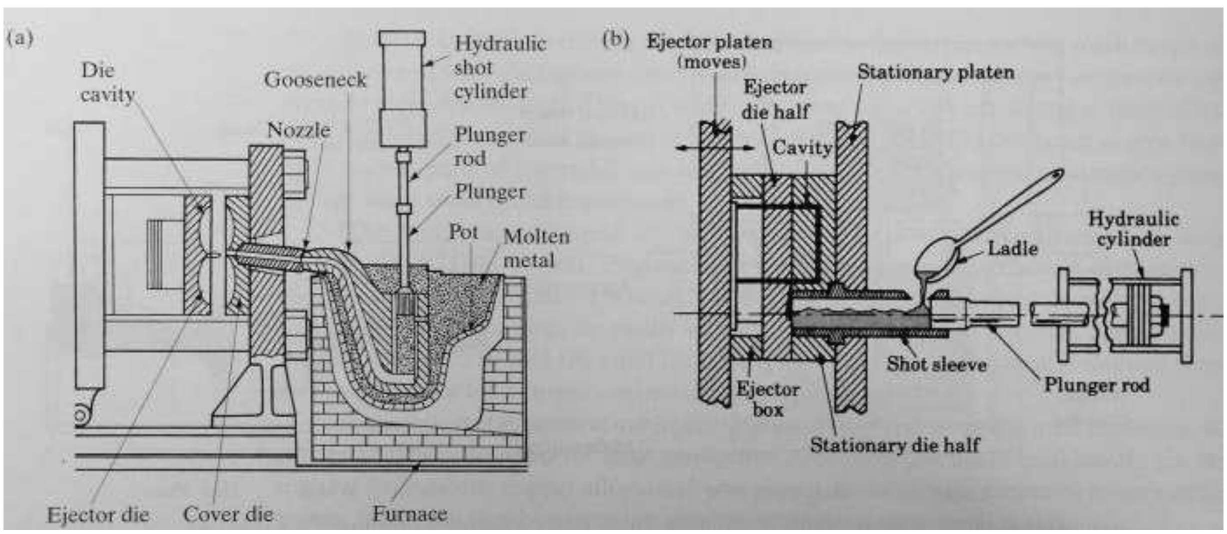
Die casting:

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.

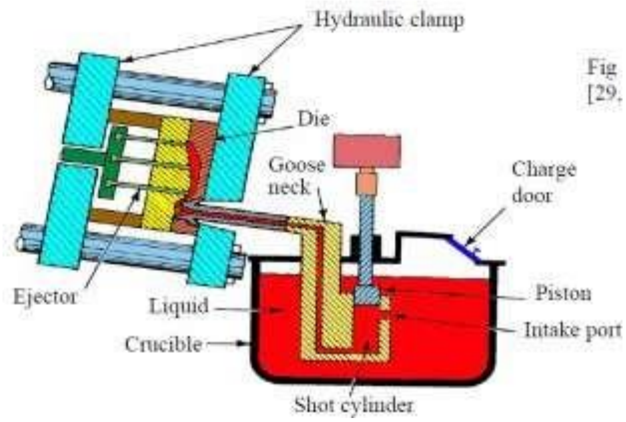
• In a cold chamber process, the molten metal is poured into the cold chamber in each cycle. The operating cycle is (i) Die is closed and molten metal is ladled into the cold chamber cylinder; (ii) plunger pushes molten metal into die cavity; the metal is held under high pressure until it solidifies; (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).



(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.

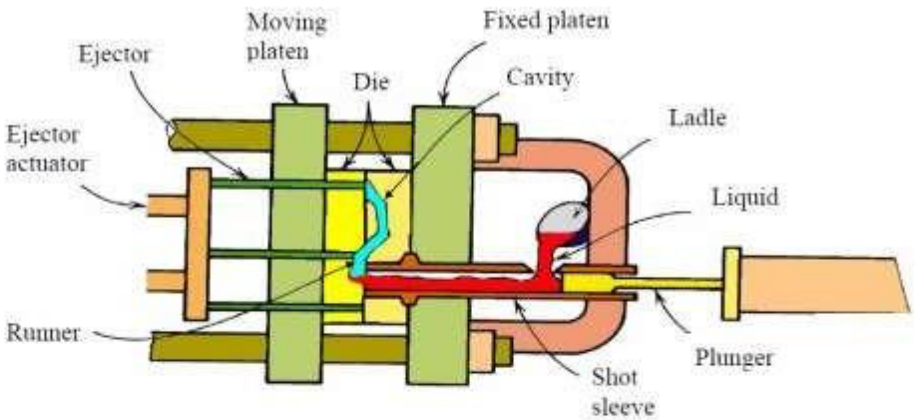


Hot-chamber process

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. 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.



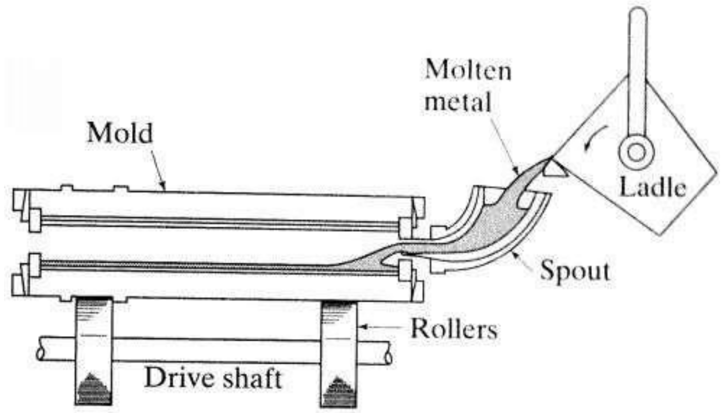
Cold-chamber process

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 favorably 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.

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.



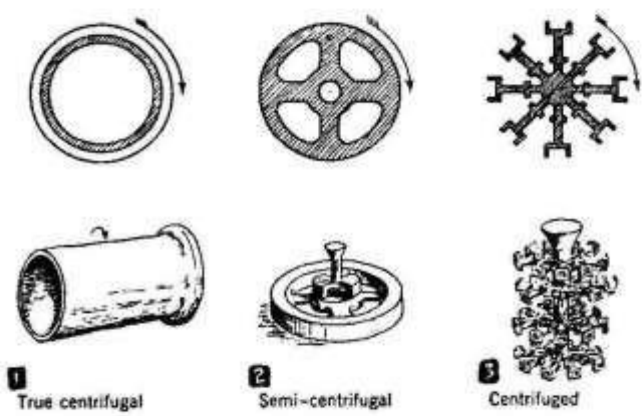
Centrifugal casting schematic

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.

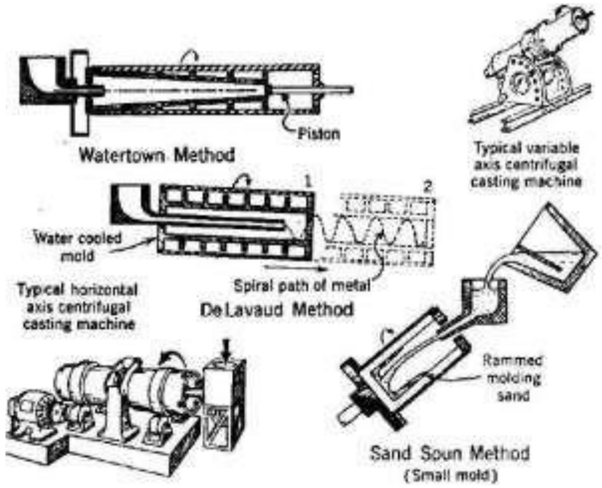
The concept of centrifugal casting is by no means a modern process. This technique which lends clarity to detail was used by Benvenuto Cellini and others in the founding arts during the 16th century. The mention of actual centrifugal casting machines is first recorded when a British inventor, A.G. Eckhardt, 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 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**)**.



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.

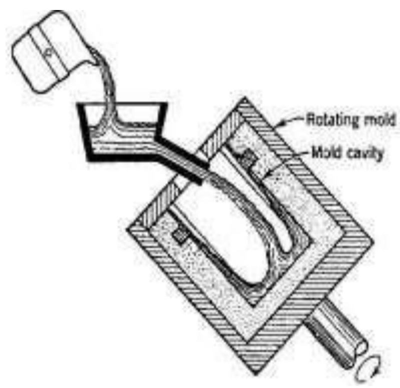
The first of these is seen in pouring, where the force can be used to distribute liquid metal over the outer surfaces of a mold. This provides a means of forming hollow cylinders and other annular shapes. The second is the development of high pressure in the casting during freezing. This, in conjunction 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.

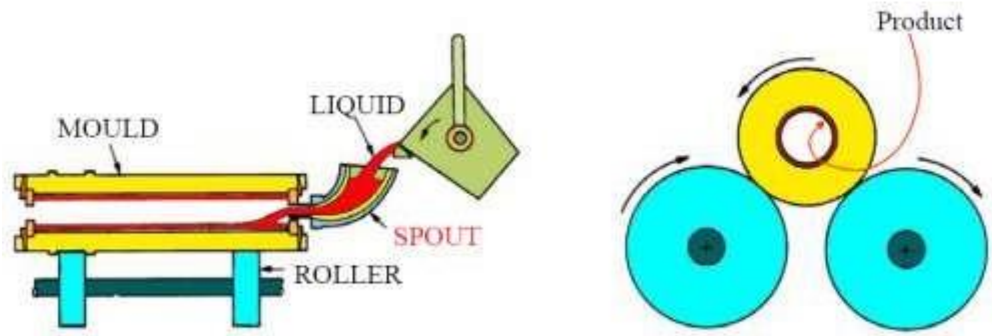
Considering first the casting of a plain cylinder, conditions can be seen to be highly favorable to directional solidification owing to the marked radial temperature gradient extending from the mold wall. Under these conditions the central mass of liquid metal, under high pressure, has ready access to 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."



True Centrifugal Casting



True Centrifugal Casting

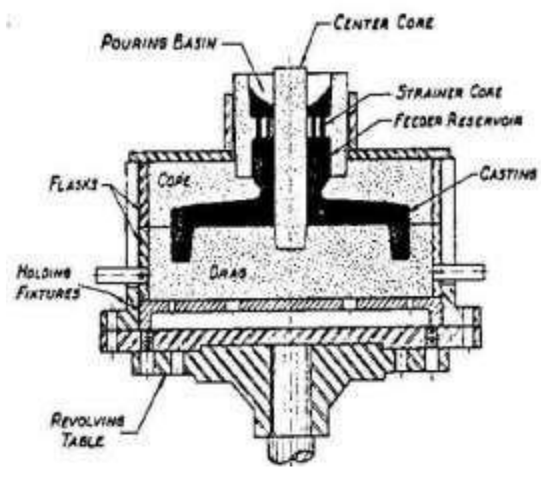
In **true centrifugal casting**, hollow cylindrical parts, e.g. pipes and lampposts, are produced by pouring liquid into a rotating mould. The axis of rotation is usually horizontal but can also be vertical. Moulds are made of steel, cast iron, or graphite and may be coated with a refractory lining to 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 Ø13 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 down sprue 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.

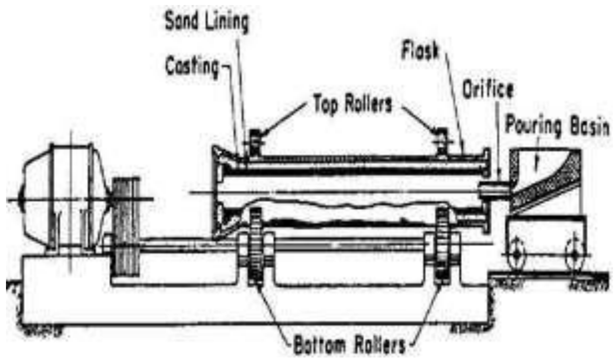
Semi-Centrifugal Casting

Such items as wheels and pulleys are occasionally cast in a semi-centrifugal setup as illustrated in 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 nonmetallic inclusions and trapped gas toward the center and into the feeder for elimination.



Semi-Centrifugal Casting

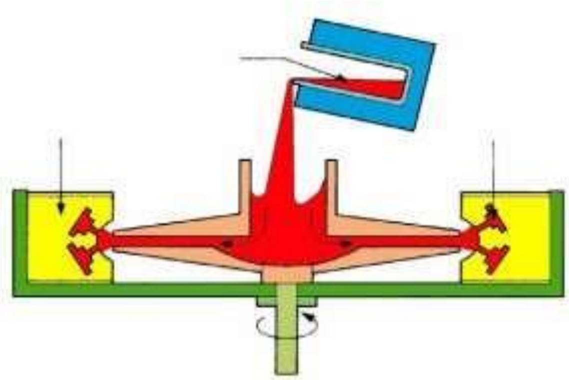
In true or open bore casting, circumferential velocity is imparted from mold to metal by frictional forces at the mold surface and within the liquid. In horizontal axis casting, the metal entering the mold must rapidly acquire sufficient velocity to prevent instability and "raining" as it passes over 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.



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.

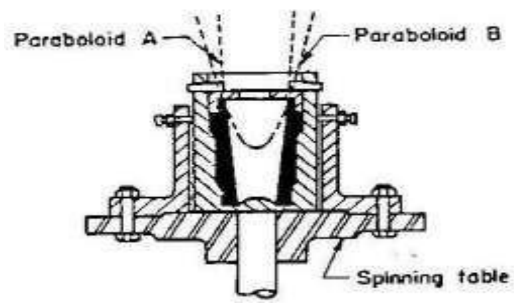
In **Centrifuging** mould cavities of odd shape are placed at a certain distance from the axis of rotation. The molten material is forced into the mould by centrifugal forces. The attributes within the castings vary with the distance from the axis of rotation.



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 non metallics 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 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.



Vertical Centrifugal Casting

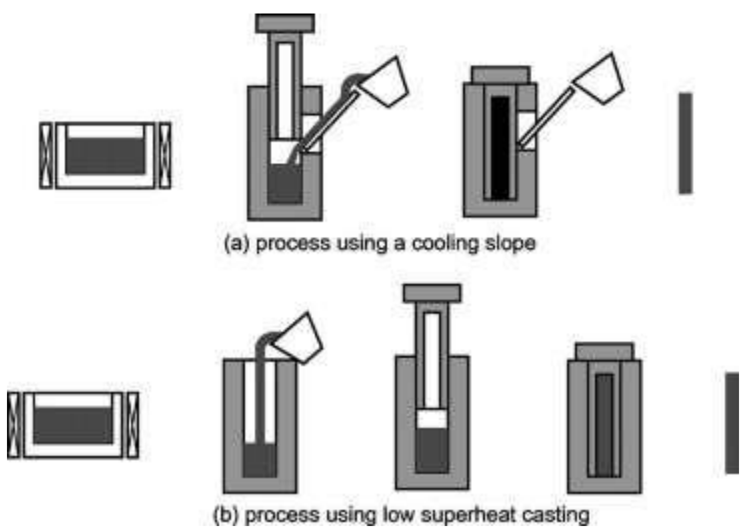
The vertical axis centrifugal casting method is not suited to the production of pipelike shapes because of the inherent taper on the inside. Likewise, it is not suited to the production of very long parts. It finds its greatest application in the production of ringlike shapes. Because the inside contour 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 run out or machine failure.

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 thixo casting process 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.

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. The cooling 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. 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.



Two kinds of Rheocasting process

Continuous Casting

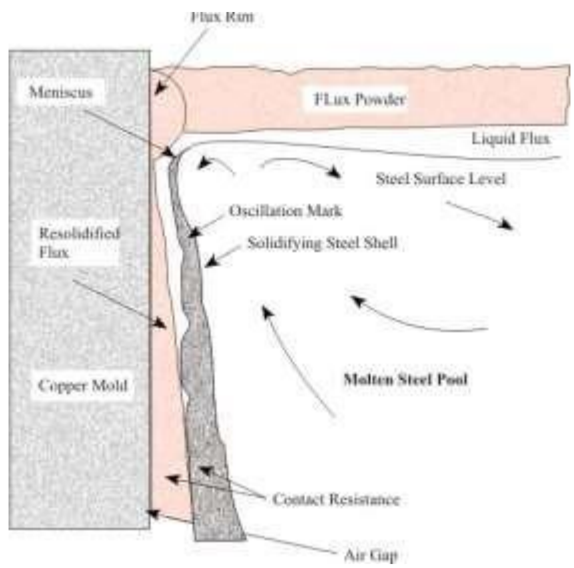
Continuous casting transforms molten metal into solid on a continuous basis and includes a variety of important commercial processes. These processes are the most efficient way to solidify large volumes of metal into simple shapes for subsequent processing. Most basic metals are mass-produced using a 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.

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. Control of height of molten steel in the mould is crucial for the success of the continuous casting.



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.

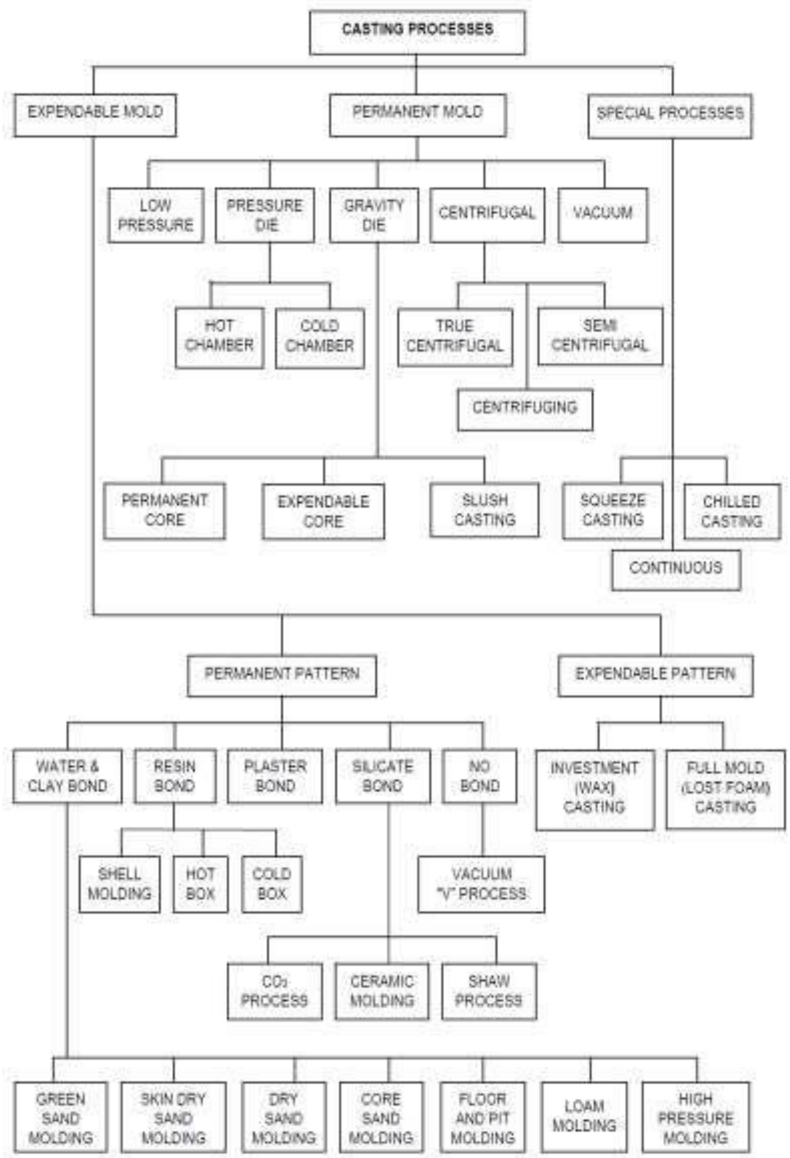
- Low viscosity
- Low liquidus temperature
- Melting rate of flux must match with the speed of the continuous casting.

The Capabilities of major casting processes are compared in Table .

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.

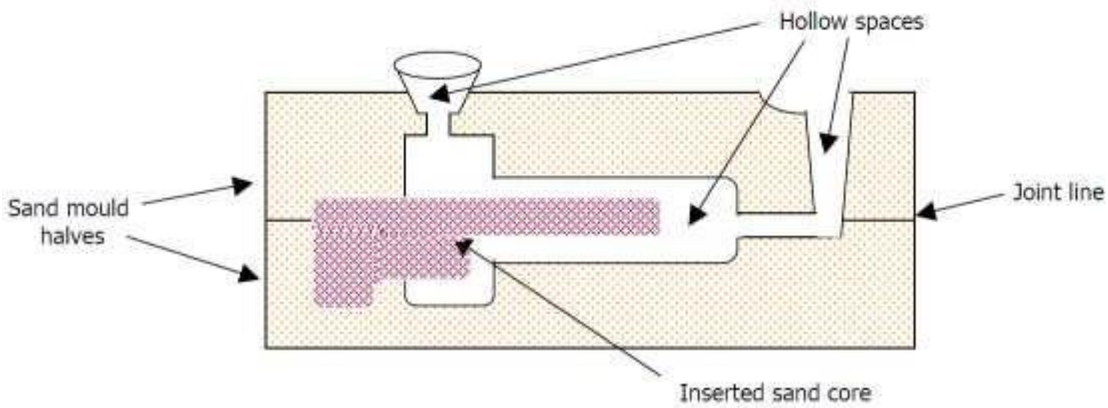


Hierarchical classification of various casting processes

Sand mould and core making

Sand casting is the most common production technique, 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 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.



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.

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

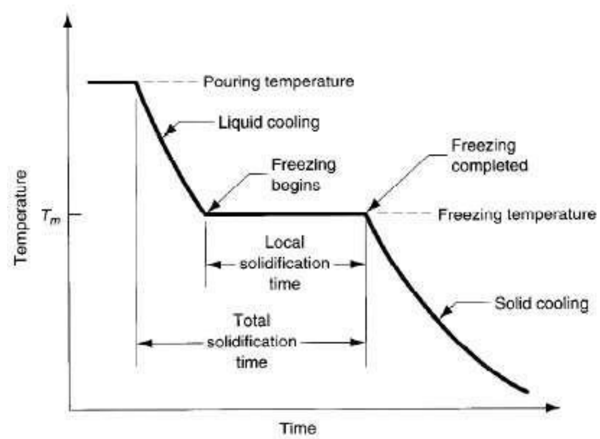
•For this step to be successful, metal must flow into all regions of the mold, most importantly the main cavity, before solidifying

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

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)



Cooling curve for a pure metal during casting

Solidification of Pure Metals

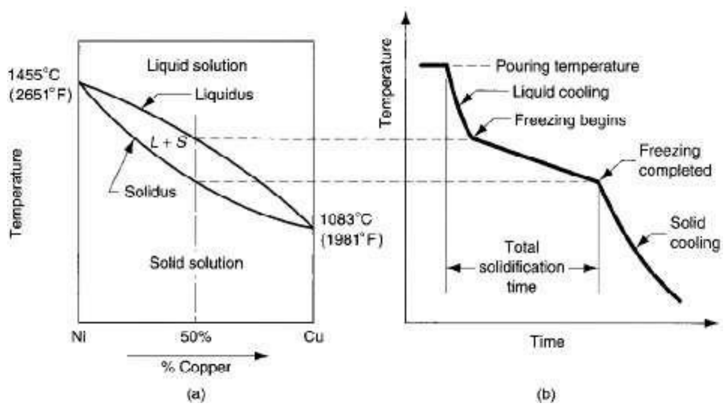
•Due to chilling action of mold wall, a thin skin of solid metal is formed at the interface immediately after pouring

•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

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

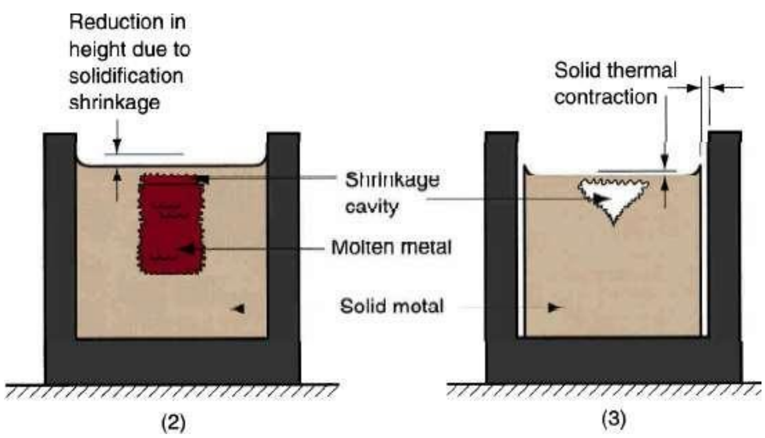
Most alloys freeze over a temperature range rather than at a single temperature



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

Characteristic grain structure in an alloy casting, showing segregation of alloying components in center of casting.

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)



(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

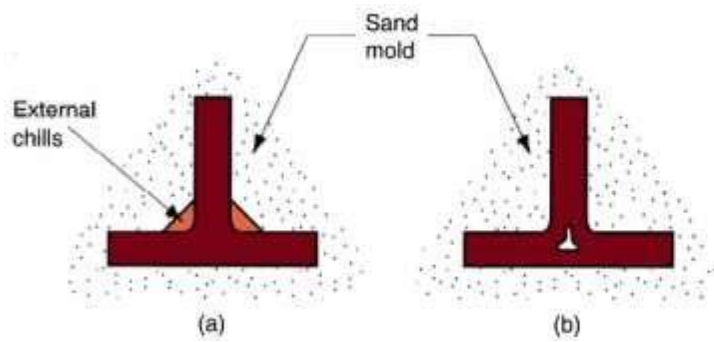
The term *directional solidification* describes this aspect of freezing and methods by which it is controlled

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



(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

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. 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 the difficulty in casting and machining. Table 3 lists the major metals in use today (by weight) along with their main characteristics and typical applications.

Introduction to Casting Defects:

Some defects are common to any and all process. These defects are illustrated in and briefly described in the following:

There are numerous opportunities in the casting operation for different defects to appear in the cast product. Some of them are common to all casting processes:

Misruns: Casting solidifies before completely fill the mold. Reasons are low pouring temperature, slow pouring or thin cross section of casting.

Cold shut: Two portions flow together but without fusion between them. Causes are similar to those of a misrun.

Cold shots: When splattering occurs during pouring, solid globules of metal are entrapped in the casting. Proper gating system designs could avoid this defect.

Shrinkage cavity: Voids resulting from shrinkage. The problem can often be solved by proper riser design but may require some changes in the part design as well.

Micro porosity: Network of small voids distributed throughout the casting. The defect occurs more often in alloys, because of the manner they solidify.

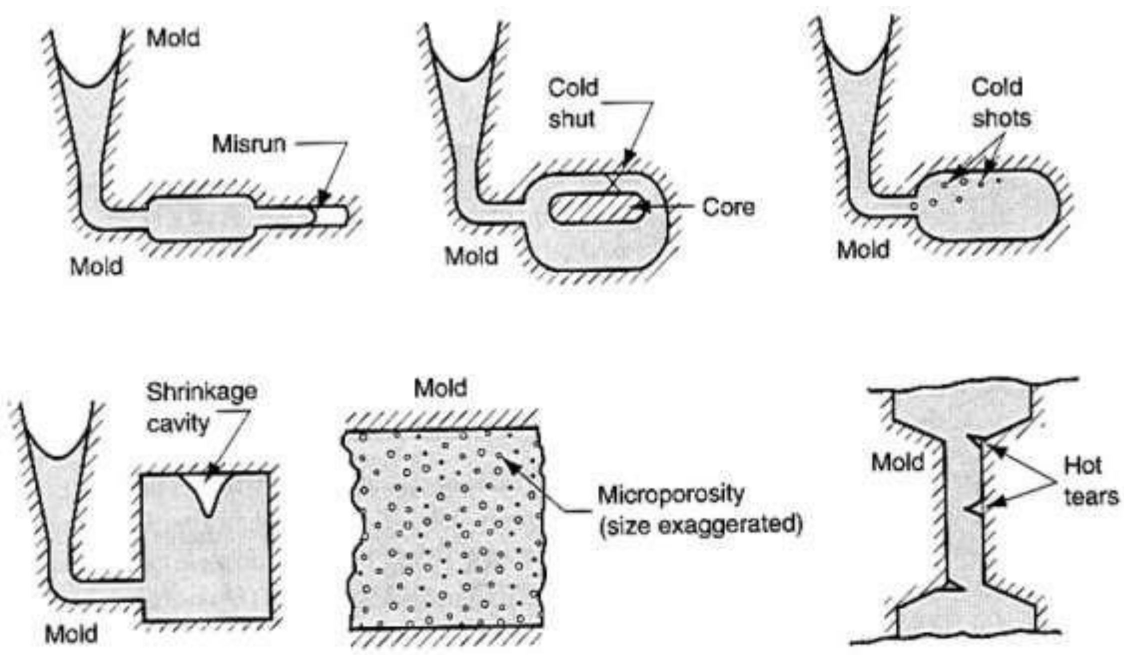
Hot tearing: Cracks caused by low mold collapsibility. They occur when the material is restrained from contraction during solidification. A proper mold design can solve the problem.

Some defects are typical only for some particular casting processes, for instance, many defects occur in sand casting as a result of interaction between the sand mold and the molten metal. Defect found primarily in sand casting are gas cavities, rough surface areas, shift of the two halves of the mold, or shift of the core, etc.

a) Misruns: A Misruns is a casting that has solidified before completely filling the mold cavity. Typical causes include

1) Fluidity of the molten metal is insufficient,
2) Pouring Temperature is too low,
3) Pouring is done too slowly and/or
4) Cross section of the mold cavity is too thin.

b) Cold Shut: A cold shut occurs when two portion of the metal flow together, but there is lack of fusion between them due to premature freezing, Its causes are similar to those of a Misruns.



Some common defects in castings

c) Cold Shots: When splattering occurs during pouring, solid globules of the metal are formed that become entrapped in the casting. Poring procedures and gating system designs that avoid splattering can prevent these defects.

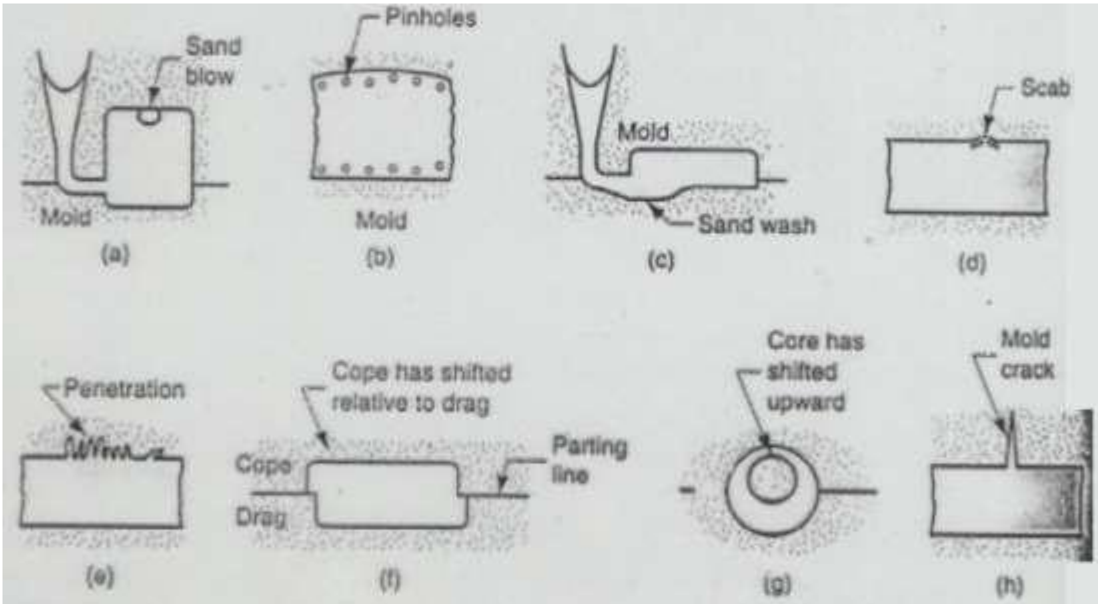
d) Shrinkage Cavity: These defects are a depression in the surface or an internal void in the casting caused by solidification shrinkage that restricts the amount of the molten metal available in the last region to freeze. It often occurs near the top of the casting in which case it is referred to as a pipe. The problem can often be solved by proper riser design.

e) Microporosity: This refers to a network of a small voids distributed throughout the casting caused by localized solidification shrinkage of the final molten metal in the dendritic structure. The defect is usually associated with alloys, because of the protracted manner in which freezing occurs in these metals.

f) Hot Tearing: This defect, also called hot cracking, occurs when the casting is restrained or early stages of cooling after solidification. The defect is manifested as a separation of the metal (hence the terms tearing or cracking) at a point of high tensile stress caused by metal's inability to shrink naturally. In sand casting and other expandable mold processes, compounding the mold to be collapsible prevents it. In permanent mold processes, removing the part from the mold immediately after freezing reduces hot tearing.

Some defects are related to the use of sand molds and therefore they occur only in sand castings. To a lesser degree, other expandable mold processes are also susceptible to these problems. Defects found primarily in sand castings are:

a) Sand Blow: This defect consists of a balloon-shaped gas cavity caused by release of mold gases during pouring. It occurs at or below the casting surface near the top of the casting. Low permeability, poor venting and high moisture content of the sand mold are the usual causes.



Other defects found primarily in sand castings

b) Pinholes: A defect similar to a sand blow involves the formation of many small gas cavitiesat or slightly below the surface of the casting.

c) Sand Wash: A wash is an irregularity in the surface of the casting that results from erosion of the sand mold during pouring. The contour of the erosion is imprinted into surface of the final cast part.

d) Scabs: This is a rough area of the casting due to encrustations of sand and metal. It is caused by portions of the mold surface flaking off during solidification and becoming embedded in the casting surface.

e) Penetration: When the fluidity of the liquid metal is high, it may penetrate into the sand mold or sand core after freezing, the surface of the casting consists of a mixture of sand grins and metal. Harder packing of the sand molds helps to alleviate this condition.

f) Mold Shift: This is manifested as a step in the cast product at the parting line caused by sidewise displacement of the cope with respect to the drag.

g) Core Shift: A similar movement can happen with the core but the displacement is usually vertical. Core shift and mold shift are caused by buoyancy of the molten metal.

h) Mold Crack: If mold strength is insufficient a crack may develop in to which liquid metal can seep to form a fin on the final casting.

Inspections of Casting

Foundry inspection procedures include;

a. Visual Inspection to detect obvious defects, such as Misruns, cold shut and severe surface flaws;

b. Dimensional measurements to ensure that tolerances have been met;

c. Metallurgical, chemical, physical and other tests concerned with the inherent quality of the cast metal. Tests in category 3 include

1) Pressure testing to locate leaks in the casting

2) Radiographic methods, magnetic particle tests, the use of fluorescent penetrants and supersonic testing to detect either surface or internal defects in the casting;

3) Mechanical testing to determine properties such as tensile strength and hardness. If defects are discovered but are not too serious, it is often possible to save the casting by welding, grinding or other salvage methods to which the customer has agreed.

Visual inspection

Visible defects that can be detected provide a means for discovering errors in the pattern equipment or in the molding and casting process. Visual inspection may prove inadequate only in the detection of sub surface or internal defects.

Dimensional inspection

Dimensional inspection is one of the important inspections for casting. When precision casting is required, we make some samples for inspection the tolerance, shape size and also measure the profile of the cast. This dimensional inspection of casting may be conducted by various methods:

- Standard measuring instruments to check the size of the cast.

- Contour gauges for the checking of profile, curves and shapes
- Coordinate measuring and Marking Machine
- Special fixtures

X-Ray Radiography

In all the foundries the flaw detection test are performed in the casting where the defects are not visible. This flaw detection test is usually performed for internal defects, surface defects etc. These tests are valuable not only in detecting but even in locating the casting defects present in the interior of the casting. Radiography is one of the important flaw detection test for casting. The radiation used in radiography testing is a higher energy (shorter wavelength) version of the electromagnetic waves that we see as visible light. The radiation can come from an X-ray generator or a radioactive source.

Magnetic particle inspection

This test is used to reveal the location of cracks that extend to the surface of iron or steel castings, which are magnetic nature. The casting is first magnetized and then iron particles are sprinkled all over the path of the magnetic field. The particles align themselves in the direction of the lines of force. A discontinuity in the casting causes the lines of the force to bypass the discontinuity and to concentrate around the extremities of the defect.

Fluorescent dye-penetration test

This method is very simple and applied for all cast metals. It entails applying a thin penetration oil-base dye to the surface of the casting and allowing it to stand for some time so that the oil passes into the cracks by means of capillary action. The oil is then thoroughly wiped and cleaned from the surface. To detect the defects, the casting is pained with a coat of whitewash or powdered with tale and then viewed under ultraviolet light. The oil being fluorescent in nature, can be easily detect under this light, and thus the defects are easily revealed.

Ultrasonic Testing

Ultrasonic testing used for detecting internal voids in casting is based on the principle of reflection of high frequency sound waves. If the surface under test contains some defect, the high frequency sound waves when emitted through the section of the casting, will be reflected from the surface of defect and return in a shorter period of time.

The advantage this method of testing over other methods is that the defect, even if in the interior, is not only detected and located accurately, but its dimension can also be quickly measured without in any damaging or destroying the casting.

Fracture test

Fracture test is done by examining a fracture surface of the casting. it is possible to observe coarse graphite or chilled portion and also shrinkage cavity, pin hole etc. The apparent soundness of the casting can thus be judged by seeing the fracture.

Macro-etching test (macroscopic examination)

The macroscopic inspection is widely used as a routine control test in steel production because it affords a convenient and effective means of determining internal defects in the metal. Macro-etching may reveal one of the following conditions:

- Crystalline heterogeneity, depending on solidification
- Chemical heterogeneity, depending on the impurities present or localized segregation and
- Mechanical heterogeneity, depending on strain introduced on the metal, if any.

Sulphur Print test

Sulphur may exist in iron or steel in one of two forms; either as iron sulphide or manganese sulphide. The distribution of sulphur inclusions can easily examined by this test.

Microscopic Examination

Microscopic examination can enable the study of the microstructure of the metal alloy, elucidating its composition, the type and nature of any treatment given to it, and its mechanical properties. In the case of cast metals, particularly steels, cast iron, malleable iron, and SG iron, microstructure examination is essential for assessing metallurgical structure and composition. Composition analysis can also be done using microscopic inspection. Distribution of phase can be observed by metallographic sample preparation of cast product. Grain size and distribution, grain boundary area can be observed by this procedure. Distribution of nonmetallic inclusion can also be found from this process of inspection.

Chill Test

Chill test offers a convenient means for an approximate evaluation of the graphitizing tendency of the iron produced and forms an important and quick shop floor test for ascertaining whether this iron will be of the class desired. In chill test, accelerated cooling rate is introduced to induce the formation of a chilled specimen of appropriate dimension. It is then broken by striking with a hammer in such a manner that the fracture is straight and midway of its length. The depth of chill obtained on the test piece is affected by the carbon and silicon present and it can therefore be related to the carbon equivalent, whose value in turn determines the grade of iron.

Metal Casting Design

The principles of successful casting design involve a systematic blend of experience and engineering basics to allow the creation of a successful casting, from inception through production. The major components of the design process are outlined in the six steps listed below and described graphically and schematically in the figure shown.

Pattern Design

Pattern making is a time - honored skill which is an integral part of the casting process. Patterns are routinely produced from wood, plastics, and metals depending upon the complexity of the casting being produced, on the number of castings required and obviously on the capability of the pattern shop that is involved. The design of patterns must include the following components:

a). An allowance for the solid state shrinkage that will always accompany the casting as it cools from the melting temperature to room temperature. This will depend upon the metal being cast, each of which will have its own unique coefficient of thermal expansion, α. For 7 example, α for aluminum at 20 oC is 23.9 x 10-6 in/inoC, for iron is
11.7 x 10-6 in/inoC and that for copper is 16.5 x 10-6 in/in oC (see page 50 - 51). Thus the linear dimensions of the pattern will always be larger than the casting by an amount determined by the linear expansion coefficient. Of course the expansion coefficients for each of the above materials will change somewhat with temperature and so the pattern maker will usually give a generous

allowance to cover the temperature dependence of the expansion coefficient.

b). Inclusion of a draft angle so that the pattern can be removed from the mold (or in the case of die casting or permanent mold casting, so the casting can be removed from the metal die) after the molding sand has been rammed around the pattern. These draft angles can vary from of enough extra stock to allow for variations in casting dimensions due to mold preparation, pattern wear, etc. This amount will depend greatly upon the casting process being employed. For example the amount of “extra” stock will be typically greater for a sand casting than for a die casting. Machining and process tolerances are typically greater for sand castings than for permanent mold castings.

Details on pattern making can be found in several publications form the American Foundry Society (AFS).

Fluid Flow and Gating Design

A major factor in making a good casting is the ability to get the metal from the container into the mold with a minimum of turbulence, slag, entrapped sand or other materials in the mold or molten metal system which could get swept into the mold cavity. Accomplishing this task consistently requires a basic understanding of fluid flow principles as well as the insight provided by experience. Consider the following simple fluid flow system.

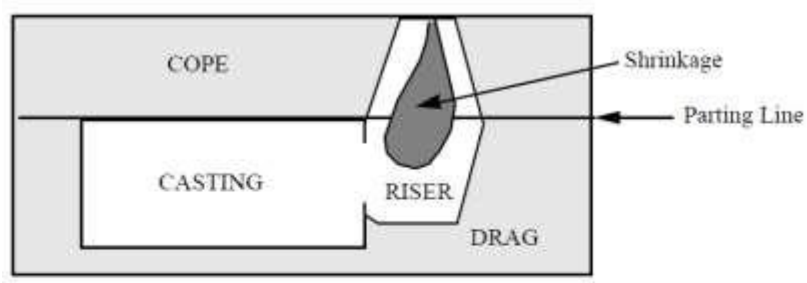
The above ratio of sprue base area to runner cross sectional area to ingate area is called the gating ratio, a common way to quantitatively describe gating systems. Filling times for just such a casting has been experimentally measured at Michigan Tech for a number of years in which the head (Distance from top of pouring basin to the parting line) and the ingate cross sectional area were independently varied to control flow rates

Pressure at Intermediate Point in Gating System

It is important to keep the actual pressure within a flowing liquid in a sand mold above atmospheric pressure. If the pressure in the molten metal drops below 1 atmosphere then air can be draw in or “aspirated” into the metal stream, thereby increasing the opportunity for defects within the casting. These defects could include the formation of metal oxides or gas porosity, a particularly troublesome problem in aluminum alloy castings which absorb hydrogen so readily in the liquid state.The number of gates needed to fill a casting cavity in an acceptable time is determined by the size of the casting as well as the casting complexity, both factors which are dealt with using experience and a certain amount of common sens

Shrinkage, Riser Design

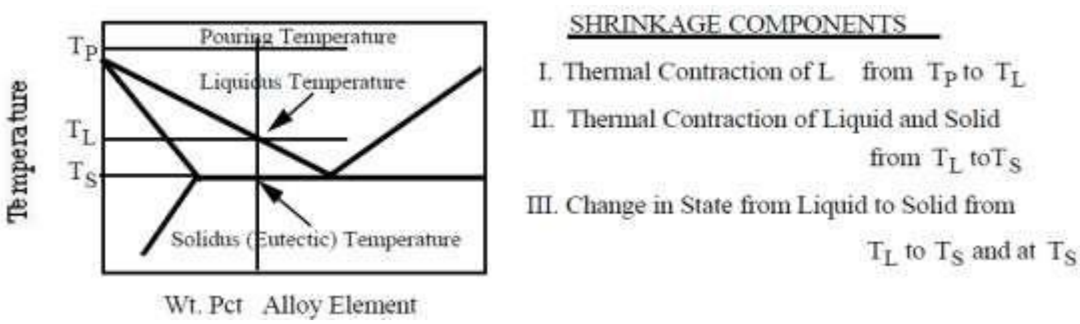
Risers are used in the production of castings for the purpose of providing molten metal for the solidifying and shrinking casting. Riser design in sand castings requires, at a minimum, that the riser solidify after the casting. A casting and riser are shown schematically in a sand mold below. The desired situation after solidification would result in all the shrinkage within the riser as illustrated .



Schematic diagram of Shrinkage

Shrinkage in Metals during Solidification

The shrinkage that occurs during solidification of metals (that ideally all ends up in the shrinkage cavity in the riser shown above) results from three distinct contributions which are illustrated below for an alloy in a eutectic system which solidifies over a temperature range (most alloys do not solidify at one temperature).



Shrinkage in Metals

The total amount of shrinkage experienced during solidification may be quite large, especially for aluminum alloys, which can shrink 6.5% during the change in state. The number of risers needed to effectively feed a casting depends upon casting geometry and feeding distance required.

Design Recommendations for Casting

1. Compensate the shrinkage of the solidified molten metal by making patterns of slightly oversize.
2. In sand casting, it is more economical and accurate if the parting line is on a flat plane. Contoured parting lines are not economical. Further, some degree of taper, or draft is

recommended to provide to the pattern for its easy removal. The recommended draft angles for patters under various conditions are given elsewhere.

3. In sand casting, it is recommended to attach the raiser near to the heavier section. The thinnest sections are farthest from the raiser and solidify first and then the solidification proceeds toward the direction of raiser i.e. towards the heavier section.
4. Sharp corners in a casting design cause uneven cooling and lead to formation of hot spots in the final cast structure. Moreover sharp corner in a casting structure acts as a stress raiser. Rounding the corner decreases the severity of the hot spot and lessens the stress concentration.
5. Abrupt changes in sections should be avoided. Fillets and tapers are preferable to sharp steps
6. The interior walls and sections are recommended to be 20% thinner than the outside members to reduce the thermal and residual stresses, and metallurgical changes.
7. When a hole is placed in a highly stressed section, add extra material around the hole as reinforcement.
8. To minimize the residual stresses in the gear, pulley or wheel casting, a balance between the section size of the rim, spokes and hub is maintained.
9. An odd number of curved wheel spokes reduce cast-in-residual stresses.
10. Similar to sand casting, permanent mold castings also require draft for the easy withdrawal of the casting from the mold. The recommended draft angles are given elsewhere.
11. Due to pattern shrinkage, investment shrinkage and metal shrinkage during solidification, there is always a tendency for an investment part to “dish” (develop concave surfaces where flat surfaces are specified). This condition takes place in areas of thick cross section. Dishing is minimized by designing parts with uniformly thin walls.

MODULE-II
WELDING

COURSE OUTCOMES (COs):

At the end of the course students are able to:		
Course Outcomes		Knowledge Level (Bloom's Taxonomy)
CO3	**Categorize** various defects and shortcomings during gas welding operation such as TIG, MIG and Spot welding etc. for real time applications.	Understand
CO4	**Illustrate** the properties and bonding techniques of plastics and various plastic molding techniques.	Understand

PROGRAM OUTCOMES (POs):

Program Outcomes (POs)		Strength	Proficiency Assessed by
PO 1	**Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.	3	CIE/Quiz/AAT
PO 2	**Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.	3	CIE/Quiz/AAT

Introduction to Welding

A welding arc is an electric discharge that develops primarily due to flow of current from cathode to anode. Flow of current through the gap between electrode and work piece needs column of charged particles for having reasonably good electrical conductivity. These charged particles are generated by various mechanisms such as thermal emission, field emission secondary emission etc. Density of charged particles in gap governs the electrical conductivity of gaseous column. In an electric arc, electrons released from cathode (due to electric field or thermo-ionic emission) are accelerated towards the anode because of potential difference between work piece and electrode. These high velocity electrons moving from cathode toward anode collide with gaseous molecules and decompose them into charged particles i.e. electrons and ions. These charged particles move towards electrode and work piece as per polarity and form a part of welding current. Ion current becomes only about 1% of electron current as ions become heavier than the electrons so they move slowly. Eventually electrons merge into anode. Arc gap between electrode and work piece acts as pure resistance load. Heat generated in a welding arc depends on arc voltage and welding current.

Coated Electrodes are specified based on core wire diameter. Commonly used electrode diameters are 2, 2.5, 3.18, 4, 5 and 6 mm. Length of electrodes may depend on diameter of core wire ranging from 250 to 450 mm i.e. larger the core diameter larger the length. However, special electrodes may be of 8-10 mm diameter. Table gives the details of electrode sizes and currents.

The electrodes are also specified based on ratio of diameter of coated portion of electrode to core wire diameter. If this ratio is lesser than 1.2 then electrodes are thin coated, if ratio ranges between 1.2 to 1.5 then medium coated and if ratio exceeds 1.5 then electrodes are heavy coated or thick coated. This ratio may vary slightly in different codes. Thin coated electrodes have very good bridgeability at the joint gap but weld bead has coarse ripples and penetration is also poor. Medium coated electrodes lead to reasonably good bridgeability, medium ripples in weld bead and modest penetration.

Thick coated electrodes have poor bridgeability, however, bead appearance is excellent with fine ripples and also excellent penetration.

The ingress of oxygen and nitrogen from the atmosphere to the weld pool and arc environment would cause embrittlement and porosity in the weld metal and this must be prevented. The Actual method of arc shielding from atmospheric nitrogen and oxygen attack varies with different type of electrodes which are in two main categories.

1. Bulk of covering material converts to a gas by the heat of the arc, only a small amount of slag is produced. Protection depends largely upon a gaseous shield to prevent atmospheric contamination as in case of cellulosic electrode.

2. Bulk of covering material converts to a slag, only a small volume of shielding gas produced as in the case of rutile and basic coated electrodes.

Electrode coating performs many functions depending upon coating constituents, during welding to improve weld metal properties. The important functions are as follows:

1. Improve the electric conductivity in the arc region to improve the arc ignition and stabilization of the arc.

2. Formation of slag, which;

(a) Influences size of droplet.

(b) Protects the droplet during transfer and molten weld pool from atmospheric gases.

(c) Protects solidified hot metal from atmospheric gases.

(d) Reduces the cooling rate of weld seam.

3. Formation of shielding gas to protect molten metal.

4. Provide deoxidizers like Si and Mn in form of FeSi and FeMn.

5. Alloying with certain elements such as Cr, Ni, Mo to improve weld metal properties.

6. Improve deposition rate with addition of iron powder in coating.

Various constituents of electrode coating are cellulose, calcium fluoride, calcium carbonate, titanium dioxide, clay, talc, iron oxide, asbestos, potassium / sodium silicate, iron powder, ferro-maganese, powdered alloys, silica etc. Each constituent performs either one or more than one functions.

Electrode metallic core wire is the same but the coating constituents give the different characteristics to the welds. Based on the coating constituents, structural steel electrodes can be classified in the following classes;

1. Cellulosic Electrodes

   Coating consists of high cellulosic content more than 30% and TiO_2 up to 20%. These are all position electrodes and produce deep penetration because of extra heat generated during burning of cellulosic materials. However, high spatter losses are associated with these electrodes.

2. Rutile Electrodes

   Coating consists of TiO_2 up to 45% and SiO_2 around 20%. These electrodes are widely used for general work and are called general purpose electrodes.

3. Acidic Electrodes

   Coating consists of iron oxide more than 20%. Sometimes it may be up to 40%, other constituents may be TiO_2 10% and $CaCO_3$ 10%. Such electrodes produce self detaching slag and smooth weld finish and are used normally in flat position.

4. Basic Electrodes

   Coating consist of $CaCO_3$ around 40% and CaF_2 15-20%. These electrodes normally require baking at temperature of approximately 250 ° C for 1-2 hrs or as per manufacturer's instructions. Such electrodes produce high quality weld deposits which has high resistance to cracking. This is because hydrogen is removed from weld metal by the action of fluorine i.e. forming HF acid as CaF_2 generates fluorine on dissociation in the heat of arc.

Classification of Electrodes as per Indian Standard:

Structural steel electrodes were classified as per IS 814:1974 and this code was revised and the revised code is IS 814:1991.

The corresponding code is given on each packet of electrode.

IS 815:1974

As per IS 815 electrodes are designated with letters and digits. P X X X X X X S

Prefix (P) is either E or R which indicates solid extruded (E) or reinforced extruded (R) Electrode.

1 st digit – Indicates type of coating.

2 nd digit – Indicates weld positions in which electrode can be used. 3 rd

digit – Indicates welding current conditions.

4 th and 5 th digit – Indicate UTS and YS of all weld metal.

6 th digit – Requirement of minimum % elongation and absorbed energy in charpy V- notch impact test of weld metal.

Suffix (s) – P – Deep penetration electrode H –

Hydrogen controlled electrode

J, K and L – Amount of metal recovery in case of iron powder electrode

Suffix (s) are optional and may or may not be given if not applicable.

IS 814:1991

As per IS 814 electrodes are designated with letters and digits as given below: E L X X

X X S

In this code E indicates extruded solid electrode, L is a letter to designate type of coating, first digit indicates UTS and YS of deposited weld metal, second digit gives percentage elongation and impact values of weld metal deposited, third digit gives welding positions in which electrode can be used and fourth digit gives the current conditions for the use of electrode.

Suffix(s) are optional and indicate special characteristics of electrode such as H1, H2, and H3 indicate hydrogen controlled electrodes with different amount of diffusible hydrogen J, K, L indicate different amount of metal recovery in weld pool in case of iron powder electrodes and X means radiographic weld quality.

Emission of Free electrons

Free electrons and charged particles are needed between the electrode and work for initiating the arc and their maintenance. Ease of emitting electrons by a material assessed on the basis of two parameters work function and ionization potential.

Emission of electrons from the cathode metal depends on the work function. The work function is the energy (ev or J) required to get one electron released from the surface of material. Ionization potential is another measure of ability of a metal to emit the electrons and is defined as energy/unit charge (v) required for removing an electron from an atom. Ionization potential is found different for different metal. For example, Ca, K, and Na have very low ionization potential (2.1-2.3ev), while that for Al and Fe is on the higher side with values of 4 and 4.5 ev respectively. Common mechanisms through which free electrons are emitted during arc welding are described below:

Thermo-ionic emission

Increase in temperature of metal increases the kinetic energy of free electrons and as it goes beyond certain limit, electrons are ejected from the metal surface. This mechanism of emission of electron due to heating of metal is called thermo ionic emission. The temperature at which thermo-ionic emission takes place, most of the metals melt. Hence, refractory materials like tungsten and carbon, having high melting point exhibit thermo ionic electron emission tendency.

Field emission:

In this approach, free electrons are pulled out of the metal surface by developing high strength electro-magnetic field. High potential difference (107 V/cm) between the work piece and electrode is established for the field emission purpose.

Secondary emission

High velocity electrons moving from cathode to anode in the arc gap collide with other gaseous molecules. This collision results in decomposition of gaseous molecules into atoms and charged particles (electrons and ions).

Zones in Arc Gap

On establishing the welding arc, drop in arc voltage is observed across the arc gap. However, rate of drop in arc voltage varies with distance from the electrode tip to the weld pool. Generally, five different zones are observed in the arc gap namely cathode spot, cathode drop zone, plasma, anode drop zone and anode spot.

Cathode spot

This is a region of cathode wherefrom electrons are emitted. Three types of cathode spots are generally found namely mobile, pointed, and normal. There can be one or more than one cathode spots moving at high speed ranging from 5-10 m/sec. Mobile cathode spot is usually produced at current density 100-1000 A/mm2. Mobile cathode spot is generally found during the welding of aluminium and magnesium. This type of cathode spot loosens the oxide layer on reactive metal like aluminium, Mg and stainless steel. Therefore, mobile cathode spot helps in cleaning action when reverse polarity is used i.e. work piece is cathode. Pointed cathode spot is formed at a point only mostly in case of tungsten inert gas welding at about 100A/mm2. Pointed tungsten electrode forms the pointed cathode-spot. Ball shaped tip of coated steel electrode forms normal cathode spot.

Cathode drop region:

This region is very close to the cathode and a very sharp drop of voltage takes placein this zone due to cooling effect of cathode. Voltage drop in this region directly affects the heat generation near the cathode which in turn governs melting rate of the electrode in case of the consumable arc welding process with straight polarity (electrode is cathode).

Plasma:

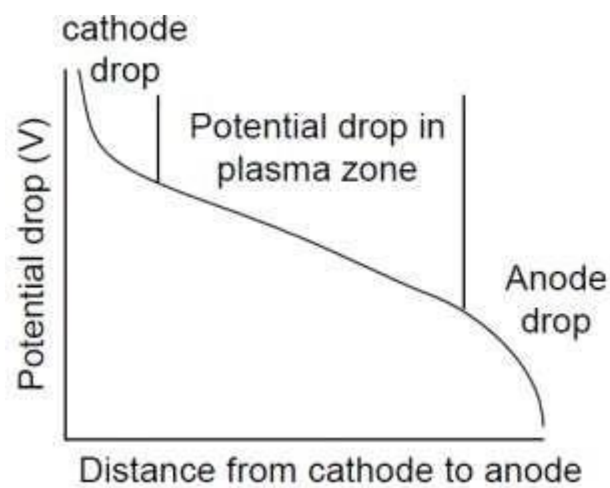
Plasma is the region between electrode and work where mostly flow of charged particles namely free electrons and positive ions takes place. In this region, uniform voltage drop takes place. Heat generated in this region has minor effect on melting of the work piece and electrode.

Anode drop region:

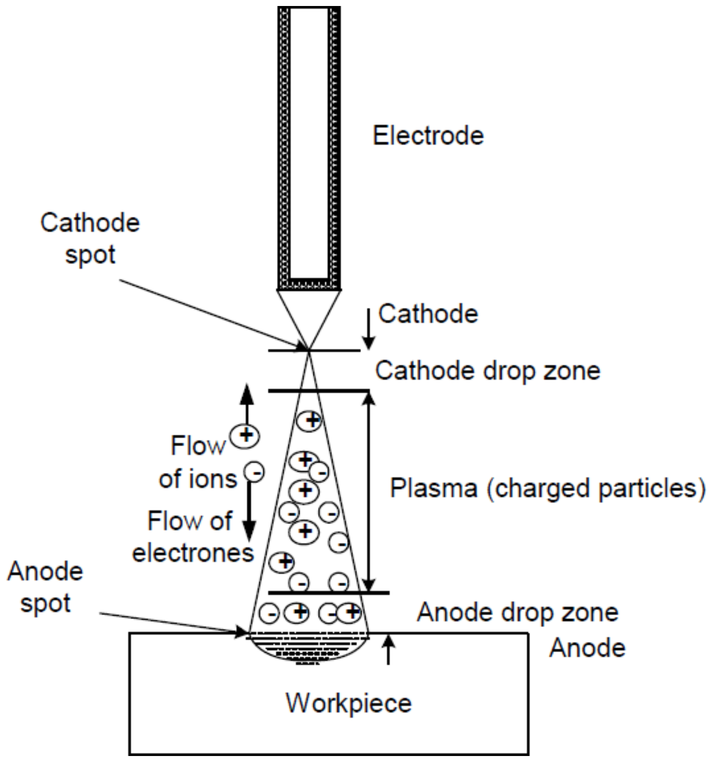
Like cathode drop region, anode drop region is also very close to the anode and a very sharp drop in voltage takes place in this region due to cooling effect of the anode. Voltage drop in this region affects the heat generation near the anode & so melting of anode. In case of direct current electrode negative (DCEN), voltage drop in this zone affects melting of the work piece.

Anode spot:

Anode spot is the region of a anode where electrons get merged and their impact generates heat for melting. However, no fixed anode spot is generally noticed on the anode like cathode spot.



Potential drop as function of distance from the cathode to anode



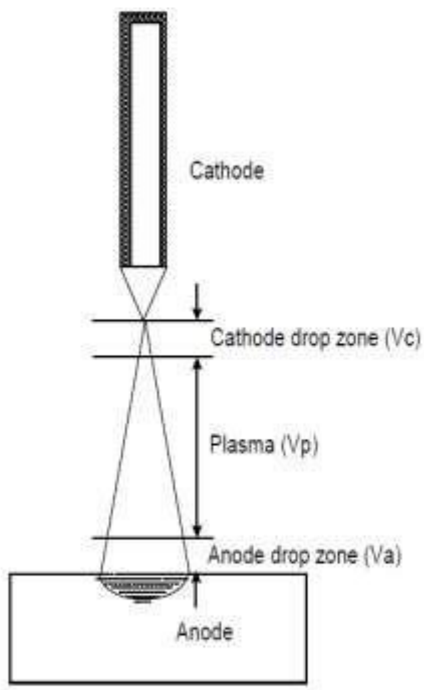
Zones in arc gap of a welding arc

Electrical Fundamentals of Welding Arc

The welding arc acts as impedance for flow of current like an electric conductor. The impedance of arc is usually found a function of temperature and becomes inversely proportional to the density of charge particles and their mobility. Therefore, distribution of charged particles in radial and axial direction in the arc affects the total impedance of the arc. Three major regions have been noticed in arc gap that accounts for total potential drop in the arc i.e. cathode drop region, plasma and anode drop region. Product of potential difference across the arc (V) and current (I) gives the power of the arc indicating the heat generation per unit time. Arc voltage (V) is taken as sum of potential drop across the cathode drop region (Vc), potential drop across the plasma region (Vp), and potential drop across the anode drop region (Va).

Power of the arc (P) = (Vc+ Vp+ Va)

Potential drop in different zones is expressed in terms of volt (V), welding current in ampere (A) and power of arc P is in watt (W). This equation suggests that the distribution of heat in three zones namely cathode, anode and arc plasma can be changed. Variation of arc length mainly affects plasma heat while shielding gas influences the heat generation in the cathode and anode drop zones. Addition of low ionization potential materials (namely potassium and sodium) reduces the arc voltage because of increased ionization in arc gap so increased electrical conductivity which in turn reduces the heat generation in plasma region. Heat generation at the anode and cathode drop zones is primarily governed by type of welding process and polarity associated with welding arc. In case of direct current (DC) welding, when electrode is connected to the negative terminal and workpiece is connected with positive terminal of the power source then it is termed as direct current electrode negative polarity (DCEN) or straight polarity and when electrode is connected to the positive terminal of the power source and workpiece is connected with negative terminal then it is termed as direct current electrode positive polarity (DCEP) or reverse polarity. TIG welding with argon as shielding gas shows 8-10 time higher current carrying capacity (without melting) than DCEP. The submerged arc welding with



DCEP generates larger amount of heat at cathode than anode as indicated by high melting rate of consumable electrode. Increase in spacing between the electrode and work-piece generally increases the potential of the arc because of increased losses of the charge carriers by radial migration to cool boundary of the plasma. Increase in the length of the arc column (by bulging) exposes more surface area of arc column to the low temperature atmospheric gas which in turn imposes the requirement of more number of charge carriers to maintain the flow of current. Therefore, these losses of charged particles must be accommodated to stabilize the arc by increasing the applied voltage. The most of the heat generated in consumable arc welding process goes to weld pool which in turn results in higher thermal efficiencies. This is more evident from the fact that the thermal efficiency of metal arc welding processes is found in range of 70- 80% whereas that for non-consumable arc welding processes is found in range of 40-60%.

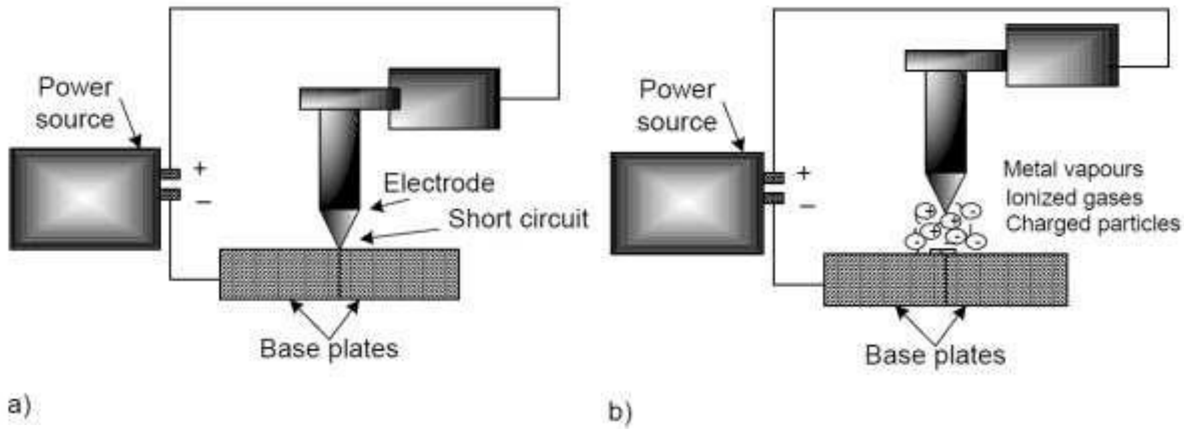
Three different zone in which voltage drop takes place

Arc Initiation

There are two most commonly used methods to initiate an electric arc in welding processes namely touch start and field start. The touch start method is used in case of all common welding processes while the later one is preferred in case of automatic welding operations and in the processes where electrode has tendency to form inclusion in the weld metal like in TIG welding or electrode remains inside the nozzle.

Touch Start

In this method, the electrode is brought in contact with the work piece and then pulled apart to create a very small gap. Touching of the electrode to the workpiece causes short-circuiting resulting in flow of heavy current which in turn leads to heating, partial melting and even slight evaporation of the metal at the electrode tip. All these events happen in very short time usually within few seconds. Heating of electrode produces few free electrons due to thermal ionization; additionally dissociation of metal vapours (owing to lower ionization potential of the metal vapours than the atmospheric gases) also produces charged particles (electron and positively charged ions). On pulling up of the electrode apart from the work piece, flow of current starts through these charged particles and for a moment arc is developed. To use the heat of electric arc for welding purpose it is necessary that after initiation of arc it must be maintained and stabilized.

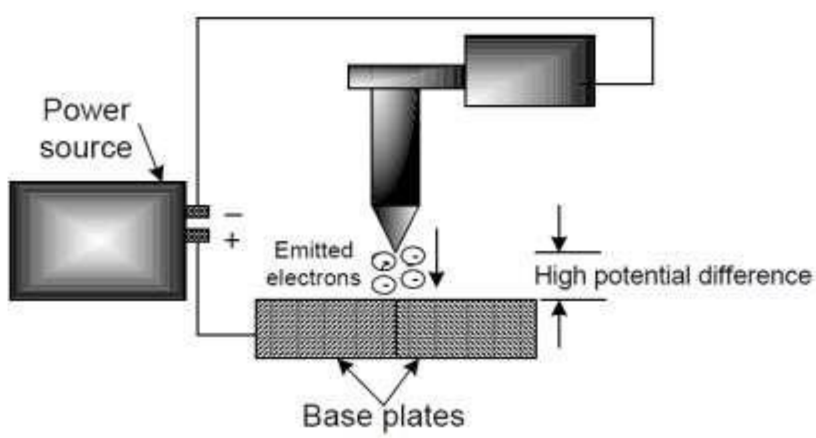


Schematic diagram showing mechanism of arc initiation by touch start method

a) When circuit closed by touching electrode with work piece b) emission of electrode on putting them apart

Field Start

In this method, high strength electric field (107 V) is applied between electrode and work piece so that electrons are released from cathode electro-magnetic field emission. Development of high strength field leads to ejection of electron from cathode spots. Once the free electrons are available in arc gap, normal potential difference between electrode and work piece ensures flow of charged particles to maintain a welding arc. This method is commonly used in mechanized welding processes such as plasma arc and GTAW process where direct contact between electrode and work piece is not preferred.



Schematic diagram showing the field-start method of arc initiation

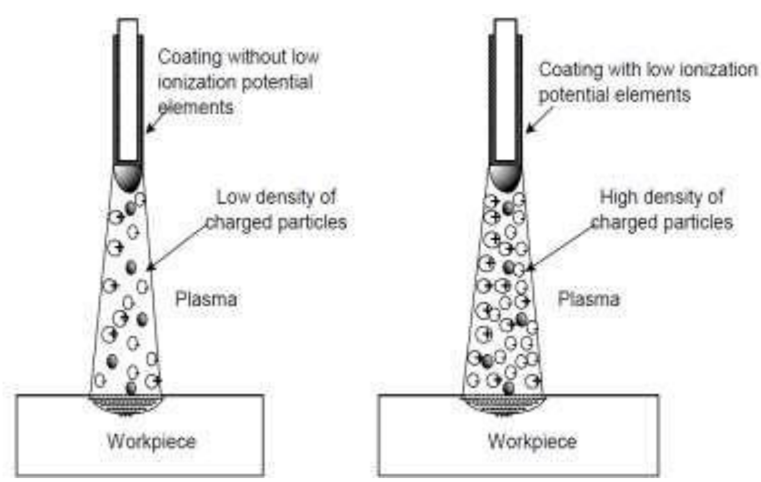
Maintenance of Arc

Once electric arc is initiated, next step is to maintain it to use the heat generated for welding purpose. For maintaining of the arc two conditions must be fulfilled (1) heat dissipation rate from the arc, region should be equal to that of heat generated to maintain the temperature of the arc and (2) number of electrons produced should be equal to that of electrons lost to the work piece and surroundings.

An electric arc primarily involves flow of current through the gap between the work piece and electrode hence there must be sufficient number of charged particles namely electrons and ions. However, some of the electrons are lost from the arc surface, to the weld pool and surroundings and few electrons reunite with ions. Loss of these electrons must be compensated by generation of new free electrons. In case of direct current,`magnitude and direction of current does not change with time hence maintaining the flow of electrons and so the arc becomes easy while in case of alternating current (A. C.) both magnitude and direction change with time and for a moment flow of current becomes zero. This makes re-ignition of an electric arc with AC somewhat difficult and therefore it needs extra precautions and provisions. There are two commonly used methods for maintaining the arc in A.C. welding: (1) use of low ionization potential elements in coatings flux and (b) use of low power factor power source.

Low Ionization Potential Elements

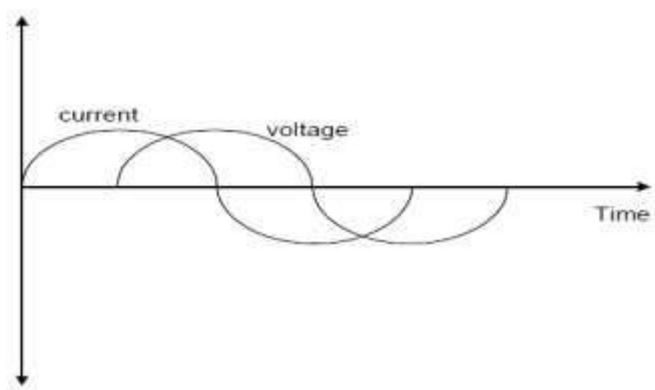
In this method, low ionization potential elements such as potassium, calcium and sodium are added in the flux covering of the electrode (coating). These elements release free electrons needed to have reasonably good electrical conductivity for maintaining welding arc even with small potential difference between electrode and work piece.



Schematic representation of effect of low ionization potential elements on density of charged particles

Low Power Factor

Power factor of a system indicates how effectively power is being utilized and it is generally preferred to have high power factor of machine or system. Power factor is defined as ratio of actual power drawn from the power source to perform the welding and apparent power drawn into the welding circuit line. Welding transformer operates at high power factor (>0.9). However, in welding usually low power factor is intentionally used to improve the arc stability and maintenance of welding arc. In this method, current and voltage are made out of phase by using proper low power factor (0.3) so that when current is zero, full open circuit voltage is available between electrode and work piece. Full open circuit voltage across the electrode and work helps in release of free electrons to maintain flow of already existing electrons which is a perquisite for maintenance of the arc.

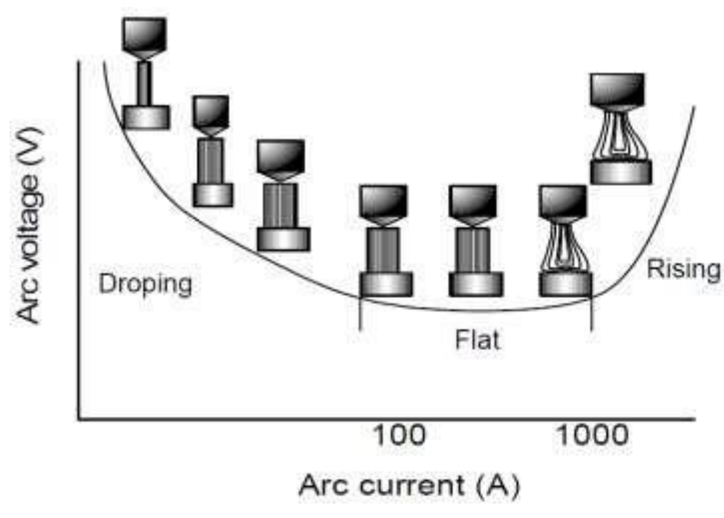


Setting proper power factor to have current and voltage out of phase

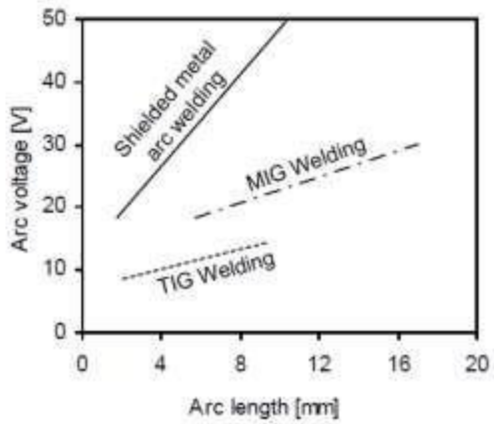
Arc Characteristic

Welding arc characteristic shows variation in the arc voltage with welding current. There are three different regions on the arc characteristic curve namely dropping, flat and rising characteristics zones. Initially at low current when arc is thin, an increase in welding current increases the temperature of arc zone which in turn enhances the number of charged particles in plasma zone of the arc due to thermal ionization and thermo-ionic emission of electrons. As a result, electrical conductivity of arc zone increases which in turn decrease arc voltage decreases with initial increase in welding current in this zone. Arc tends to be stable in this region. This trend continues up to certain level of current and beyond that increase in current increases the diameter of cylindrical arc that increases the surface area of the arc. Increase in surface area of the arc in turn increases loss of heat from the arc surface. Therefore, no significant rise in arc temperature takes place with increase of current hence arc voltage is not affected appreciably over a range of current in flat zone of the curve. Further, increase in current bulges the arc, which in turn increases the resistance to flow of current (due to increased losses of charge carriers and heat from arc) so arc voltage increases with increase in welding current in rising characteristic zone. These three zones of arc characteristic curve are called drooping, flat and rising characteristics. Increase in arc length in general increases arc voltage during welding. However, the extent of increase in arc voltage with increase in arc length varies with process as shown in Fig. In general, arc voltage increases almost lineally with increase in arc length (within reasonable limits) and the same is attributed to increase in resistance to the flow of current due to reduction in charged particle density in arc zones with increase in arc length.

Variation in charged particle density in arc zones associated different arc welding processes such as SMAW, GMAW and GTAW is attributed to appreciable difference in arc voltage vs. arc length relationship. For example, GTAW process due to tungsten electrode (having high electron emitting capability) results in higher charged particle density in arc region than GMAW and SMAW which in turn leads to lower arc voltage/arc length ratio for GTAW than LMAW & SMAW process.



Schematic diagram showing welding arc characteristic curve

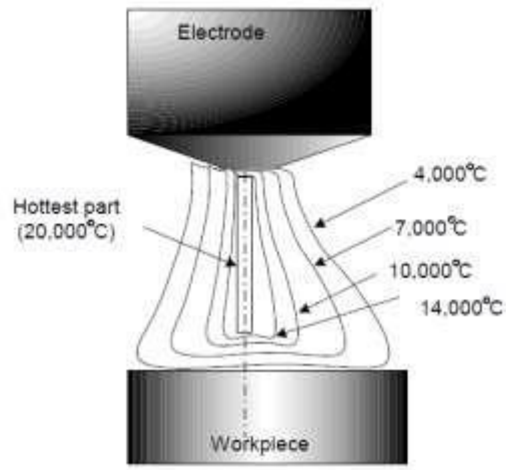


Variation in arc voltage as function of arc length for different arc welding processes

Temperature of the Arc

In addition to arc voltage and current parameters (governing the power of arc), thermal properties (thermal conductivity) of shielding gases present in arc zone predominantly affect the temperature and its distribution in the arc region. Thermal conductivity of most of the gases (He, N, Ar) increases with rise in temperature however, this increase is not continuous for some of the gases such as Helium. Thermal conductivity of base metal/shielding gas governs temperature gradient in the arc region. Reduction in thermal conductivity increases the temperature gradient.

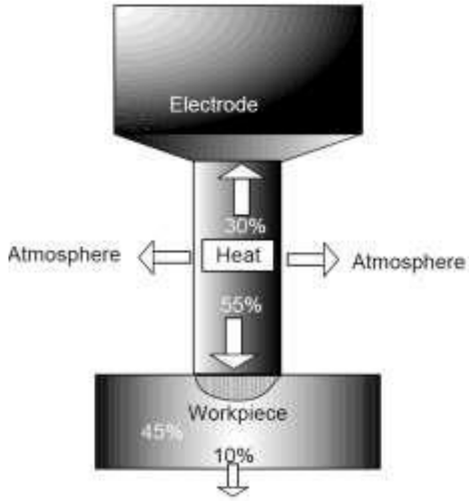
Therefore, a very rapid decrease in temperature of arc is observed with increase in distance from the axis (center) of the arc. Maximum temperature is observed at core (along the axis of electrode) of the arc and it decreases rapidly with increase in distance away from the core. Temperatures in anode and cathode drop zones are generally lower than the plasma region due to cooling effect of electrode/work piece. Temperature of arc can vary from 5000-30,000K depending upon the current voltage shielding gas and plasma gas. For example, in case of SMAW, temperature of arc is about 6000K while that for TIG/MIG welding arc it is found in range of 20000-25000K.



Schematic diagram showing typical temperature distribution in the arc

Arc Efficiency

Arc welding basically involves melting of faying surfaces of base metal using heat generated by arc under a given set of welding conditions i.e. welding current and arc voltage. However, only a part of heat generated by the arc is used for melting purpose to produce weld joint and remaining is lost in various ways namely through conduction to base metal, by convention and radiation to surrounding. Moreover, the heat generation on the work piece side depends on the polarity in case of DC welding while it is equally distributed in work piece and electrode side in case of AC welding. Further, it can be recalled that heat generated by arc is dictated by the power of the arc (VI) where V is arc voltage i.e. mainly sum voltage drop in cathode drop (VC), plasma (Vp) and anode drop regions (Vp) apart from of work function related factor and I is welding current. Product of welding current (I) and voltage drop in particular region governs the heat generated in that zone e.g. near anode, cathode and in plasma region. In case of DCEN polarity, high heat generation at work piece facilitates melting of base metal to develop a weld joint of thick plates.



Distribution of heat from the welding arc in DCEN polarity

Rationale behind variation in arc efficiency of different arc welding processes

Under simplified conditions (with DCEN polarity), ratio of the heat generated at anode and total heat generated in the arc is defined as arc efficiency. However, this ratio indicates the arc efficiency only in case of non-consumable arc welding processes such as GTAW, PAW, Laser and electron beam welding processes where filler metal is not commonly used. However, this definition doesn't reflect true arc efficiency for consumable arc welding processes as it is doesn't include use of heat generated in plasma region and cathode side for melting of electrode or filler metal and base metal. Therefore, arc efficiency equation for consumable arc welding processes must include heat used for melting of both work piece and electrode. Since consumable arc welding processes (SMAW, SAW, GMAW) use heat generated both at cathode and anode for melting of filler and base metal while in case of non-consumable arc welding processes (GTAW, PAW) heat generated at the anode only is used for melting of the base metal, therefore, in general, consumable arc welding processes offer higher arc efficiency than non-consumable arc welding processes. Additionally, in case of consumable arc welding processes (SMAW, SAW) heat generated is more effectively used because of reduced heat losses to surrounding as weld pool is covered by molten flux and slag. Welding processes in ascending order of arc efficiency are GTA, GMA, SMA, and SAW. GTAW offer's lower arc efficiency (21-48%) than SMAW/GMAW (66- 85%) and SA welding (90-99%)

Determination of arc efficiency

Heat generated at the anode is found from sum of heat generated due to electron emission and that from anode drop zone.

$q_a = [\phi + V_a]\, I$..(equation 8.1)

where q_a = is the heat at anode

ϕ is work function of base metal at temperature T = [(ϕ_0 +1.5 kT) ....(equation 8.2)

ϕ_0 is work function of base metal at temperature OK

k is the Boltzmann constant

T temperature in Kelvin

V_a anode voltage drop

I welding current

Heat generated in plasma region $q_p = V_p\, I$..................................(equation 8.3)

Say it's a fraction m % of the heat generated in plasma region goes to anode/work piece for melting = m (V_p I) ....(equation 8.4)

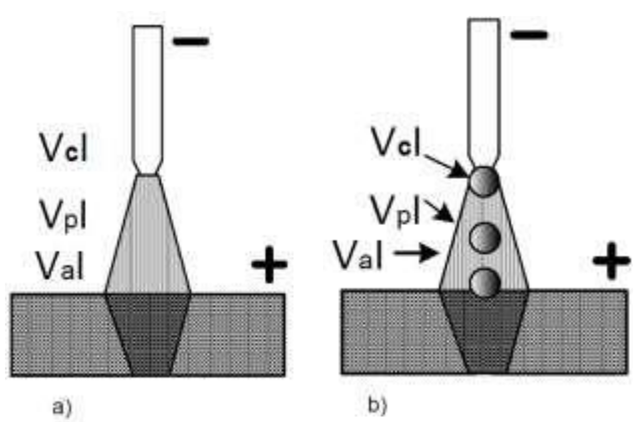
So arc efficiency = total heat used / total heat generated in arc= [q_a + m (V_p I)]/VI..................................(equation 8.5)

Where V is arc voltage = $V_a + V_p + V_c$

Another way is that [{total heat generated in arc- (heat with plasma region + heat of cathode drop zone)}/total heat generated in arc}]

So arc efficiency [{VI-[q_c + (1-m) (V_p I)}/VI}] or [{VI-[V_cI + (1-m) (V_p I)}/VI}]..................................(equation 8.6)

Where q_c is the heat generated in cathode drop zone.



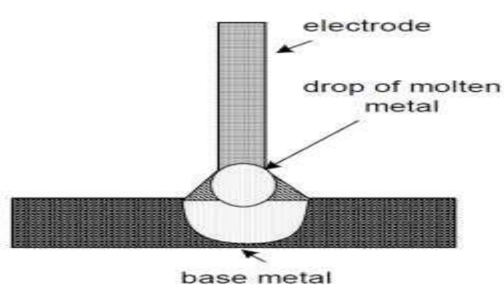
Schematic of heat generation in different zones of the arc of a) non consumable arc and b) consumable arc welding processes.

Metal Transfer

Metal transfer refers to the transfer of molten metal from the tip of a consumable electrode to the weld pool and is of great academic and practical importance for consumable electrode welding processes as it directly affects the control over the handling of molten metal, slag and spattering. However, metal transfer is considered to be more of academic importance for GMA and SA welding than practical need. Shielding gas, composition of the electrode, diameter and extension of the electrodes are some of the arc welding related parameters, which affect the mode of metal transfer for a given power setting namely welding current and voltage. Four common modes of metal transfer are generally observed in case of consumable arc welding processes. These have been described in the following sections.

Short Circuit Transfer

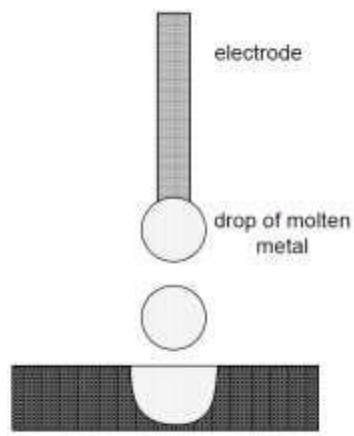
This kind of metal transfer takes place, when welding current is very low but high enough to have stable arc and arc gap is small. Under these welding conditions, molten metal droplet grows slowly at the tip of the electrode and then as soon as drop touches weld pool, short-circuiting takes place. Due to narrow arc gap, molten drop does not attain a size big enough to fall down on its own (by weight) under gravitational force. On occurrence of short circuit, welding current flowing through the droplet to the weld pool increases abruptly which in turn results in excessive heat generation that makes the molten metal of droplet thinner (low surface tension). Touching of the molten metal drop to weld pool leads to transfer of molten metal into weld pool by surface tension effect. Once molten metal is transferred to the weld pool, an arc gap is established which in turn increases arc voltage abruptly. This increase in arc voltage (due to setting up of the arc-gap) re-ignites arc and flow of current starts. This whole process is repeated at a rate varying from 20 to more than 200 times per second during the welding



(a) Schematic of short circuiting metal transfer

Globular Transfer

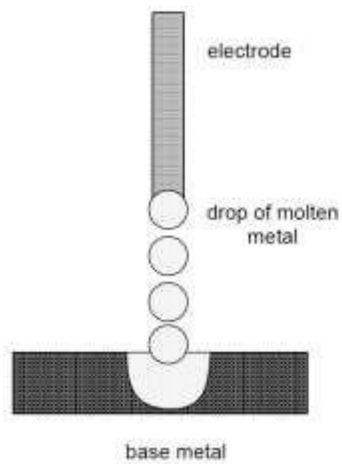
Globular metal transfer takes place when welding current is low (but higher than that for short circuit transfer) and arc gap is large enough so molten metal droplet can grow slowly (at the tip of the electrode) with melting of the electrode tip. Drop continues to grow until gravitational force on drop (due to its own weight) exceeds the surface tension force other forces if any trying to add the drop at the tip of electrode. As soon as drop attains large size enough and so gravitational force becomes more than other drop-holding-forces such as surface tension force, drop detaches from the electrode tip and is transferred to the weld pool. The transfer of molten metal drop normally occurs when it attains size larger than the electrode diameter. No short-circuit takes place in this mode of metal transfer.



(b) Schematic of globular metal transfer

Spray Transfer

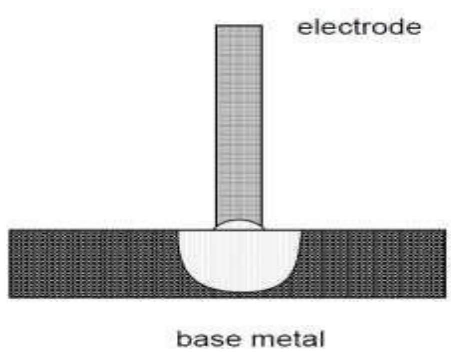
This kind of metal transfer takes place when welding current density is higher than that is required for globular transfer. High welding current density results in high melting rate and greater pinch force as both melting rate and pinch force are directly related with welding current and are found proportional to square of welding current. Therefore, at high welding current density, droplets are formed rapidly and pinched off from the tip of electrode quickly by high pinch force even when they are of very small in size. Another reason for detachment of small droplets is that high welding current increases temperature of arc zone which in turn lowers the surface tension force. Reduction in surface tension force decreases the resistance to detachment of which in turn facilities detachment of drops even when they are of small size enough drop from the electrode tip. The transfer of molten metal from electrode tip appears similar to that of spray in line of axis of the electrode. This feature helps to direct the molten metal in proper place where it is required especially in difficult to access areas.



(c) Schematic of spay metal transfer

Dip Transfer

Dip type of metal transfer is observed when welding current is very low and feed rate is high. Under these welding conditions, electrode is short-circuited with weld pool, which leads to the melting of electrode and transfer of molten drop. Approach wise dip transfer is similar to that of short circuit metal transfer and many times two are used interchangeably. However, these two differ in respect of welding conditions especially arc gap that lead to these two types of metal transfers. Low welding current and narrow arc gap (at normal feed rate) results in short circuit mode of metal transfer while the dip transfer is primarily caused by abnormally high feed rate even when working with recommended range of welding current and arc gap.



(d) Schematic of dip transfer

Characteristics of power source

Each welding power source has set of characteristics indicating the capability and quality of the power source. These characteristics help in selection of suitable welding power source for a given welding condition. Basic characteristics of a welding power source are given below: Open circuit voltage (OCV) Power factor (pf) Static characteristics Dynamic characteristics Current rating and duty cycle

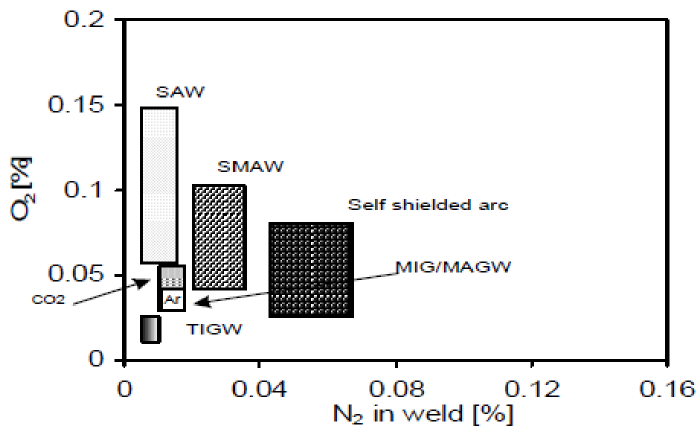
Open circuit voltage (OCV)

OCV shows the potential difference between the two terminals of the power source when there is no load. Setting up of correct open circuit voltage is important for stability of welding arc especially when AC is used. The selection of an optimum value of OCV (50-100V) depends on the type of base metal, composition of electrode coating, type of welding current and polarity, type of welding process etc. Base metal of low ionization potential (indicating ease of emitting free of electrons) needs lower OCV than that of high ionization potential metal. Presence of low ionization potential elements such as K, Na and Ca in electrode coating/flux in optimum amount reduces OCV setting required for welding. AC welding needs higher OCV compared with DC owing to problem of arc stability as in case of AC welding current continuously changes its direction and magnitude while in case DC it remains constant. In the same line, GTAW needs lower OCV than GMAW and other welding processes like SMAW and SAW because GTAW uses tungsten electrode which has good free electron emitting capability by thermal and field emission mechanism. Abundance of free electron in GTAW under welding conditions lowers the OCV needed for having stable welding arc. Too high OCV may cause electric shock. OCV is generally found to be different from arc voltage. Arc voltage is potential difference between the electrode tip and work piece surface when there is flow of current. Any fluctuation in arc length affects the resistance to flow of current through plasma and hence arc voltage is also affected. Increase in arc length or electrode extension increases the arc voltage. Further, electrical resistance heating of electrode increases with electrode extension for given welding parameters.

Chemical Reaction in Welds

Welding process and cleanliness of the weld

In fusion welding, the application of heat of the arc or flame results in the melting of the faying surfaces of the plates to be welded. At high temperature metals become very reactive to atmospheric gases such as nitrogen, hydrogen and oxygen present in and around the arc environment. These gases either get dissolved in weld pool or form their compound. In both the cases, gases adversely affect the soundness of the weld joint and mechanical performance. Therefore, various approaches are used to protect the weld pool from the atmospheric gases such as developing envelop of inactive (GMAW, SMAW) or inert gases (TIGW, MIGW) around arc and weld pool, welding in vacuum (EBW), covering the pool with molten flux and slag (SAW,



ESW). The effectiveness of each method for weld pool protection is different. That is why adverse effect of atmospheric gases in weld produced by different arc welding processes is different.

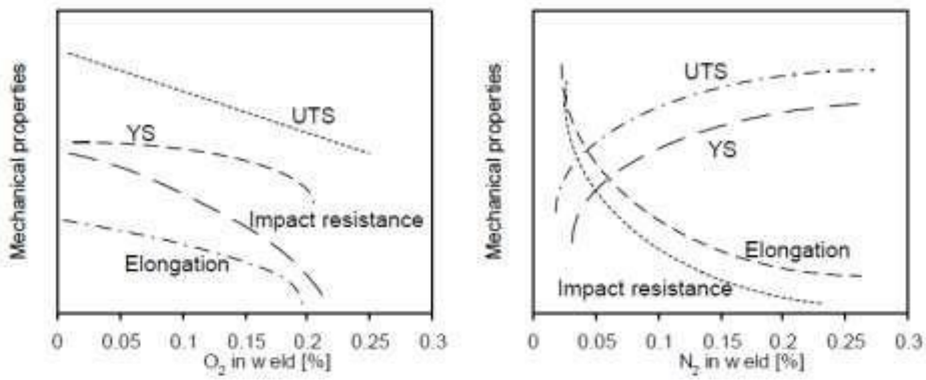
Schematic diagram showing nitrogen and oxygen content in different welding processes

Amongst the most commonly used arc welding processes, the cleanest weld (having minimum nitrogen and oxygen) is produced by gas tungsten arc welding (GTAW) process due to two important factors associated with GTAW: a) short arc length and b) very stable arc produced by using non-consumable tungsten electrode. A combination of short and stable arc with none-consumable tungsten electrode results a firm shielding of arc and protection of the weld pool by inert gases restricts the entry of atmospheric gases in the arc zone. Gas metal arc welding (GMAW) also offers clean weld but not as clean as produced by GTAW because in case of GMAW arc length is somewhat greater and arc stability is poorer than GTAW. Submerged arc weld (SAW) joints are usually high in oxygen and less in nitrogen because SAW uses flux containing mostly metallic oxides. These oxides decompose and release oxygen in arc zone. The self-shielded fluxed cored metal arc welding processes use electrodes having fluxes in core act as de-oxidizer and slag formers to protect the weld pool. However, weld produced by the self-shielded fluxed arc welding processes are not as clean as those produced with GMAW.

Effect of atmospheric gases on weld joint

The gases present in weld zone (atmospheric or dissolved in liquid metal) affect the soundness of weld joint. Gases such as oxygen, hydrogen, nitrogen etc. are commonly present in and around the liquid metal. Both oxygen and hydrogen are very important in welding of ferrous and non-ferrous metals; these are mostly produced by decomposition of water vapours (H_2O) in high arc temperature. Oxygen reacts with carbon in case of steel to form CO or CO_2. These gases should escape out during the solidification; due to high solidification rate encountered in welding processes these gases may not come up to the surface of molten metal and may get trapped. This causes gaseous defects in the weldment, like porosity, blowhole etc. Chances for these defects further increases if the difference in solubility of these gases in liquid and solid state is high. Oxygen reacts with aluminium and form refractory alumina which forms inclusions and reduces the weldability. It's formation can be reduced by proper shielding of arc zone either by inert or inactive gases. Only source of nitrogen is atmosphere and it may form nitrides but it creates fewer problems. Hydrogen is a main problem creator in welding of steel and aluminium alloy due to high difference in liquid and solid state solubility. In case of steel, besides the porosity and blow holes hydrogen causes the problem of cold cracking even if it is present in very small amount, whereas in case of aluminium hydrogen causes pin hole porosity.

Oxides and nitrides formed by these gases if not removed from the weld, act as site of weak zone in form of inclusions which in turn lower the mechanical performance of the weld joint e.g. iron reacts with nitrogen to form hard and brittle needle shape iron nitride (Fe_4N). These needle shape micro-constituents offer high stress concentration at the tip of particle matrix interface which under external tensile stresses facilitate the easy nucleation and propagation of crack, therefore fracture occurs at limited elongation (ductility). Similar logic can be given for reduction in mechanical performance of weld joints having high oxygen/oxide content. However, the presence of N_2 in weld metal is known to increase the tensile strength due to the formation of hardness and brittle iron nitride needles.



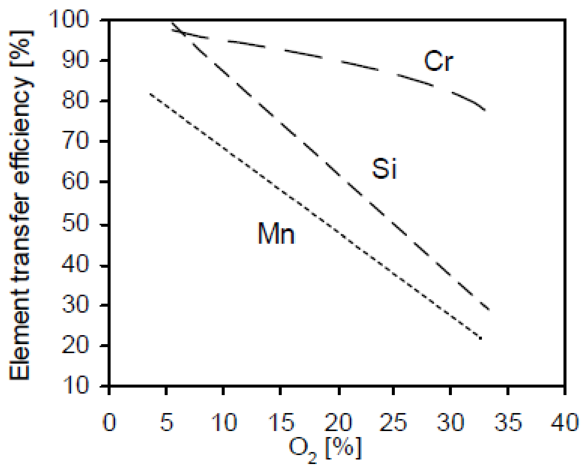
Influence of oxygen and nitrogen as impurities on mechanical properties of steel weld joints

Additionally, these inclusions formed by oxygen, nitrogen and hydrogen break the discontinuity of metal matrix which in turn decreases the effective load resisting cross section area. Reduction in load resisting cross sectional area lowers the load carrying capacity of the welds. Nitrogen is also a austenite stabilizer which in case of austenitic stainless steel (ASS) welding can place crucial role. Chemical composition of ASS is designed to have about 5-8% ferrite in austenite matrix to control solidification cracking of weld. Presence of nitrogen in weld metal either from atmosphere or with shielding gas (Ar) stabilizes the austenite (so increases the austenite content) and reduces ferrite content in weld which in turn increases the solidification cracking tendency because ferrite in these steels acts as sink for impurities like P and S which otherwise increase cracking tendency of weld.

Effect on weld compositions

Presence of oxygen in arc environment not only increases chances of oxide inclusion formation tendency but also affects the element transfer efficiency from filler/electrode to weld pool due to oxidation of alloying elements. Sometime composition of the weld is adjusted to get desired combination of mechanical, metallurgical and chemical properties by selecting electrode of suitable composition. Melting of electrode and coating and then transfer of the elements from the electrode across the arc zone causes the oxidation of some of the highly reactive elements which may be removed in form of slag. Thus transfer of especially reactive elements to weld pool is reduced which in turn affects the weld metal composition and so mechanical and other performance characteristics of weld.

Influence of oxygen concentration on element transfer efficiency of common elements

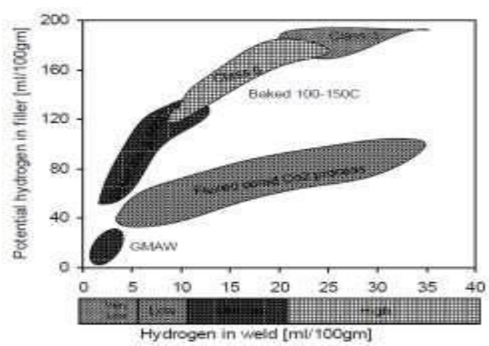


Effect of hydrogen on steel and aluminium weld joints Hydrogen

Hydrogen in weld joints of steel and aluminium is considered to be very harmful as it increases the cold cracking tendency in hardenable steel and porosity in aluminium welds. Hydrogen induced porosity in aluminium welds is formed mainly due to high difference in solubility of hydrogen in liquid and solid state. The hydrogen rejected by weld metal on solidification if doesn't get enough time for escaping then it is entrapped in weld and results in hydrogen induced fine porosity. Welds made using different processes produce varying hydrogen concentration owing to difference in solidification time, moisture associated with consumable and protection of the weld pool from atmospheric gases, use of different consumables. Hydrogen in steel and aluminium weld joint is found mainly due to high difference in solubility of hydrogen in liquid and solid state.

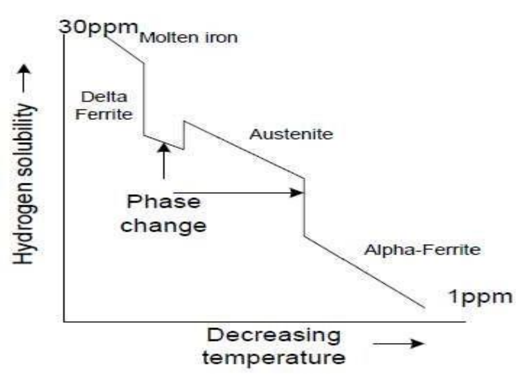
Cold cracking is caused by hydrogen especially when hard and brittle martensitic structure is formed in the weld and HAZ of hardenable steel. Many theories have been advanced to explain the cold cracking due to hydrogen. Accordingly to one of hypothesis, hydrogen diffuses towards the vacancies, grain boundary area and other crystallographic imperfections. At these locations, segregation of the hydrogen results in first transformation of atomic hydrogen into gaseous molecules and then builds up the pressure until it is high enough to cause growth of void by propagation of cracks in one of directions having high stress concentration. Thereafter, process of building up of the pressure and growth of crack is repeated until complete fracture of the weld without any external load occurs. Existence of external or residual tensile stresses further accelerate the crack growth rate and so lower the time required for failure to occur by cold cracking. Presence of both of above discontinuities (cracks and porosity) in the weld decreases mechanical performance of weld joint. Hydrogen in arc zone can come from variety of sources namely:

- Moisture (H2O) in coating of electrode or on the surface of base metal,
- Hydrocarbons present on the faying surface of base metal in the form of lubricants paints etc
- Inert gas (Ar) mixed with hydrogen to increase the heat input
- Hydrogen in dissolved state in metal (beyond limits) being welded such as aluminium and steel

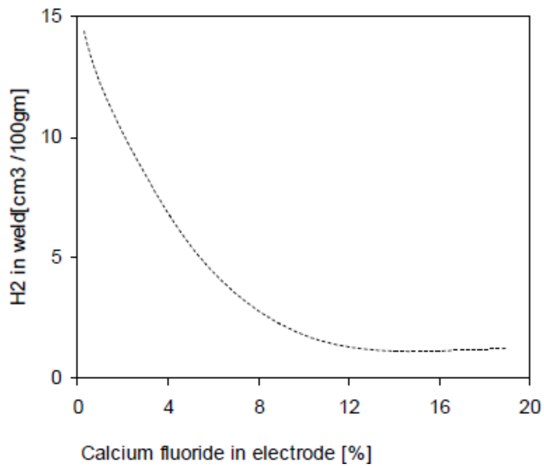


Hydrogen content in weld developed using different welding processes

It has been reported that proper baking of electrodes directly reduces the cold cracking tendency and time for failure delayed cracking. Therefore, attempt should be made to avoid the hydrogen from above sources by taking suitable corrective action.



Schematic of hydrogen solubility as a function of temperature of iron



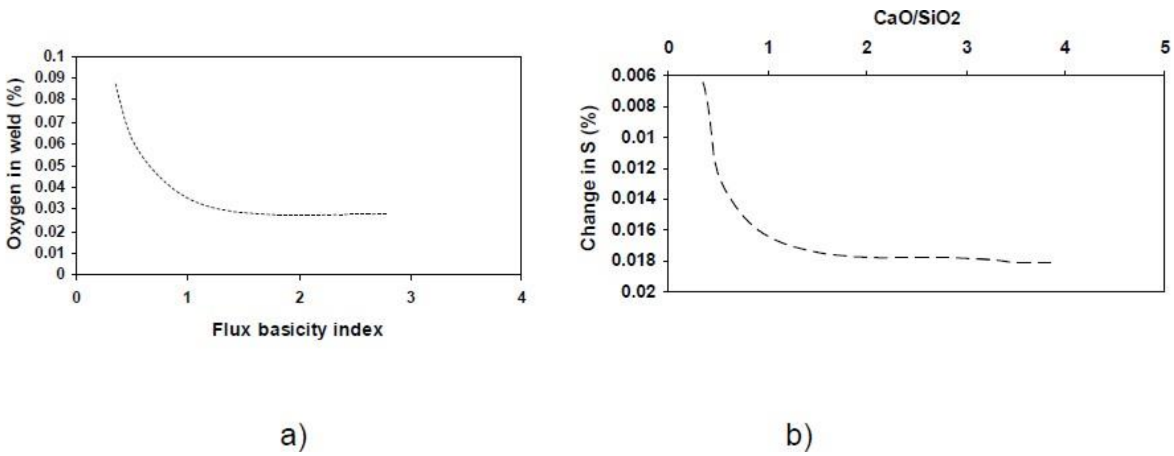
Influence of calcium fluoride on hydrogen concentration in weld joints

Basicity of the flux

The composition of fluxes is adjusted so as to get proper basicity index as it affects the ability of flux to remove impurities like sulpher and oxygen from melt. The basicity index of the flux refers to ratio of sum of amount of all basic oxides and that of non-basic oxides. Basic oxides (CaO is most common) are donors of the oxygen while acidic oxides (such as SiO2) are acceptor of oxygen. Common acidic and basic oxides are shown in table below. Flux having BI <1 is called acidic flux, neutral fluxes have 1<BI<1.2 while basic fluxes have BI>1.2. Increase in BI of the flux from 1 to 5 results in significant decrease in sulphur content of the weld. The basic oxides act de-sulphurizer as sulphur is removed from the weld in the form of SO2 by reaction between oxygen released by basic oxides and S. Thus, the weld is de-suphurized (Table).

Type of oxide	Decreasing Strength						
	1	2	3	4	5	6	7
Acidic	SiO_2	TiO_2	P_2O_5	V_2O_5			
Basic	K_2O	Na_2O	CaO	MgO	BaO	MnO	FeO
Neutral	Al_2O_3	Fe_2O_3	Cr_2O_3	V_2O_3	ZnO		

In general, an increase in basicity of the flux up to 1.5 decreases the S and oxygen concentration (from about 900 PPM to 250 PPM) in weld joints. Thereafter, oxygen content remains constant at about 200-250 PPM level despite of using fluxes of high basicity index. Further, there is no consensus among the researchers on the mechanism by which an increase in basicity index decreases the oxygen content.



Influence of basicity of flux on a) oxygen and b) sulphur concentration in weld.

These oxides get decomposed at high temperature in arc environment. Stability of each oxide is different. Oxides with decreasing stability are as follows: (i) CaO, (ii) K2O, (iii) Na2O and TiO2, (iv) Al2O3, (v) MgO, (vi) SiO2, (vii) MnO and FeO. On decomposition, these oxides invariably produce oxygen and result-in oxidation of reactive elements in weld metal.

Understanding weldability

Weldability is considered as ease of accomplishing a satisfactory weld joint and can be in determined from quality of the weld joint, effort and cost required for developing the weld joint. Quality of the weld joint however, can be determined by many factors but the weld must fulfil the service requirements. The characteristics of the metal determining the quality of weld joint includes tendency to cracking, hardening and softening of HAZ, oxidation, evaporation, structural modification and affinity to gases. While efforts required for producing sound weld joint are determined by properties of metal system in consideration namely melting point, thermal expansion coefficient, thermal and electrical conductivity, defects inherent in base metal and surface condition. All the factors adversely affecting the weld quality and increasing the efforts (& skill required) for producing a satisfactory weld joint will in turn be decreasing the weldability of metal.

In view of above, it can be said that weldability of metal is not an intrinsic property as it is influenced by a) all steps related with welding procedure, b) purpose of the weld joints and c) fabrication conditions. Welding of a metal using one process may show poor weldability (like Al welding with SMA welding process) and good weldability when the same metal is welded with some other welding process (Al welding with TIG/MIG). Similarly, a steel weld joint may perform well under normal atmospheric conditions and the same may exhibit very poor toughness and ductility at very low temperature condition. Steps of the welding procedure namely preparation of surface and edge, preheating, welding process, welding parameters, post weld treatment such as relieving the residual stresses, can influence the weldability of metal appreciably. Therefore, weldability of a metal is considered as a relative term.

Weldability of steels

To understand the weldability of steel, it important to look into the different phases, phase mixtures and intermetallic generally found in steel besides the changes in phase that can occur during welding due to heating and cooling cycles. All these aspects can be understood by going through following section presenting significance of Fe-C diagram, time-temperature-transformation diagram and continuous cooling transformation diagram.

Fe-C Equilibrium Phase Diagram

Fe-C diagram is also called iron-iron carbide diagram because these are the two main constituents observed at the room temperature in steel while the presence of other phases depends on the type and amount of alloying elements. It shows the various phase transformations as a function of temperature on heating / cooling under equilibrium conditions.

Weldability of steel and composition

Weldability of steels can be judged by two parameters (a) cleanliness of weld metal and (b) properties of HAZ. Cleanliness of weld metal is related with presence of inclusion in the form of slag or gases whereas HAZ properties are primarily controlled by hardenability of the steel. Proper shielding of arc zone and degassing of molten weld metal can be used to control first factor. Proper shielding can be done by inactive gases released by combustion of electrode coatings in SMA or inert gases (Ar, He, Co2) in case of TIG, MIG welding. Hardenability of steel is primarily governed by the composition. All the factors increasing the hardenability adversely affect the weldability because steel becomes more hard, brittle and sensitive to fracture/cracking, therefore it needs extra care. So, more the precautions should be taken to produce a sound weld joint. Addition of all alloying elements (C, Mn, Ni, W, Cr etc.) except cobalt increases the hardenability which in turn decreases the weldability. To find the combined effect of alloying elements on hardenability/weldability, carbon equivalent (CE) is determined.

Different types of steel and welding

Carbon steel generally welded in as rolled condition (besides annealed and normalized one). The weldable carbon steel is mostly composed of carbon about 0.25 %, Mn up to 1.65%, Si up to 0.6% with residual amount of S and P below 0.05%. High strength low alloy steel (HSLA) is designed to have yield strength in range of 290-550 MPa using alloying concentration lesser than 1% in total. These can be welded in conditions same as that of carbon steel. Quench and tempered (Q & T) steels can be a carbon steel or HSLA steel category that are generally heat treated to impart yield strength in range of 350 to 1030 MPa. Heat treatable steels generally contain carbon more than carbon steel or HSLA steels, to increase their response to the heat treatment (Kou, S welding metallurgy, John Willey, 2003). However, presence of high carbon in these steels increases the hardenability which in turn decreases the weldability owing to increased embrittlement and cracking tendency of heat affected zone. Further, PWHT of heat treatable steel weld joints is done to enhance their toughness and induce ductility because presence of high carbon in these heat treatable steels. Cr-Mo steels are primarily designed to have high resistance to corrosion, thermal softening and creep at elevated temperature (up to 700 0C). Therefore, these are commonly used in petrochemical industries and thermal power plants. Weld joints of Cr-Mo steels are generally given PWHT to regain ductility, toughness, and corrosion resistance and reduce the residual stresses.

Common problems in steel welding

Cracking of HAZ due to hardening

The cooling rate experienced by the weld metal and HAZ during welding generally exceeds the critical cooling (CCR) which in turn increases the chances martensitic transformation. It is well known from the physical metallurgy of the steels that this transformation increases the hardness and brittleness and generates tensile residual stresses. This combination of high hardness and tensile residual stresses makes the steel prone to the cracking.

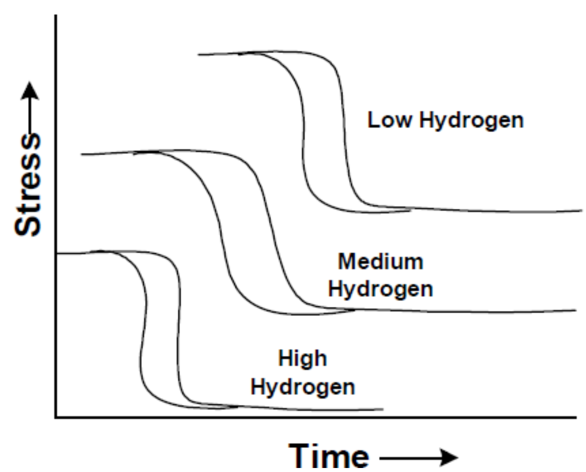
Cold cracking

Another important effect of solid state transformation is the cold cracking. It is also termed as delayed/hydrogen induced cracking because these two factors (delay and hydrogen) are basically responsible for cold cracking. It can be observed that increase in stress decreases the time required for initiation and complete fracture by cold cracking. Origin of this problem lies in the variation of solubility of hydrogen in the steel with the temperature. Reduction in temperature decreases solubility of hydrogen in solid state due to change in crystal structure from F. C. C. to B. C. C. High temperature transformation (like austenite to pearlite or bainite) allows escape of some of excess hydrogen (beyond the solubility) by diffusion. But in case of low temperature transformation (austenite into martensite), when rate of diffusion reduces significantly, hydrogen cannot escape and is trapped in steel as solid solution. Dissolved hydrogen has more damaging effect in presence of martensite and the same has been explained below. Hydrogen dissolved in atomic state at low temperature tends to diffuse out gradually toward the vacancies and other cavities. At these locations atomic hydrogen converts into diatomic H2 gas and with time, continued diffusion of hydrogen towards these discontinuities as this gas starts to build up pressure in the cavities. If the pressure exceeds the fracture stress of metal, cavities expands by cracking. Cracking of metal increases the volume which in turn reduces the pressure. Due to continuous diffusion of hydrogen toward the cavities after some time again as pressure exceeds the fracture stress, and crack propagates further. This process of building up on pressure and propagation of cracks is repeated until compete fracture takes place without external load. Since this type cracking and fracture takes place after some time of welding hence it is called delayed cracking. Delay for complete fracture depends on the following factors:

- Hardenability of steel
- Amount of hydrogen dissolved in atomic
- state Magnitude of residual tensile stress

Hardenability of steel affects the critical cooling rate. Steel of high hardenability promotes the martensitic transformation therefore it has high hardness and brittleness. High hardness increases the cracking tendency whereas soft and ductile metals reduce it. Crack tips are blunted in case of ductile metals so they reduce the cracking sensitivity and increases the stress level for fracture. As a result crack propagation rate is reduced in case of ductile and low strength metal. Therefore, steels of low hardenability will therefore minimize the cold/delayed cracking. Larger the amount of dissolved hydrogen faster will be the delayed/hydrogen induced cracking.

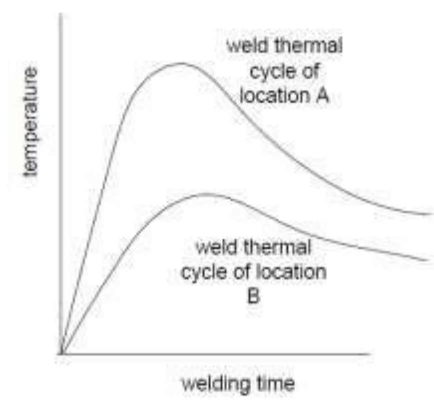
Use of low hydrogen electrodes will reduce the hydrogen content in weld metal. Preheating of the plate will reduce the cooing rate, which will allow longer time for gases to escape during the liquid to solid state and solid-solid transformation. It may also reduce the cooling rate below the critical cooling rate so that martensitic transformation can be avoided and austenite can be transformed into softer phases and phase mixtures like pearlite, bainite etc. These soft phases further reduce the cracking tendency. Use of austenitic electrode also avoids the martensite formation and provides mainly austenite matrix in weld zone. Austenite is a soft and tough phase having high solubility (%) for hydrogen. All these characteristics of austenite reduce the cold/delayed cracking.



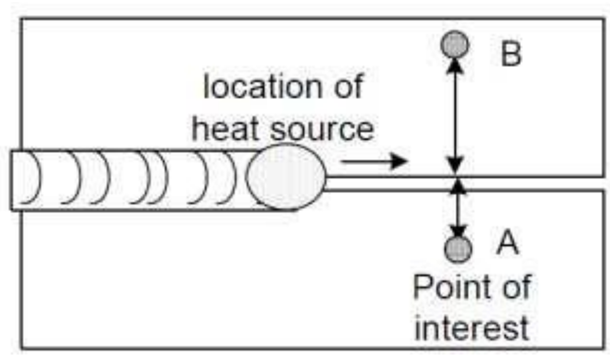
Schematic diagram showing effect of hydrogen concentration on cold cracking at different stress levels

Introduction to Heat Flow in Welding

Arc welding processes involve the melting of the faying surfaces and the filler metal, if any, followed by solidification of the molten weld metal. Melting and solidification steps of welding are associated with the flow of heat and are affected by rate of heat transfer in and around the weld metal. Metallurgical structure of metal in weld and region close to the weld metal is mainly determined by the extent of rise in temperature and then cooling rate experienced by the metal at particular location of HAZ and weld. Further, differential heating and cooling experienced of different zones of weld joint cause not only metallurgical heterogeneity but also non-uniform volumetric change which in turn produces the residual stresses. These residual stresses adversely affect the mechanical performance of the weld joint besides distortion in the welded components if proper care is not taken. Since heating, soaking and cooling cycle affect the metallurgical & mechanical properties, development of residual stresses and distortion of the weld joints therefore it is pertinent to study various aspects related with heat flow in welding such as weld thermal cycle, cooling rate and solidification time, peak temperature, width of heat affected zone. Further, mechanisms of development of residual stresses and common methods relieving residual stresses apart from the distortion and their remedy will be discussed on heat flow in welding.



Schematic of weld thermal cycle of two different locations away from the weld centerline



Schematic of welding showing location of two points A & B

Weld Thermal Cycle

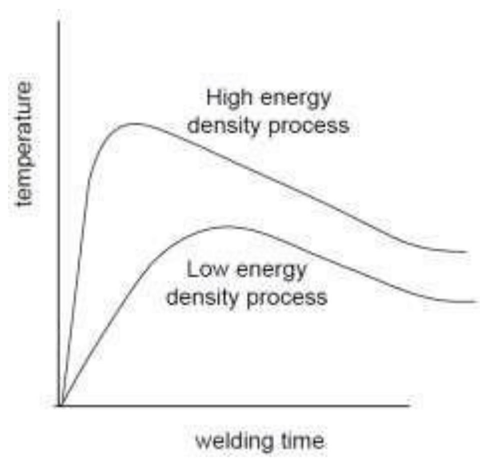
Weld thermal cycle shows variation in temperature of a particular location (in and around the weld) during the welding as a function of welding time. As the heat source (welding arc or flame) approaches close to the location of interest first temperature increases heating regime followed by gradual decrease in temperature cooling regime. A typical weld thermal cycle shows the rate of heating (slope of a b), peak temperature, and time required for attaining the peak temperature, cooling rate (slope of b c). Since distance of the point of interest away from the weld centerline directly affects all the above parameters heating and cooling rate, peak temperature of weld thermal cycle therefore each location/point offers different and unique weld thermal cycle. In general, an increase in distance of point of interest away from the weld center-line:

- decreases the peak temperature
- decreases the rate of heating and cooling
- increases time to attain peak temperature
- decreases rate of cooling with increase in time

Factors affecting welding thermal cycle

However, weld thermal cycle varies with distance from the weld center line but it is also influenced by heat input rate, amount of heat supplied for welding, weldment geometry, thermal properties of base metal and initial plate temperature. Rate of heat input is primarily governed by the energy density of heat input source which to a great extent depends upon the welding process being used for development of weld joints besides the welding parameters. High energy density processes like plasma arc welding and laser beam welding offer higher rate of heating, peak temperature and cooling rates than low energy density processes such as gas welding, shielded metal arc welding . Higher is the energy density of welding process, lower will be the heat input. Weld geometry parameters such as thickness of plates being welded also affect the heating rate, soaking time and cooling rate for a given rate of heat input (welding parameters) owing to changes in heat transfer conditions. In general, an increase in thickness of plate increases the rate of heat transfer from the weld pool/heat affected zone to the base metal which in turn a) decreases the high temperature retention time of HAZ, b) decreases the solidification time and c) increases the cooling rate experienced by the HAZ and weld metal.

Thermal properties of metal like thermal conductivity and specific heat also have effect on weld thermal cycle similar to that of thickness of plates as they increase the rate of heat transfer from the weld metal and HAZ. Preheating of the plates reduces the rate of heating and cooling and increases the peak temperature and soaking period above certain temperature because preheating reduces the rate of heat transfer away from the weld zone. Peak temperature near the weld fusion boundary decides the width of heat affected zone (HAZ). Heating and cooling rate affect the microstructure of weld metal and HAZ therefore weld thermal cycle of each point becomes of great interest especially in structure sensitive metals like high carbon steels.

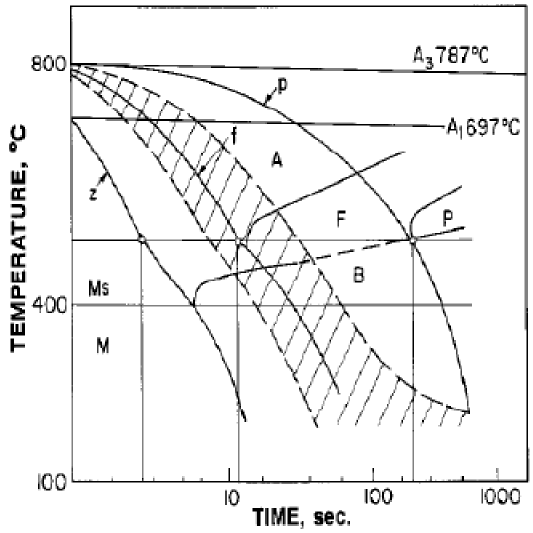


Influence of energy density of heat source related with welding process on weld thermal cycle of HAZ.

Cooling Rate

The final microstructure of weld zone and HAZ is primarily determined by the cooling rate (CR) from the peak temperature attained due to weld thermal cycle during welding. Cooling rate above a particular temperature say 550^{o}C for plain carbon eutectoid steel is of great importance in case of hardenable steel where a cooling rate (CR) determines the final microstructure and mechanical properties of weldment and HAZ. Since microstructure of hardenable steel has direct correlation with mechanical properties therefore, structure sensitive mechanical properties are affected by the cooling rate experienced by the weld metal and heat affected zone.

This is evident from the continuous cooling diagram of hypo-eutectoid steel. In the diagram, letter A, F, P, B, M indicates regions of austenite, ferrite, pearlite, bainite and martensite respectively.



Effect of cooling on structure of weld joints shown in form of CCT diagram

Weld thermal cycle indicates both heating and cooling rate. Cooling rate varies as a function of time, location of point of interest and temperature (at any moment on commencement of the cooling) during cooling regime of weld thermal cycle. The cooling rate calculation for HAZ of hardenable steel weld joint is mostly made at 5500C (corresponding to nose temperature of CCT) as cooling rate at this temperature predominantly decides the end microstructure and mechanical properties of the HAZ and weld joint. During welding, two welding parameters dictate the cooling rate a) net heat input during the welding and b) initial plate temperature besides the thermal and dimensional properties of material being welded. In general, increases in heat input decreases the cooling rate while reverse happens with increase of initial plate temperature during welding of a given metal having specific thickness and thermal properties. An increase in both heat input and initial plate temperature raises temperature of base metal around the weld which in turn decreases the rate of transfer away from the weld zone primarily due to reduction in temperature difference between the weld zone and surrounding base metal. Reduction in heat transfer rate from the weld metal to the base metal with increase in heat input and initial plate temperature means decrease in cooling rate. In view of above, major practical application of cooling rate equation is to determine the preheat requirement for plate to be welded so as to avoid critical cooling rate in weld and HAZ.

Net heat input (Hnet) during welding is obtained using following relationship:

$H_{net} = f \cdot VI/S$

where V is arc voltage (V), I welding current (A) and S welding speed mm/sec and f is the fraction of heat generated and transferred to the plate.

Example

Calculate the net heat input used during welding of plates if welding of steel plate is given below:

– Welding current: 150 A

– Arc voltage: 30 V

– Welding speed: 0.5 mm/sec

– 80 % of heat generated by the arc is used for welding.

Solution

Net heat input: Hnet = f .VI/S

= 0.8 X 30 X150/0.5

= 600 J/mm

= 0.6 kJ/mm

Critical cooling rate (CCR) under welding conditions

To determine the critical cooling rate for a steel plate under welding conditions, beadon plate welds are made with varying heat input. On the basis of thickness of the plate (5 mm) to be welded suitable electrode diameter is chosen first and then accordingly welding current and arc voltage are selected (20V, 200A, To=300C) for bead-on-plate (BOP) welding. Number of BOP welds is deposited using increasing welding speed (8, 9, 10, 11, 12……mm/sec). Once the BOP weld is completed at different welding speed, transverse section of weld is cut to measure the hardness.

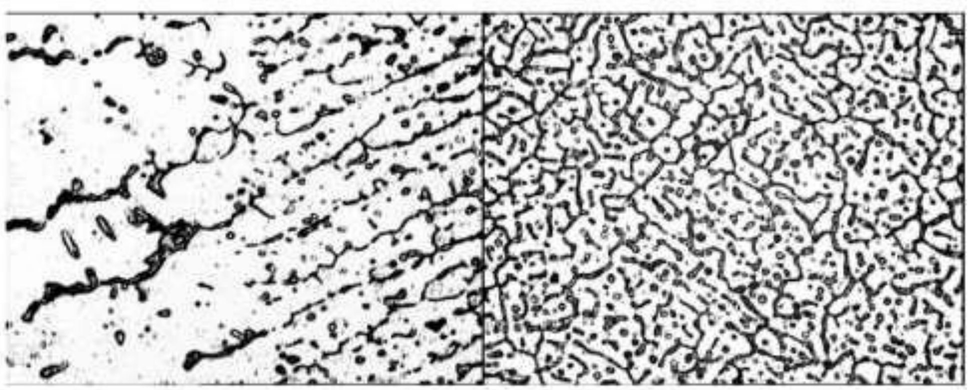
Solidification Rate

The solidification of weld metal takes place in three stages a) reduction in temperature of liquid metal, b) liquid to solid state transformation and c) finally reduction in temperature of solid metal up to room temperature. The time required for solidification of weld metal depends up on the cooling rate. Solidification time is the time interval between start to end of solidification. Solidification time is also of great importance as it affects the structure, properties and response to the heat treatment of weld metal. It can be calculated using following equation:

Solidification time of weld (St) = $LQ/2\pi k\rho c(tm-to)^2$ in sec

Where L is heat of fusion (for steel 2 J/mm^3)

Above equation indicates that solidification time is the function of net heat input, initial plate temperature and material properties such as latent heat of fusion (L), thermal conductivity (k), volumetric specific heat (C) and melting point (tm). Long solidification time allows each phase to grow to a large extent which in turn results in coarse-grained structure of weld metal. An increase in net heat input (with increase in welding current / arc voltage or reduction in welding speed) increases the solidification time. An increase in solidification time coarsens the grain structure which in turn adversely affects the mechanical properties. Non-uniformity in solidification rates in different regions of molten weld pool also brings variation in grain structure and so mechanical properties. Generally, centerline of the weld joint shows finer grain structure and better mechanical properties than those at fusion boundary primarily because of difference in solidification times. Micrographs indicate the coarser structure near the fusion boundary than the weld center.



Variation in microstructure of weld of Al-Si alloys of a) fusion boundary andb) weld centre owing to difference in cooling rate (200X)

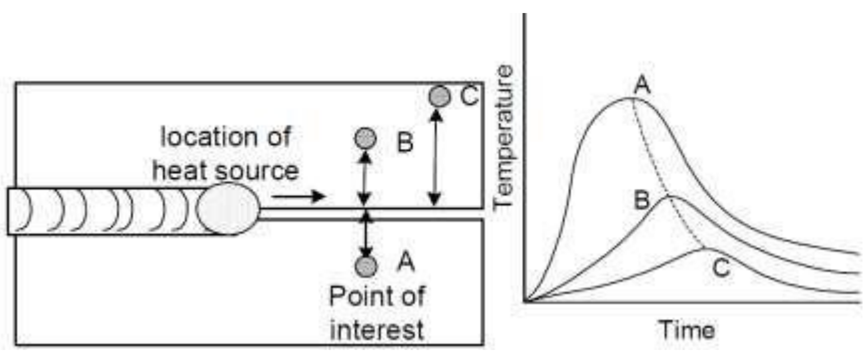
Residual stresses

Residual stresses are locked-in stresses present in the engineering components even when there is no external load and these develop primarily due to non-uniform volumetric change in metallic component irrespective of manufacturing processes such as heat treatment, machining, mechanical deformation, casting, welding, coating etc. However, maximum value of residual stresses doesn't exceed the elastic limit of the metal because stresses higher than elastic limit leads to plastic deformation and thus residual stresses greater than elastic limit are accommodated in the form of distortion of components. Residual stresses can be tensile or compressive depending up on the location and type of non-uniform volumetric change taking place due to differential heating and cooling like in welding and heat treatment or localized stresses like in contour rolling, machining and shot peening etc.

Residual stresses in welding

Residual stresses in welded joints primarily develop due to differential weld thermal cycle (heating, peak temperature and cooling at the any moment during welding) experienced by the weld metal and region closed to fusion boundary i.e. heat affected zone. Type and magnitude of the residual stresses vary continuously during different stages of welding i.e. heating and cooling. During heating primarily compressive residual stress is developed in the region of base metal which is being heated for melting due to thermal expansion and the same (thermal expansion) is restricted by the low temperature surrounding base metal.

After attaining a peak value compressive residual stress gradually decreases owing to softening of metal being heated. Compressive residual stress near the faying surfaces eventually reduces to zero as soon as melting starts and a reverse trend is observed during cooling stage of the welding. During cooling as metal starts to shrink, tensile residual stresses develop (only if shrinkage is not allowed either due to metallic continuity or constraint from job clamping) and their magnitude keeps on increasing until room temperature is attained. In general, greater is degree of constraint and elastic lami of melt higher will be the value of residual stresses.



Weld thermal cycle of a) locations A, B, C and b) temperature vs time relation of A, B and C

Mechanisms of residual stress development

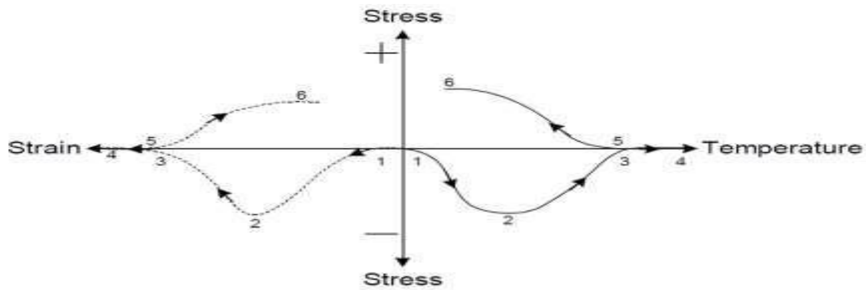
The residual stresses in the weld joints develop mainly due to typical nature of welding process i.e. localized heating and cooling leading to differential volumetric expansion and contraction of metal around the weld zone. The differential volumetric change occurs both at macroscopic and microscopic level. Macroscopic volumetric changes occurring during welding contribute to major part of residual stress development and are caused by a) varying expansion and contraction and b) different cooling rate experienced by top and bottom surfaces of weld & HAZ.

Microscopic volumetric changes mainly occur due to metallurgical transformation (austenite to martensitic transformation) during cooling. Further, it is important to note that whenever residual stresses develop beyond the yield point limit, the plastic deformation sets in the component. If the residual stress magnitude is below the elastic limit then a stress system having both tensile and compressive stresses for equilibrium is developed.

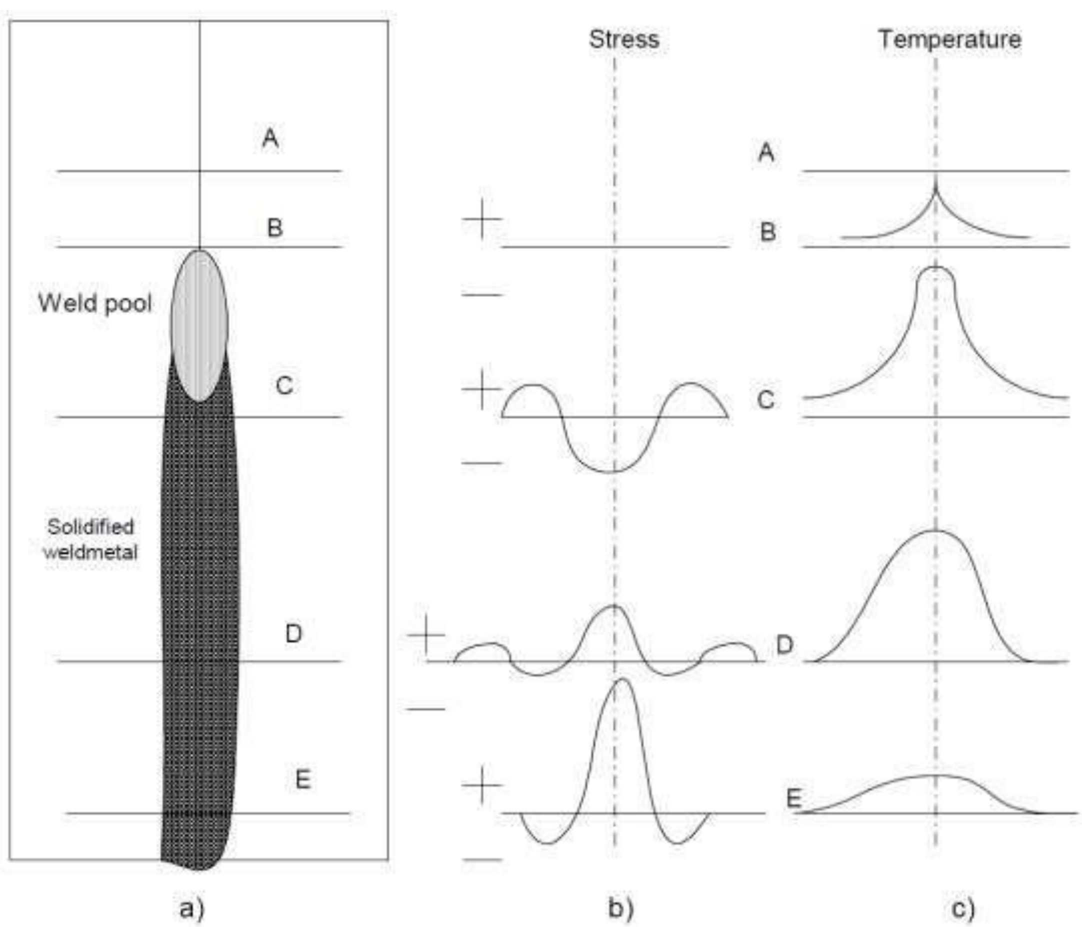
Differential heating and cooling

Residual stresses develop due to varying heating and cooling rate in different zones near the weld as function of time are called thermal stresses. Different temperature conditions lead to varying strength and volumetric changes in base metal during welding. The variation in temperature and residual stresses owing to movement of heat source along the centerline of weldment is shown schematically. As heat source comes close to the point of interest, its temperature increases. Increase in temperature decreases the yield strength of material and simultaneously tends to cause thermal expansion of the metal being heated. However, surrounding low temperature base metal restricts any thermal expansion which in turn develops compressive strain in the metal during heating. Compressive strain initially increases non-linearly with increase in temperature due to variation in yield strength and expansion coefficient of metal with temperature rise. Further, increase in temperature softens the metal, therefore, compressive strain reduces gradually and eventually it is vanished. As the heat source crosses the point of interest and starts moving away from the point of interest, temperature begins to decrease gradually.

Reduction in temperature causes the shrinkage of hot metal in base metal and HAZ. Initially at high temperature contraction occurs without much resistance due to low yield strength of metal but subsequently shrinkage of metal is resisted as metal gains strength owing to reduction in temperature during cooling regime of weld thermal cycle. Therefore, further contraction in shrinking base and weld metal is not allowed with reduction in temperature. This behavior of contraction leaves the metal in strained condition which means that metal which should have contracted, is not allowed to do so and this leads to development of the tensile residual stresses (if the contraction is prevented). The magnitude of residual stresses can be calculated from the product of locked-in strain and modulus of elasticity of metal being welded.



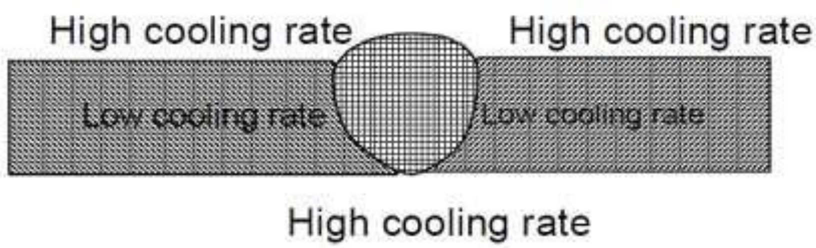
The residual stress along the weld is generally tensile in nature while balancing compressive residual stress is developed adjacent to the weld in heat affected zone on cooling to the room temperature as evident from the Figure.



Schematic diagram showing a) plate being welded, b) stress variation across the weld centerline at different locations and c) temperature of different locations

Differential cooling rate in different zone

During welding, higher cooling rate is experienced by the top and bottom surfaces of weld joint than the core/middle portion of weld and HAZ. This causes differential expansion and contraction through the thickness (direction) of the plate being welded. Contraction of metal near the surface starts even when material in core portion is still hot. This leads to the development of compressive residual stresses at the surface and tensile residual stress in the core.



Schematic showing different cooling rates at surface and core regions ofthe weld

Metallurgical Transformation

During welding, heat affected zone of steel and weld zone invariably experience transformation of austenite into other phases phase mixture like pearlite, bainite or martensite. All these transformations occur with increase in specific volume at microscopic level. The transformations (from austenite to pearlite and bainite) occurring at high temperature are easily accommodated with this increase in specific volume owing to low yield strength and high ductility of these phases and phase mixtures at high temperature (above 550 0C) therefore such metallurgical transformations don’t contribute much towards the development of residual stresses.

Transformation of austenite into martensite takes place at very low temperature with significant increase in specific volume. Hence, this transformation contributes significantly towards development of residual stresses. Depending upon the location of the austenite to martensitic transformation, residual stresses may be tensile or compressive. For example, shallow hardening causes such transformation from austenite to martensite near the surface layers only and develops compressive residual stresses at the surface and balancing tensile stress in core while through section hardening develops reverse trend of residual stresses i.e. tensile residual stresses at the surface and compressive stress in the core.

Effect of residual stresses

The residual stresses whether they are tensile or compressive type predominantly affect the soundness, dimensional stability and mechanical performance of the weld joints. Since magnitude of residual stresses increases gradually to peak value until weld joint is cooled down to the room temperature therefore mostly the effects of residual stresses are observed either near the last stage of welding or after some time of welding in the form of cracks (hot cracking, lamellar tearing, cold cracking), distortion and reduction in mechanical performance of the weld joint.

Presence of residual stresses in the weld joints can encourage or discourage failures due to external loading as their effect is additive in nature. Conversely, compressive residual stresses decrease failure tendency under external tensile stresses primarily due to reduction in net tensile stresses acting on the component (net stress on the component: external stresses + residual stresses). Residual stress of the same type as that of external one increases the failure tendency while opposite type of stresses (residual stress and externally applied stress) decrease the same.

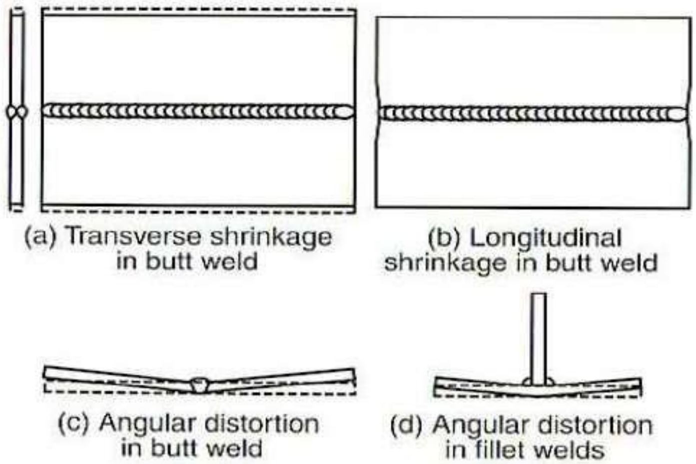
Since more than 90% failure of mechanical component occurs under tensile stresses by crack nucleation and their propagation under tensile loading conditions therefore presence of tensile residual stresses in combination with external tensile loading adversely affect the performance in respect of tensile load carrying capacity while compressive residual stresses under similar loading conditions reduce the net stresses and so discourage the failure tendency.

Hence, compressive residual stresses are intentionally induced to enhance tensile and fatigue performance of mechanical components whereas efforts are made to reduce tensile residual stresses using various approaches such as post weld heat treatment, shot peening, spot heating etc.

In addition to the cracking of the weld joint under normal ambient conditions, failure of weld joints exposed in corrosion environment is also accelerated in presence of tensile residual stresses by a phenomenon called stress corrosion cracking.

Presence of tensile residual stresses in weld joints causes cracking problems which in turn adversely affect their load carrying capacity. The system residual stress is usually destabilized during machining and may lead to distortion of the weld joints. Therefore, residual stresses must be relieved from the weld joint before undertaking any machining operation.Weld Distortion

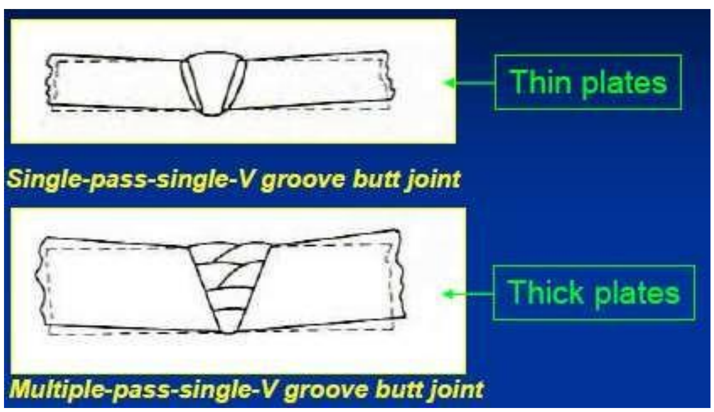
Weld distortions due to solidification shrinkage and thermal contraction of the weld metal during welding.



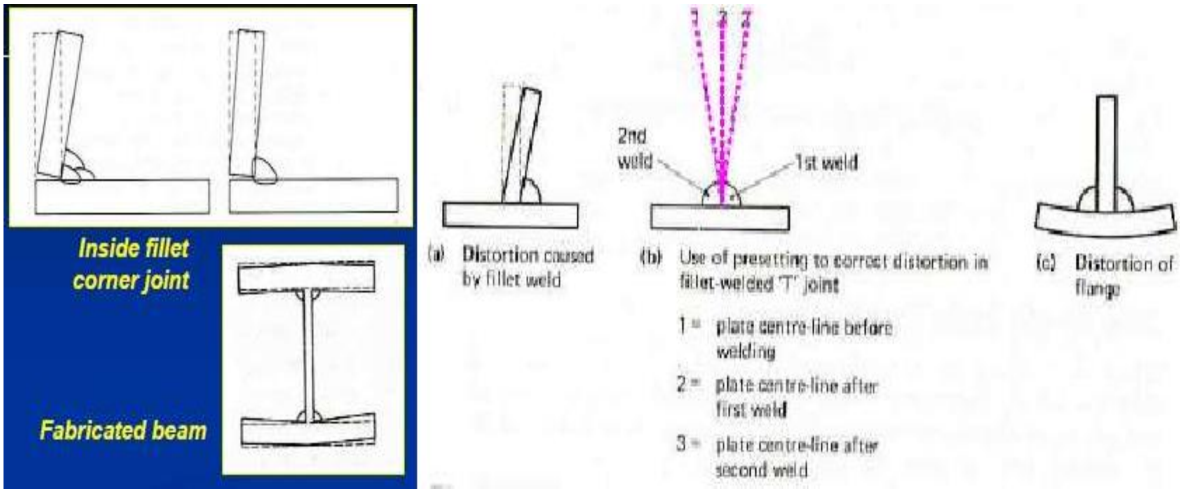
Distortion in welded structure

Angular distortion

Upward angular distortion usually occurs when the weld is made from the top of the workpiece alone. The weld tends to be wider at the top than the bottom, causing more solidification shrinkage and thermal contraction.



Angular Distortions in butt welded plates

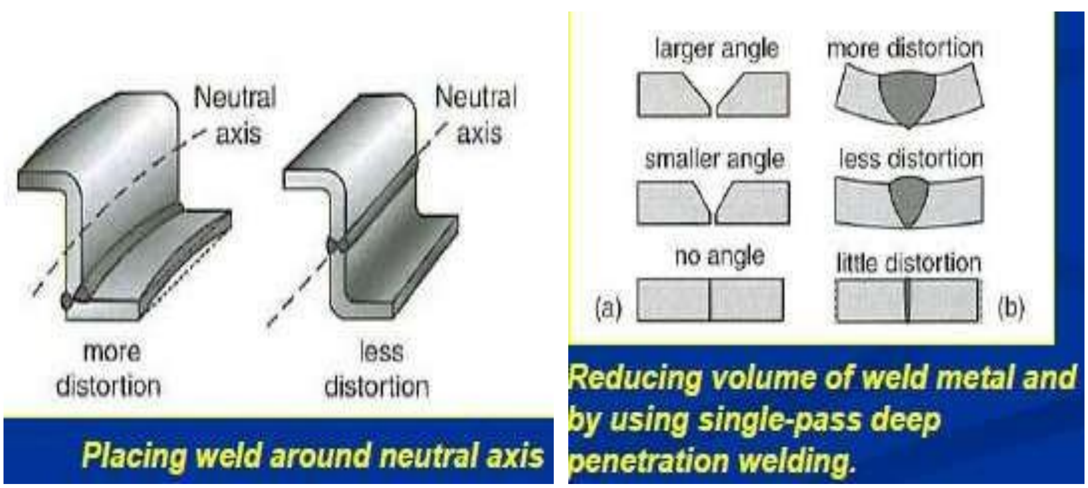


Angular Distortions in fillet joint

Remedies for angular distortion

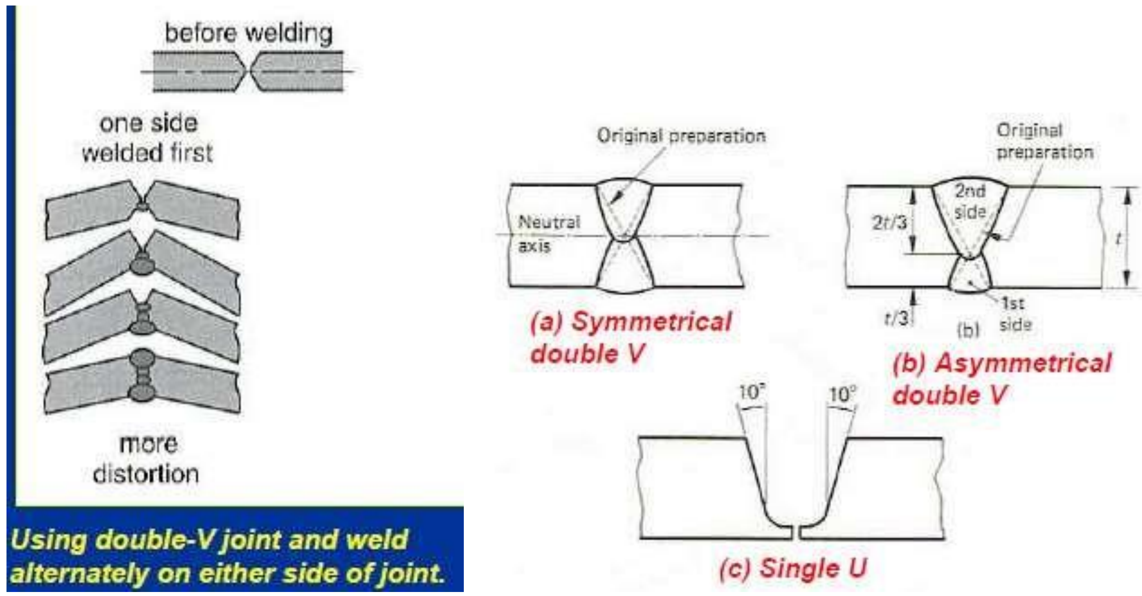
There are several techniques used to reduce angular distortion.

- Reducing volume of weld metal
- Using double-V joint and alternate welding
- Placing welds around neutral axis
- Controlling weld distortion



Angular Distortions prevention techniques

Balancing the angular weld distortion on either side of the double V joint



Angular Distortions prevention for different grooves

• Double V-joints balance the shrinkage _ almost same amount of contraction on each side (a).

• Asymetrical double V: The first weld always produces more angular distortion _the second side is larger too pull back the distortion when the first weld is made (b).

• A single U joint gives a uniform weld with through the section (c).

Methods for controlling weld distortion:

(a) Preseting

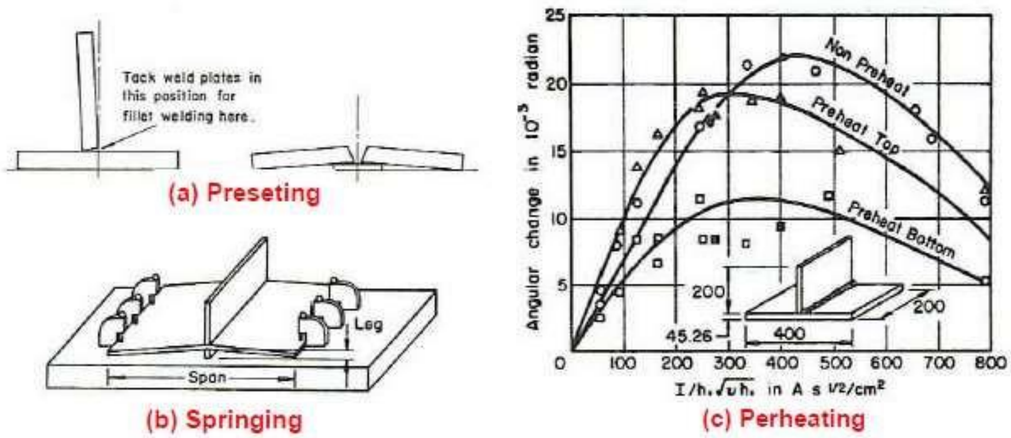
(b) Springing

(c) Perheating

• Presetting: by compensating the amount of distortion to occur in welding.

• Elastic prespringing can reduce angular changes after restraint is removed.

• Preheating and post weld treatment



Methods for controlling weld distortion

Longitudinal distortion

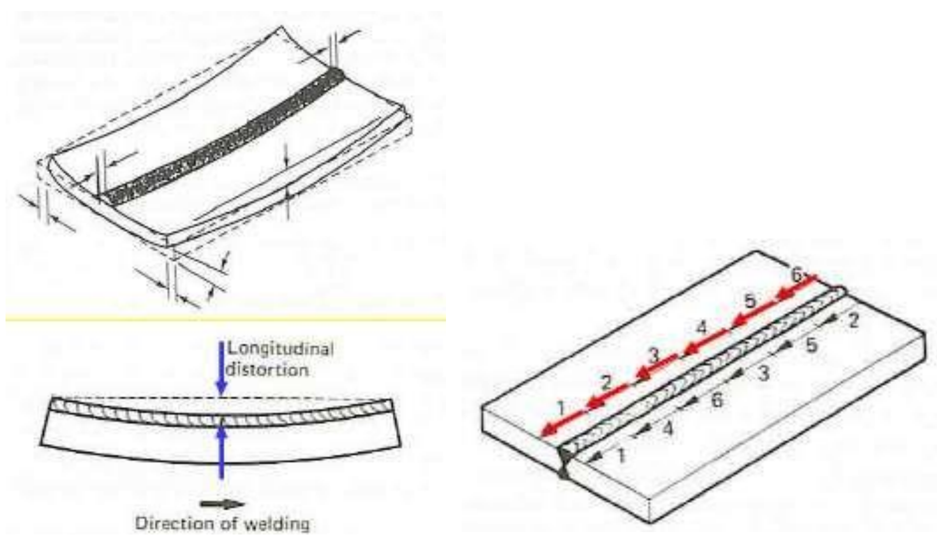
• Heating and cooling cycles along the joint during welding build up a cumulative effect of longitudinal bowing.

Remedies

• Welding short lengths on a planned or random distribution are used to controlled this problem.

• Mechanical methods: straightening press, jacks, clamps

• Thermal methods: local heating to relieve stresses (using torches) but cannot be used for highly conductive metal such as Al and Cu.



Methods for controlling weld distortion

Sequences for welding short lengths of a joint to reduce longitudinal bowing

• Angular distortion and longitudinal bowing can also be observed in joints made with fillet welds such as fillet-welded T joint

Remedies

• Back-step technique is also used. Each small increment will have its own shrinkage pattern which then becomes insignificant to the whole pattern of weldment. (But time consuming)

• Using the smallest possible weld size.

Fatigue analysis of welded joints

Fatigue of welds is even more complex. Welding strongly affects the material by the process of heating and subsequent cooling as well as by the fusion process with additional filler material, resulting in inhomogeneous and different materials. Furthermore, a weld is usually far from being perfect, containing inclusions, pores, cavities, undercuts etc. The shape of the weld profile and non-welded root gaps create high stress concentrations with widely varying geometry parameters. Last but not least residual stresses and distortions due to the welding process affect the fatigue behaviour. As a consequence, fatigue failures appear in welded structures mostly at the welds rather than in the base metal, even if the latter contains notches such as openings or re-entrant corners. For this reason, fatigue analyses are of high practical interest for all cyclic loaded welded structures, such as ships, offshore structures, cranes, bridges, vehicles, railcars etc. In view of the complexity of the subject and the wide area of application it is not surprising that several approaches for fatigue analysis of welded joints exist. However, it is almost impossible to follow up the great amount of related literature dealing with fatigue testing and the development or application of approaches to consider all the different influence parameters.

Fatigue analysis approaches

Different approaches exist for the fatigue analysis of welded joints, which can be distinguished by the parameters used for the description of the fatigue life N or fatigue strength. In general, the approaches can be subdivided into the following categories:

* Nominal stress approach, using the nominal stress range determined by the external or internal loads and by the related cross section properties.

* Structural or hot-spot stress approach, using the structural stress range at the weld to consider additionally the effect of the structural discontinuity.

Notch stress and notch intensity approach, using the elastic notch stress range or an equivalent parameter such as the stress intensity to take the notch effect of the weld toe or root into account.

* Notch strain approach, using the local elastic–plastic strain range and/or other parameters describing the relevant damage process in the material.
* Crack propagation approach, using special parameters such as the J-integral or the range of the stress intensity to describe the increase of the crack length per cycle, i.e. the crack propagation rate.

To produce quality weld joints, it is necessary to keep an eye on what is beingdone in three different stages of the welding

- Before welding such as cleaning, edge preparation, baking of electrode etc. to ensure sound and defect free weld joints.
- During welding various aspects such as manipulation of heat source, selection of input parameters (pressure of oxygen and fuel gas, welding current, arc voltage, welding speed, shielding gases and electrode selection) affecting the heat input and so melting, solidification and cooling rates besides protection of the weld pool from atmospheric contamination.
- After welding steps, if any, such as removal of the slag, peening, post welding treatment

Selection of optimal method and parameters of each of above steps and their execution meticulously in different stages of production of a weld joint determine the quality of the weld joint. Inspection is mainly carried out to assess ground realties in respect of progress of the work or how meticulously things are being implemented. Testing helps to: a) assess the suitability of the weld joint for a particular application and b) to take decision on whether to go ahead (with further processing or accept/reject the same) at any stage of welding and c) quantify the performance parameters related with soundness and performance of weld joints.

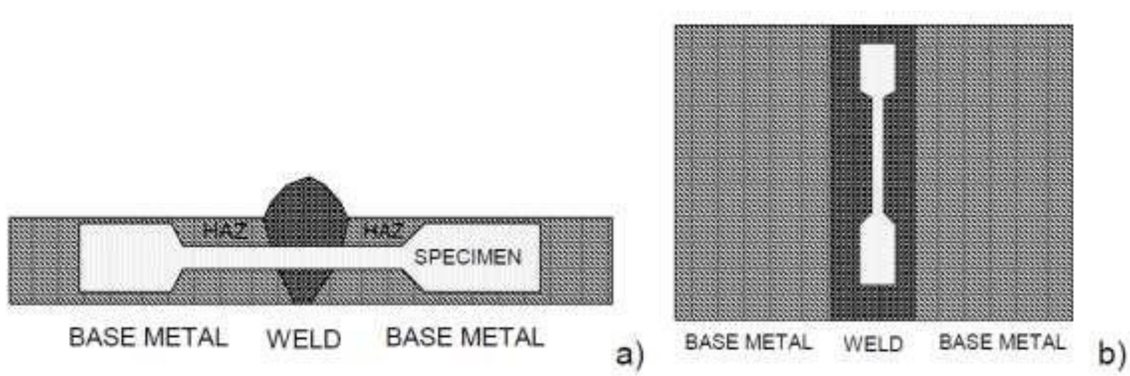
Testing methods of the weld joint are broadly classified as destructive testing and non-destructive testing. Destructive testing methods damage the test piece to more or less extent. The extent of damage on (destructive) tested specimens sometime can be up to complete fracture (like in tensile or fatigue testing) thus making it un-useable for the intended purpose while in case of non-destructive tested specimen the extent of damage on tested specimen is either none or negligible which does not adversely affect their usability for the intended purpose in anyways.

Weld joints are generally subjected to destructive tests such as hardness, toughness, bend and tensile test for developing the welding procedure specification and assessing the suitability of weld joint for a particular application.

Visual inspection reflects the quality of external features of a weld joint such as weld bead profile indicating weld width and reinforcement, bead angle and external defects such as craters, cracks, distortion etc. only.

Tensile test

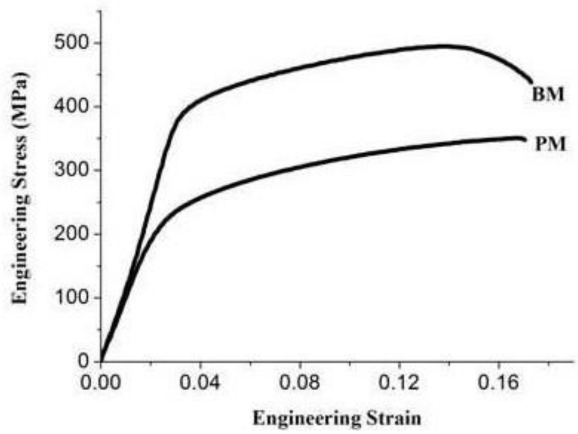
Tensile properties of the weld joints namely yield and ultimate strength and ductility (%age elongation, %age reduction in area) can be obtained either inambient condition or in special environment (low temperature, high temperature, corrosion etc.) depending upon the requirement of the application using tensile test which is usually conducted at constant strain rate (ranging from 0.0001 to 10000 mm/min). Tensile properties of the weld joint are obtained in two ways a) taking specimen from transverse direction of weld joint consisting base metal heat-affected zone-weld metal-heat affected zone-base metal and b) all weld metal specimen



Schematic of tensile specimens from a) transverse section of weld joints and b) all weld specimen

Tensile test results must be supported by respective engineering stress and strain diagram indicating modulus of elasticity, elongation at fracture, yield and ultimate strength. Tests results must include information on following point about test conditions

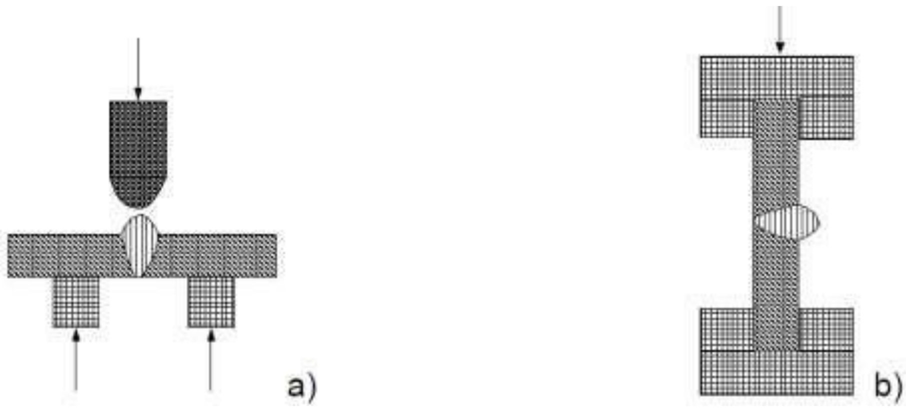
- Type of sample (transverse weld, all weld specimen)
- Strain rate (mm/min)
- Temperature or any other environment in which test was conducted if any
- Topography, morphology, texture of the fracture surface indicating the mode of fracture and respective stress state



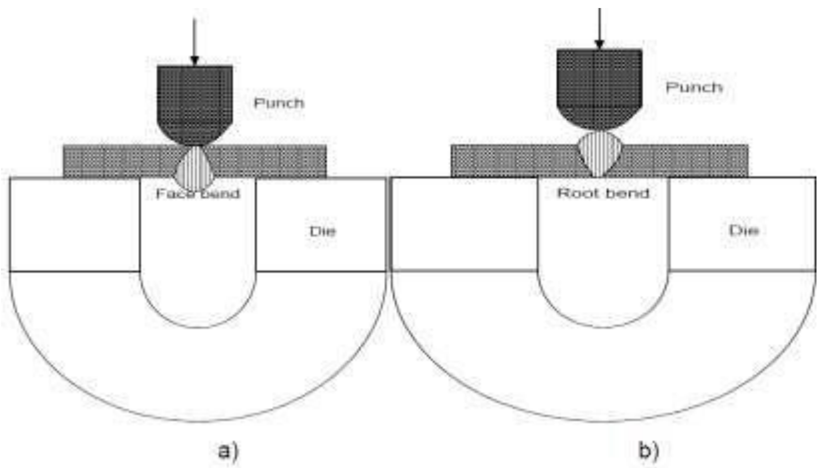
Typical stress stain diagram for AA 7039 in as received (BM) and friction stir prcoessed (PM) condition

Bend test

Bend test is one of the most important and commonly used destructive tests to determine the ductility and soundness (for the presence porosity, inclusion, penetration and other macro-size internal weld discontinuities) of the weld joint produced using under one set of welding conditions. Bending of the weld joint can be done from face or root side depending upon the purpose i.e. whether face or root side of the weld is to be assessed. The root side bending shows the lack of penetration and fusion if any at the root. Further, bending can be performed using simple compressive/bending load and die of standard size for free and guided bending respectively. Moreover, free bending can be face or root bending while guided bending is performed by placing the weld joint over the die as needs for bending is better and controlled condition.



Schematics of free bend tests



Schematics of guided bend tests a) face bend and b) root bend

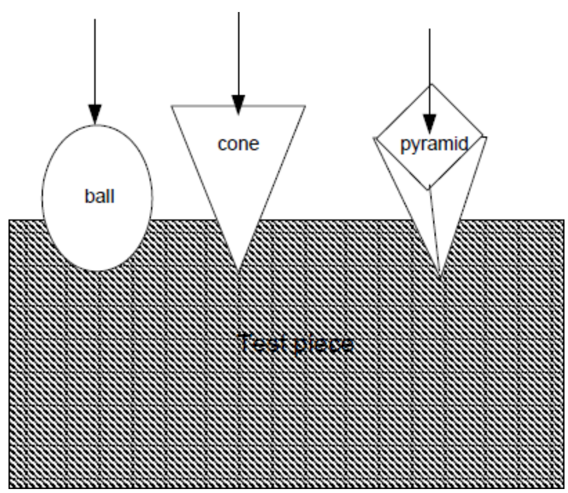
For bend test, the load increased until cracks start to appear on face or root ofthe weld for face and root bend test respectively and angle of bend at this stageis used as a measured of ductility of weld joints. Higher is bend angle (needed forcrack initiation) greater is ductility of the weld. Fracture surface of the joint fromthe face/root side due to bending reveals the presence of internal welddiscontinuities if any.

Hardness test

Hardness is defined as resistance to indentation and is commonly used as a measure of resistance to abrasion or scratching. For the formation of a scratch or causing abrasion, a relative movement is required between two bodies and out of two one body must penetrate/indent into other body. Indentation is the penetration of a pointed object (harder) into other object (softer) under the external load. Resistance to the penetration of pointed object (indenter) into the softer one depends on the hardness of the sample on which load is applied through the indenter.

All methods of hardness testing are based on the principle of applying the standard load through the indenter (a pointed object) and measuring the penetration in terms of diameter/diagonal/depth of indentation . High penetration of an indenter at a given standard load suggests low hardness. Various methods of hardness testing can be compared on the basis of following three criteria 1) type of indenter, 2) magnitude of load and 3) measurement of indentation.

Parameter	Brinell	Rockwell	Knoop	Vickers
Load	500-2000 kg	Minor: 10 kg Major: 60 to 200 kg as dictated by scale to be used (A-C)	10 to 3000 g	
Indenter	Ball	Ball or cone	Cone	Pyramid
Measurement	Diameter	Depth	Diagonal	Diagonal



Schematic diagram showing indentation using different indenters corresponding to different hardness test methods

Penetration due to applied normal load is affected by unevenness on the surface and presence of hard surface films such as oxides, lubricants, dust and dirt etc. if any. Therefore, surface should be cleaned and polished before hardness test. In case of Brinell hardness test, full load is applied directly for causing indentation for measuring hardness while in case of Rockwell hardness test, minor load (10 kN) is applied first before applying major load. Minor load is applied to ensure the firm metallic contact between the indenter and sample surface by breaking surface films and impurities if any present on the surface. Minor load does not cause indentation. Indentation is caused by major load only. Therefore, cleaning and polishing of the surface films becomes mandatory for accuracy in hardness test results in case of Brinell test method as major load is applied directly. Steel ball of different diameters (D) is used as an indenter in Brinell hardness test. Diameter of indentation (d) is measured to calculate the projected area and determine the hardness. Brinell hardness test results are expressed in terms of pressure generated due to load (P). It is calculated by the ratio of load applied and projected contact area. Load in the range of 500 to 3000 kg can be applied depending upon the type of material to be tested. Higher load is applied for hardness testing of hard materials as compared to soft materials.

$$\mathrm{BHN} = \frac{2P}{\pi D[D - (D^2 - d^2)]^{1/2}}$$

In case of Rockwell hardness test first minor load of 10 kg is applied and then major load of 50-150kg is applied on the surface of the work-piece through the indenter and the same is decided by scale (A, B, C and D) to be used as per type of material to be tested. Minor load is not changed. Out of mainly scales, B and C scales are commonly used. Different indenter and major load are required for each scale. Steel ball and diamond cone are two types of indenters used in Rockwell testing. B scale uses hardened steel ball and major load of 90kg whereas C scale uses diamond cone and major load of 140kg accordingly hardness is written in terms of HRB and HRC respectively.

Non-destructive testing (NDT)

To determine the presence of surface and surface imperfections, non-destructive testing of weld joints can be carried out using variety of techniques as per needs. Apart from the visual inspection, many non-destructive testing methods including dye penetrant test(DPT), magnetic particle test (MPT), eddy current test (ECT), ultrasonic test (UT), radiographic test (RT) etc. are used in manufacturing industry for assessing the soundness of weld joints. In following section, principle and capability of some nondestructive testing methods have been described.

Dye penetrant test

This is one of the simplest non-destructive testing methods primarily used for detectingthe presence of surface defects only. In this method surface to be tested a thin low viscosity and low surface tension liquid containing suitable dye is applied. The thin liquid penetrates (by capillary action) into fine cavities, pores and cracks, if any, present on the surface. Excess liquid present at surface is wiped out. Then suitable developer like talc or chalk powder is sprinkled over the surface. Developer sucks out thin liquid with dye wherever it is present inside the surface discontinuities present on the weld joints. Dye with liquid changes colour of developer and indicates location, and size of surface defects.

This is due to variation in the welding current which is caused by changes in the surface condition of the workpiece, changes in the electrode tip diameter fit-up, and changes in the impedance of the welding circuit. The shunting effect which may be a consequence of the presence of other spot welds is another source of quality variation. This necessitates the development of in-process control techniques that can produce a uniform weld quality regardless of the welding environment changes. Many variables associated with the welding process have been examined for the quality monitoring. More frequently referred variables seem to be the dynamic resistance and the electrode movement. Several attempts have been made to correct weld quality utilizing these variables. One such method is to utilize the dynamic resistance as a quality control variable but essentially an ON-OFF feedback system. Recently a resistance tracking method has been attempted to explore the possibility of using the instantaneous resistance value as an on-line feedback signal. The performance of this tracking control showed that more uniform weld strength can be obtained with this controller. But the control performance appeared to be very sensitive to the choice of controller gain parameters due to the complex shape of the resistance curve. Besides these methods, welding voltage and welding current have been used as a control variable, but these techniques are essentially regulating the control variables to the specified input values and do not use the process state variables for on-line feedback control.

In this approach a new digital control technique is developed to obtain uniform weld quality regardless of the changing welding environments. The control system utilizes a proportional (P) control algorithm, incorporating with the electrode movement as an output feedback variable. In this controller the welding current is generated so as to track a desired trace of the electrode movement (reference electrode movement curve) throughout welding time. The electrode movement trace was measured by a non contacting displacement sensor and sampled via an A/D converter to compute the command control current. A series of experiments was performed to evaluate the performance of this tracking controller.

MODULE-III

METAL FORMING

COURSE OUTCOMES (COs):

At the end of the course students are able to:		
Course Outcomes		**Knowledge Level (Bloom's Taxonomy)**
CO5	**Apply** the appropriate metal forming techniques, for producing components like hexagonal bolt, nut etc.,	Apply
CO6	**Explain** the working principle of hot and cold extrusion processes and their application in industries for making of pipes and tubes.	Apply

PROGRAM OUTCOMES (POs):

Program Outcomes (POs)		**Strength**	**Proficiency Assessed by**
PO 2	**Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.	3	CIE/Quiz/AAT
PO 3	**Design/development of solutions:** Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.	2	Seminar/ conferences/ Research papers

Cold working

Cold working or cold forming is any metalworking process in which metal is shaped below its recrystallization temperature, usually at the ambient temperature. Such processes are contrasted with hot working techniques like hot rolling, forging, welding, etc.

Cold forming techniques are usually classified into four major groups: squeezing, bending, drawing, and shearing. They generally have the advantage of being simpler to carry out than hot working techniques. Unlike hot working, cold working causes the crystal grains and inclusions to distort following the flow of the metal; which may cause work hardening and anisotropic material properties.

Work hardening makes the metal harder, stiffer, and stronger, but less plastic, and may cause cracks of the piece

Hot working

Hot working process metals are plastically deformed above their recrystallization temperature. Being above the recrystallization temperature allows the material to recrystallize during deformation. This is important because recrystallization keeps the materials from strain hardening, which ultimately keeps the yield strength and hardness low and ductility high. This contrasts with cold working. Many kinds of working, including rolling, forging, extrusion, and drawing, can be done with hot metal.

Maintaining temperature:

The lower limit of the hot working temperature is determined by its recrystallization temperature. As a guideline, the lower limit of the hot working temperature of a material is 60% its melting temperature (on an absolute temperature scale). The upper limit for hot working is determined by various factors, such as: excessive oxidation, grain growth, or an undesirable phase transformation. In practice materials are usually heated to the upper limit first to keep forming forces as low as possible and to maximize the amount of time available to hot work the workpiece.

The most important aspect of any hot working process is controlling the temperature of the workpiece. 90% of the energy imparted into the workpiece is converted into heat. Therefore, if the deformation process is quick enough the temperature of the workpiece should rise, however, this does not usually happen in practice. Most of the heat is lost through the surface of the workpiece into the cooler tooling. This causes temperature gradients in the workpiece, usually due to non-uniform cross-sections where the thinner sections are cooler than the thicker sections. Ultimately, this can lead to cracking in the cooler, less ductile surfaces. One way to minimize the problem is to heat the tooling. The hotter the tooling the less heat lost to it, but as the tooling temperature rises, the tool life decreases. Therefore the tooling temperature must be compromised; commonly, hot working tooling is heated to 325–450 °C (500–850 °F).

Difference between Hot and Cold Working

Cold working may be defined as plastic deformation of metals and alloys at a temperature below the recrystallization temperature for that metal or alloy. In cold working process the strain hardening which occurs as a result of mechanical working, does not get relieved. In fact as the metal or alloys gets progressively strain hardened, more and more force is required to cause further plastic deformation. After sometime, if the effect of strain hardening is not removed, the forces applied to cause plastic deformation may cause cracking and failure of material.

Hot working may be explained as plastic deformation of metals and alloys at such a temperature above recrystallization temperature at which recovery and recrystallization take place simultaneously with the strain hardening.

Recrystallization temperature is not a fixed temperature but is actually a temperature range. Its value depends upon several factors. Some of the important factors are:

- Nature of metal or alloy: It is usually lower for pure metals and higher for alloys. For pure metals, recrystallization temperature is roughly one third of its melting point and for alloys about half of the melting temperature.

- Amount of cold work already done: The recrystallization temperature is lowered as the amount of strain-hardening done on the work piece increases.
- Strain-rate: Higher the rate of strain hardening, lower is the recrystallization temperature. For mild steel, recrystallization temperature range may be taken as 550– 650°C. Recrystallization temperature of low melting point metals like lead, zinc and tin, may be taken as room temperature. The effects of strain hardening can be removed by annealing above the recrystallization temperature.

Advantages and Disadvantages Of Cold And Hot Working Processes

- As cold working is practically done at room temperature, no oxidation or tarnishing of surface takes place. No scale formation is there, hence there is no material loss where as in hot working, there is scale formation due to oxidation besides, hot working of steel also results in partial decarburization of the work piece surface as carbon gets oxidized as CO_2.
- Cold working results in better dimensional accuracy and a bright surface. Cold rolled steel bars are therefore called bright bars, while those produced by hot rolling process are called black bars (they appear greyish black due to oxidation of surface.
- In cold working heavy work hardening occurs which improves the strength and hardness of bars, and high forces are required for deformation increasing energy consumption. In hot working this is not so.
- Due to limited ductility at room temperature, production of complex shapes is not possible by cold working processes.
- Severe internal stresses are induced in the metal during cold working. If these stresses are not relieved, the component manufactured may fail prematurely in service. In hot working, there are no

residual internal stresses and the mechanically worked structure is better than that produced by cold working.

• The strength of materials reduces at high temperature. Its malleability and ductility improve at high temperatures. Hence low capacity equipment is required for hot working processes. The forces on the working tools also reduce in case of hot working processes.

• Sometimes, blow holes and internal porosities are removed by welding action at high temperatures during hot working.

• Non-metallic inclusions within the work piece are broken up. Metallic and non-metallic segregations are also reduced or eliminated in hot working as diffusion is promoted at high temperatures making the composition across the entire cross-section more uniform.

Annealing:

"The term annealing is a very general term used in heat treatments of metals and alloys. It includes any cycle of heating and cooling of metallic materials, irrespective of temperatures, rates and terms involved in the cycle. Depending upon the material being treated and the object of treatment, annealing operations may involve any of a very broad range of heating rates, soaking temperatures and soaking times and cooling rates. These methods can be used for stress-relieving, recrystallization and grain growth.

During annealing, the material is heated to a temperature not far below the critical seized for a adequate period of time to achieve the desired changes meant for the heat treatment, and then cooled to room temperature on a desired time. The purpose of annealing is to eliminate partially or completely the strain hardening produced by earlier mechanical forming operations, so that it can be put into service in a relatively soft, ductile condition. It must be realized that annealing involves recrystallization in which a combination of cold working and subsequent heating causes new stress-free crystals in a matrix which is itself stress free. A full anneal treatment is a process intended to reduce the metal treated to its softness possible condition. The term, "annealing" is generally used, without qualifications or further description, as full anneal. The full anneal is widely used on steels to remove the effects of cold working, eliminate residual stress and improve the machinability of medium and high carbon grades.

Recovery

In cold work changes takes place in both physical and mechanical properties. Plastic deformation increases strength, hardness and electrical resistance but it decrease ductility." . "The initial change in structure and properties that occur upon annealing a cold-worked metal is considered the beginning of recovery. As recovery progress, the following structural changes occur in sequence.

1. The disappearance (annealing out) of point defects, vacancies and their clusters.

2. The eradication and reorganization of dislocations.

3. Polygonization (Sub-grain formation and Subgrain growth).

4. The arrangement of recrystallization nuclei energetically capable of more growth." "These structural changes do not engage high angle boundary migration. Consequently, during this stage of annealing, the quality of the deformed metal essentially does not change."

"In the recovery phase of annealing, the physical and mechanical properties tend to recovery their original values. That the variety of physical and mechanical properties does not recover their values at the same speed indicates complicated nature of the recovery method. Another anisothermal curve corresponding to the energy released on heating cold work polycrystalline nickel. Point C defines the region of recrystallization. Plotted on the same diagram are curves showing change in electrical resistivity and hardness as a function of temperature. It is visible that the resistivity is completely recovered before the start of recrystallization. But, the most important change is in the hardness simultaneously with recrystallization of the matrix.

Relative to its absolute melting temperature produces microstructural and property changes that include (1) a change in grain shape (2) strain hardening and (3) an increase in dislocation density. Some fraction of the energy expended in deformation is stored in the metal as strain energy, which is associated with tensile, compressive, and shear zones around the newly created dislocations. Furthermore, other properties such as electrical conductivity and corrosion resistance may be modified as a consequence of plastic deformation.

These properties and structures may revert back to the pre cold-worked states by appropriate heat treatment (sometimes termed an *annealing treatment*). Such restoration results from two different processes that occur at elevated temperatures: *recovery* and *recrystallization,* which may be followed by *grain growth.*

RECOVERY

During recovery, some of the stored internal strain energy is relieved by virtue of dislocation motion (in the absence of an externally applied stress), as a result of enhanced atomic diffusion at the elevated temperature. There is some reduction in the number of dislocations, and dislocation configurations are produced having low strain energies. In addition, physical properties such as electrical and thermal conductivities are recovered to their precold-worked states.

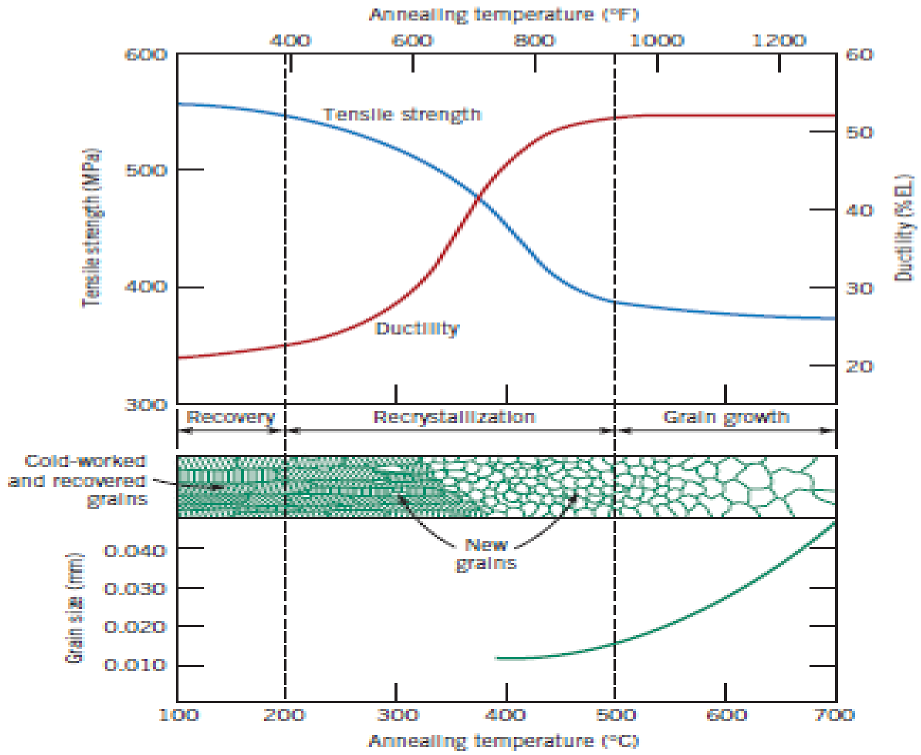
RECRYSTALLIZATION

Even after recovery is complete, the grains are still in a relatively high strain energy state. Recrystallization is the formation of a new set of strain-free and equiaxed grains (i.e., having approximately equal dimensions in all directions) that have low dislocation densities and are characteristic of the precold-worked condition. The driving force to produce this new grain structure is the difference in internal energy between the strained and unstrained material. The new grains form as very small nuclei and grow until they completely consume the parent material, processes that involve short-range diffusion. Several stages in the recrystallization process in these photomicrographs, the small speckled grains are those that have recrystallized. Thus, recrystallization of cold worked metals may be used to refine the grain structure.

Also, during recrystallization, the mechanical properties that were changed as a result of cold working are restored to their precold-worked values; that is, the metal becomes softer and weaker, yet more ductile. Some heat treatments are designed to allow recrystallization to occur with these modifications in the mechanical characteristics.

Recrystallization is a process the extent of which depends on both time and temperature.The recrystallization behaviour of a particular metal alloy is sometimes specified in terms of a recrystallization temperature, the temperature at which recrystallization just reaches completion in 1 hr. Thus, the recrystallization temperature for the brass alloy of Figure 7.22 is about 450C (850F). Typically, it is between one-third and one-half of the absolute melting temperature of a metal or alloy and depends on several factors, including the amount of prior cold work and the purity of the alloy. Increasing the percentage of cold work enhances the rate of recrystallization, with the result that the recrystallization temperature is lowered, and approaches a constant or limiting value at high deformations. Furthermore, it is this limiting or minimum recrystallization temperature that is normally specified in the literature. There exists some critical degree of cold work below which recrystallization cannot be made to occur, normally, this is between 2% and 20% cold work.

Recrystallization proceeds more rapidly in pure metals than in alloys. During recrystallization, grain-boundary motion occurs as the new grain nuclei form and then grow. It is believed that impurity atoms preferentially segregate at and interact with these recrystallized grain boundaries so as to diminish their (i.e., grain boundary) mobilities; this results in a decrease of the recrystallization rate and raises the recrystallization temperature, sometimes quite substantially. For pure metals, the recrystallization temperature is normally 0.4Tm, where Tm is the absolute melting temperature; for some commercial alloys it may run as high as 0.7Tm. Recrystallization and melting temperatures for a number of metals and alloys.



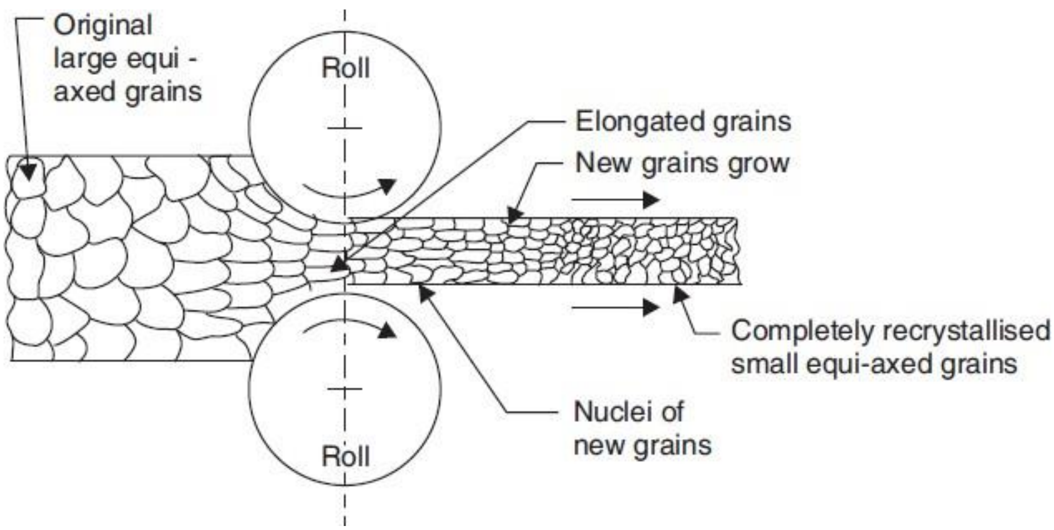
GRAIN GROWTH:

After recrystallization is complete, the strain-free grains will continue to grow if the metal specimen is left at the elevated temperature; this phenomenon is called grain growth. Grain growth does not need to be preceded by recovery and recrystallization; it may occur in all polycrystalline materials, metals and ceramics alike. An energy is associated with grain boundaries,. As grains increase in size, the total boundary area decreases, yielding an attendant reduction in the total energy; this is the driving force for grain growth.

Grain growth occurs by the migration of grain boundaries. Obviously, not all grains can enlarge, but large ones grow at the expense of small ones that shrink. Thus, the average grain size increases with time, and at any particular instant there will exist a range of grain sizes. Boundary motion is just the short-range diffusion of atoms from one side of the boundary to the other. The directions of boundary movement and atomic motion are opposite to each other

Rolling

In this process, metals and alloys are plastically deformed into semifinished or finished products by being pressed between two rolls which are rotating. The metal is initially pushed into the space between two rolls, thereafter once the roll takes a ‘‘bite’’ into the edge of the material, the material gets pulled in by the friction between the surfaces of the rolls and the material. The material is subjected to high compressive force as it is squeezed (and pulled along) by the rolls. This is a process to deal with material in bulk in which the cross-section of material is reduced and its length increased. The final cross-section is determined by the impression cut in the roll surface through which the material passes and into which it is compressed. The essentials of the rolling process can be understood from the Fig



Rolling is done both hot and cold. In a rolling mill attached to a steel plant, the starting point is a cast ingot of steel which is broken down progressively into blooms, billets and slabs. The slabs are further hot rolled into plate, sheet, rod, bar, rails and other structural shapes like angles, channels etc. Conversion of steel into such commercially important sections is usually done in another rolling mill called merchant mill.

Rolling is a very convenient and economical way of producing commercially important sections. In the case of steel, about three-fourth’s of all steel produced in the country is ultimately sold as a rolled product and remaining is used as forgings, extruded products and in cast form. This shows the importance of rolling process.

NOMENCLATURE OF ROLLED PRODUCTS

The following nomenclature is in common usage:

(i) **Blooms:** It is the first product obtained from the breakdown of Ingots. A bloom has a cross section ranging in size from 150 mm square to 250 mm square or sometimes 250 × 300 mm rectangle.

(ii) **Billet:** A billet is the next product rolled from a bloom. Billets vary from 50 mm square to

125 mm square.

(iii) **Slab:** Slab is of rectangular cross-section with thickness ranging from 50 to 150 mm and is available in lengths up to 112 metres.

(iv) **Plate:** A plate is generally 5 mm or thicker and is 1.0 or 1.25 metres in width and 2.5 metres in length.

(v) **Sheet:** A sheet is up to 4 mm thick and is available in same width and length as a plate.

(vi) **Flat:** Flats are available in various thickness and widths and are long strips of material of specified cross-section.

(vii) **Foil:** It is a very thin sheet.

(viii) **Bar:** Bars are usually of circular cross-section and of several metres length. They are common stock (raw material) for capstan and turret lathes.

(ix) **Wire:** A wire is a length (usually in coil form) of a small round section; the diameter of which specifies the size of the wire.

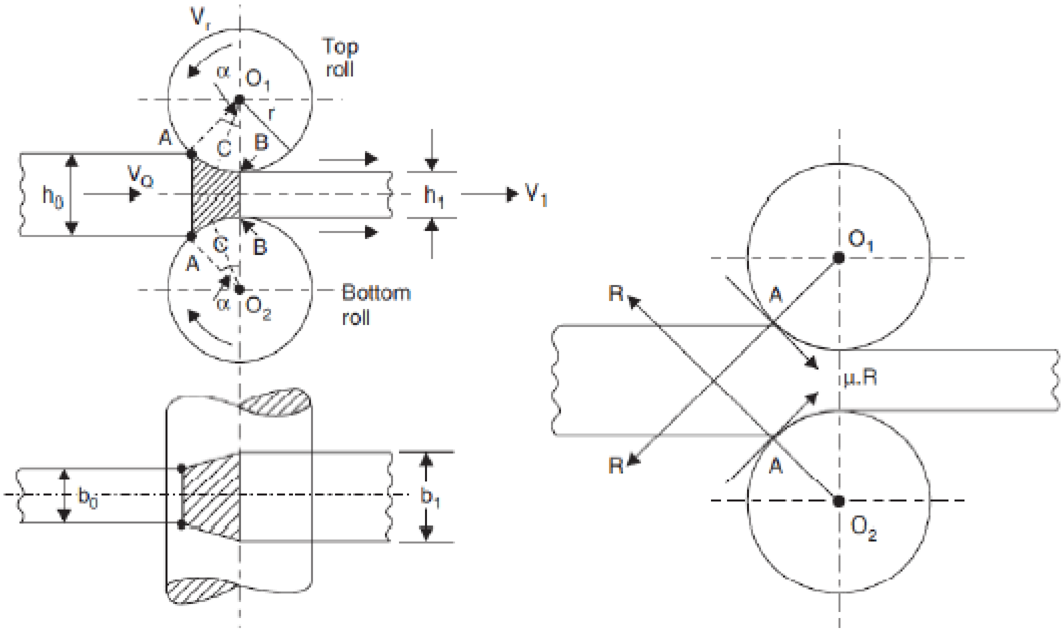
MECHANISM OF ROLLING

Each of the two rolls contact the metal surface along the arc *AB*, which is called arc of contact. Arc *AB* divided by the radius of rolls will gives angle of contact (α). The rollers pull the material forwards only due to the friction existing between roll surface and the metal. At the moment of the bite, the reaction at the contact point *A* will be *R* acting along radial line *O*1*A* and frictional force will be acting along tangent at *A* at right angles to *O*1*A*. In the limiting case,

$R \sin \alpha = \mu R \cos \alpha$

$\therefore \mu = \tan \alpha$ or $\alpha = \tan^{-1} \mu$

If α is greater than $\tan^{-1} \mu$, the material would not enter the rolls unaided.



(a) Schematic diagram of rolling process

(b) Forces during rolling

$$\cos\alpha = \frac{r - \frac{1}{2}(h_0 - h_1)}{r}$$

Where h_0 is the thickness of material and h_1 is the gap between two rollers at the narrowest point and *r* is the radius of rollers. For a given diameter of rollers and gap between them the value of *h*0 is limited by the value of μ which in turn depends upon the material of rolls and job being rolled, the roughness of their surfaces and the rolling temperature and speed. In case of hot rolling when maximum reduction is cross-section per pass is aimed at, it may be necessary to artificially increase the value of μ by ‘‘ragging’’ the surface of rolls. Ragging means making the surface of rolls rough by making fine grooves on the roll-surface. However, in cold rolling which is a finishing operation and cross-section reduction is limited, ragging of rolls is neither required nor desirable. In fact, in that case, some lubrication is resorted to in addition to giving a fine finish to the rolls. Another reason for making do with a lower coefficient of friction in cold rolling is that in this process, very high pressures are used and even with a low value of μ, adequate frictional force becomes available.

The usual values of biting angles employed in industry are: 2–10° ... for cold rolling of sheets and strips; 15–20° ... for hot rolling of sheets and strips;24–30° ... for hot rolling of heavy billets and blooms.

In the rolling process, although the material is being squeezed between two rolls, the width (b_0) of the material does not increase or increases only very slightly. Since volume of material entering the rolls is equal to the volume of material leaving the rolls, and the thickness of material reduces from h_0 to h_1, the velocity of material leaving the rolls must be higher than the velocity of material entering the rolls. The rolls are moving at a uniform r.p.m. and their surface speed remains constant. The rolls are trying to carry the material into the rolls with the help of friction alone, there is no positive grip between rolls and the material. On one side, therefore, *i.e.*, point *A* where contact between the rolls and work material starts, the rolls are moving at faster surface speed than the work material. As the material gets squeezed and passes through the rollers, its speed gradually increases and at a certain section *CC* called neutral or no slip section, the velocity of metal equals the velocity of rolls. As material is squeezed further, its speeds exceed the speed of the rolls. The angle subtended at the centre of the roll at the neutral section is called angle of no slip or critical angle (angle BO_1C).

The deformation zone to the left of the neutral section is called lagging zone and the deformation zone to the right of the neutral section is termed leading zone. If V_r is the velocity of roll surface, V_0 the velocity of material at the entrance to the deformation zone and V_1 at the exit of the rolls, we have

$$\text{Forward slip} = \frac{V_1 - V_r}{V_r} * 100 \text{ percent}$$

$$\text{Backward slip} = \frac{V_r - V_0}{V_r} * 100 \text{ percent}$$

The value of forward slip normally is 3–10% and increases with increase in roll diameter and coefficient of friction and also with reduction in thickness of material being rolled. Some other useful terms associated with rolling are explained below:

Absolute draught: Delta $h = h_i - h_0$ mm

Relative draught: $\frac{\text{Delta}h}{h_1} * 100$ percent

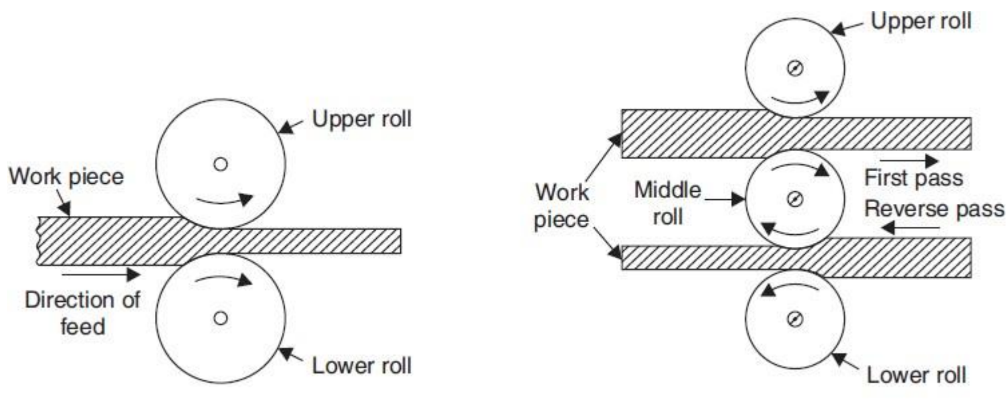
Δl = Final length – Original length of work material Coefficient of elongation = Final length/Original length

Absolute spread = Final width of work material – Original width of material

TYPES OF ROLLING MILLS

Different types of rolling mills are described below in brief:

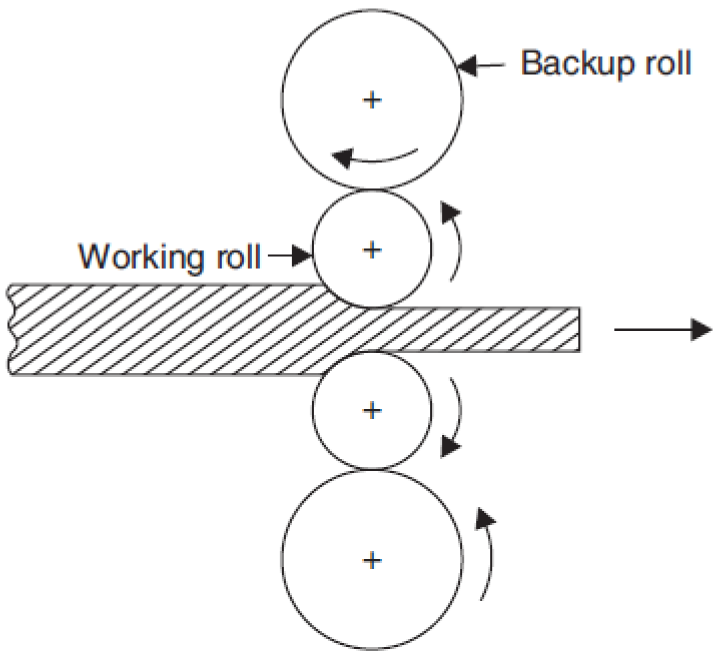
Two high mills: It comprises of two heavy rolls placed one over the other. The rolls are supported in bearings housed in sturdy upright frames (called stands) which are grouted to the rolling mill floor. The vertical gap between the rolls is adjustable. The rolls rotate in opposite directions and are driven by powerful electrical motors. Usually the direction of rotation of rolls cannot be altered, thus the work has to be fed into rolls from one direction only. If rolling entails more than one 'pass' in the same set of rolls, the material will have to be brought back to the same side after the first pass is over. Since transporting material (which is in red hot condition) from one side to another is difficult and time consuming (material may cool in the meantime), a ''two high reversing mill'' has been developed in which the direction of rotation of rolls can be changed. This facilitates rolling of material by passing it through back and forth passes. A two high rolling mill arrangement is shown in Fig.



(a) A two high mill (b) A three high rolling mill

Three high mills: A three high rolling mill arrangement is shown in Fig. It consists of three rolls positioned directly over one another as shown. The direction of rotation of the first and second rolls are opposite as in the case of two high mill. The direction of rotation of second and third rolls is again opposite to each other. All three rolls always rotate in their bearings in the same direction. The advantage of this mill is that the work material can be fed in one direction between the first and second roll and the return pass can be provided in between the second and third rolls. This obviates the transport of material from one side of rolls to the other after one pass is over

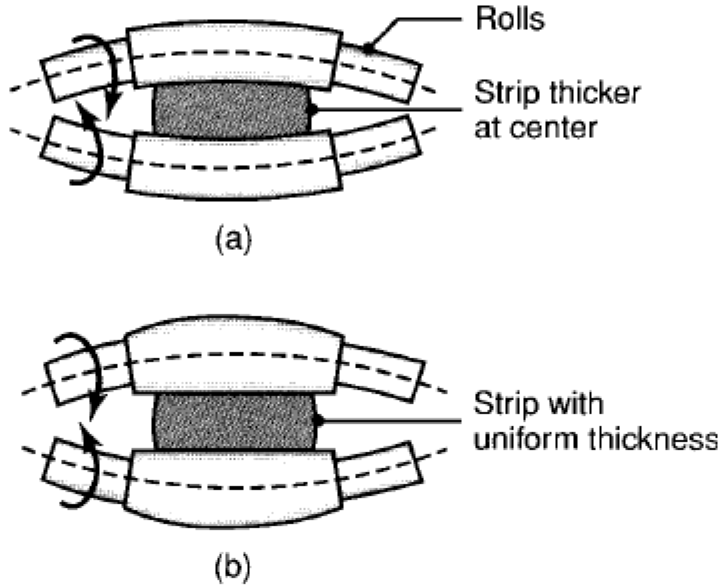
Four high mills: As shown in Fig, this mill consists of four horizontal rolls, two of smaller diameter and two much larger ones. The larger rolls are called backup rolls. The smaller rolls are the working rolls, but if the backup rolls were not there, due to deflection of rolls between stands, the rolled material would be thicker in the centre and thinner at either end. Backup rolls keep the working rolls pressed and restrict the deflection, when the material is being rolled. The usual products of these mills are hot and cold rolled plates and sheets.



Cluster mills: It consists of two working rolls of small diameter and four or more backing rolls. The large number of backup rolls provided becomes necessary as the backup rolls cannot exceed the diameter of working rolls by more than 2–3 times. To accommodate processes requiring high rolling loads (*e.g.*, cold rolling of high strength steels sheets), the size of working rolls becomes small. So does the size of backup rolls and a stage may be reached that backup rolls themselvesmay offer deflection. So the backup rolls need support or backing up by further rolls.

Geometric Considerations

Because of the forces acting on them, rolls undergo changes in shape during rolling. just as a straight beam deflects under a transverse load, roll forces tend to bend the rolls elastically during rolling As expected, the higher the elastic modulus of the roll material, the smaller the roll deflection. As a result of roll bending, the rolled strip tends to be thicker at its center than at its edges (crown). The usual method of avoiding this problem is to grind the rolls in such way that their diameter at the center is slightly larger than at their edges (camber). Thus, when the roll bends, the strip being rolled now has a constant thickness along its width For rolling sheet metals, the radius of the maximum camber point is generally 0.25 mm greater than that at the edges of the roll. However, as expected, a particular camber is correct only for a certain load and strip width. To reduce the effects of deflection, the rolls also can be subjected to external bending by applying moments at their bearings

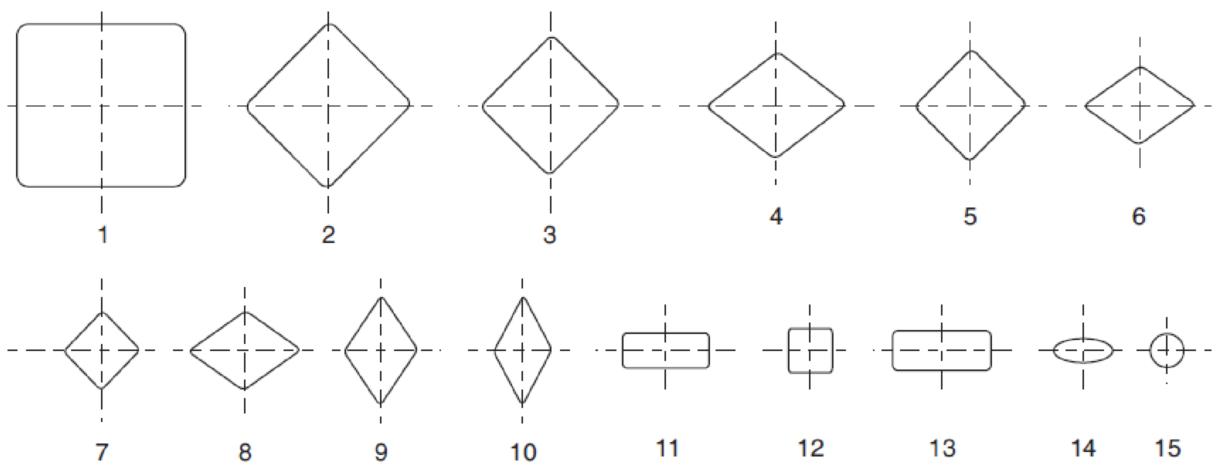


(a) Bending of straight cylindrical rolls caused by roll forces. (b) Bending of rolls ground with camber, producing a strip with uniform thickness through the strip width.

ROLLS AND ROLL PASS DESIGN

Two types of rolls—Plain and Grooved are shown in Figure. Rolls used for rolling consists of three parts *viz*., body, neck and wabbler. The necks rest in the bearings provided in the stands and the starshaped wabblers are connected to the driving shaft through a hollow cylinder. Wabbler acts like a safety device and saves the main body of the roll from damage if too heavy a load causes severe stresses. The actual rolling operation is performed by the body of the roll. The rolls are generally made from a special variety of cast iron, cast steel or forged steel. Plain rolls have a highly finished hard surface and are used for rolling flats, plates and sheets. Grooved rolls

have grooves of various shapes cut on their periphery. One-half of the required shape of rolled product is sometimes cut in the lower roll and one-half in the upper roll, so that when the rolls are assembled into its stands, the required shape in full will be produced on the work material, once it passes (*i.e.*, rolled) through the groove in question. However it should be understood that the desired shape of the rolled section is not achieved in a single pass. The work material has to be rolled again and again through several passes and each pass brings the cross-section of the material closer to the final shape required. These passes are carefully designed to avoid any rolling defect from creeping in. Rolling is a painstaking process as would be noticed from the scheme of passes shown in Figure for conversion of a steel billet into a round bar.



Various stages of rolling and the number of passes for converting a steel billet into round bar

Various passes fall into the following groups:

(i) Breakdown or roughing passes,

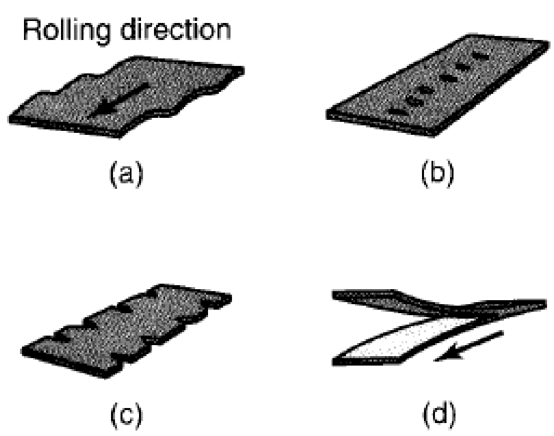
(ii) Leader passes, and

(iii) Finishing passes.

Breakdown passes are meant to reduce the cross-sectional area. The leader passes gradually bring the cross-section of the material near the final shape. The final shape and size is achieved in finishing passes. Allowance for shrinkage on cooling is given while cutting the finishing pass grooves.

Defects in Rolling

Defects may be present on the surfaces of rolled plates and sheets, or there may be internal structural defects. Defects are undesirable not only because they compromise surface appearance, but also because they may adversely affect strength, formability, and other manufacturing characteristics. Several surface defects (such as scale, rust, scratches, gouges, pits, and cracks) have been identified in sheet metals. These defects may be caused by inclusions and impurities in the original cast material or by various other conditions related to material preparation and to the rolling operation. Wavy edges on sheets are the result of roll bending. The strip is thinner along its edges than at its center); thus, the edges elongate more than the center. Consequently, the edges buckle because they are constrained by the central region from expanding freely in the longitudinal (rolling) direction. The cracks are usually the result of poor material ductility at the rolling temperature. Because the quality of the edges of the sheet may affect sheet-metal-forming operations, edge defects in rolled sheets often are removed by shearing and slitting operations. Alligatoring is the phenomenon and typically is caused by non uniform bulk deformation of the billet during rolling or by the presence of defects in the original cast material.



(a) wavy edges; (b) zipper cracks in the center of the strip; (c) edge cracks; and (d) alligatoring

MODULE- IV
EXTRUSION AND RAPID PROTOTYPING

COURSE OUTCOMES (COs):

At the end of the course students are able to:		
Course Outcomes		**Knowledge Level (Bloom's Taxonomy)**
CO7	**Analyze** the manufacturing defects as well as material characterization and its application.	Apply
CO8	**Classify** the various forging techniques based on functionality, cost and time in development of critical products.	Understand

PROGRAM OUTCOMES (POs):

Program Outcomes (POs)		**Strength**	**Proficiency Assessed by**
PO 2	**Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.	3	CIE/Quiz/AAT
PO 3	**Design/development of solutions:** Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.	2	Seminar/ conferences/ Research papers

Extrusion is a process in which the metal is subjected to plastic flow by enclosing the metal in a closed chamber in which the only opening provided is through a die. The material is usually treated so that it can undergo plastic deformation at a sufficiently rapid rate and may be squeezed out of the hole in the die. In the process the metal assumes the opening provided in the die and comes out as a long strip with the same cross-section as the die-opening. Incidentally, the metal strip produced will have a longitudinal grain flow. The process of extrusion is most commonly used for the manufacture of solid and hollow sections of nonferrous metals and alloys *e.g.*, aluminium, aluminium-magnesium alloys, magnesium and its alloys, copper, brass and bronze etc. However, some steel products are also made by extrusion. The stock or the material to be extruded is in the shape of cast ingots or billets. Extrusion may be done hot or cold. The cross- sections of extruded products vary widely.

Some advantages of extrusion process are described below:

- The complexity and range of parts which can be produced by extrusion process is very large.

- Dies are relative simple and easy to make.
- The extrusion process is complete in one pass only. This is not so in case of rolling, amount of reduction in extrusion is very large indeed. Extrusion process can be easily automated.
- Large diameter, hollow products, thin walled tubes etc. are easily produced by extrusion process.
- Good surface finish and excellent dimensional and geometrical accuracy is the hall mark of extruded products. This cannot be matched by rolling.

Pressure required for extrusion depends upon the strength of material and upon the extrusion temperature. It will reduce if the material is hot. It will also depend upon the reduction in cross-section required and the speed of extrusion. There is a limit to the extrusion speed. If extrusion is done at a high speed, the metal may crack. The reduction of cross-sectional area required is also called “extrusion ratio”. There is a limit to this also. For steel extruded hot, this ratio should not exceed 40 : 1, but for aluminium extruded hot it can be as high as 400 : 1.

EXTRUSION PROCESSES

Extrusion processes can be classified as followed:

(A) Hot Extrusion

(i) Forward or Direct extrusion.

(ii) Backward or Indirect extrusion.

(B) Cold Extrusion

(i) Hooker extrusion.

(ii) Hydrostatic extrusion.

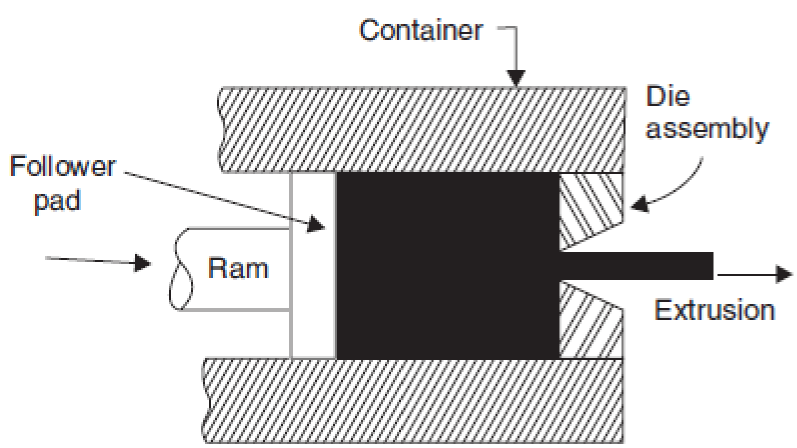
(iii) Impact extrusion.

(iv) Cold extrusion forging.

A. Hot Extrusion Processes

(*i*) **Forward or direct extrusion process:** In this process, the material to be extruded is in the form of

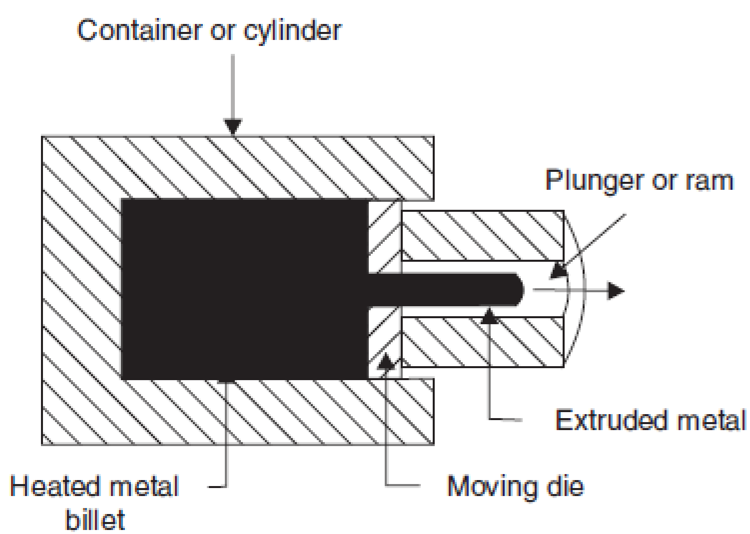
a block. It is heated to requisite temperature and then it is transferred inside a chamber as shown in Fig. In the front portion of the chamber, a die with an opening in the shape of the cross-section of the extruded product, is fitted. The block of material is pressed from behind by means of a ram and a follower pad. Since the chamber is closed on all sides, the heated material is forced to squeeze through the die-opening in the form of a long strip of the required cross-section.



Forward or direct extrusion

The process looks simple but the friction between the material and the chamber walls must be overcome by suitable lubrication. When extruding steel products, the high temperature to which the steel has to be heated makes it difficult to find a suitable lubricant. The problem is solved by using molten glass as a lubricant. When lower temperatures are used, a mixture of oil and graphite is used as a lubricant. At the end of the extrusion process, a small piece of metal is left behind in the chamber which cannot be extruded. This piece is called butt—end scrap and is thrown away. To manufacture a tubular rod, a mandrel of diameter equal to that of tube—bore is attached to the ram. This mandrel passes centrally through the die when the material is extruded. The outside diameter of the tube produced will be determined by the hole in the die and the bore of tube will be equal to mandrel diameter. The extrusion process will then called "tubular extrusion".

Backward or indirect extrusion: This process is depicted in Figure. As shown, the block of heated metal is inserted into the container/chamber. It is confined on all sides by the container walls except in front; where a ram with the die presses upon the material. As the ram presses backwards, the material has to flow forwards through the opening in the die. The ram is made hollow so that the bar of extruded metal may pass through it unhindered.



Backward or Indirect extrusion

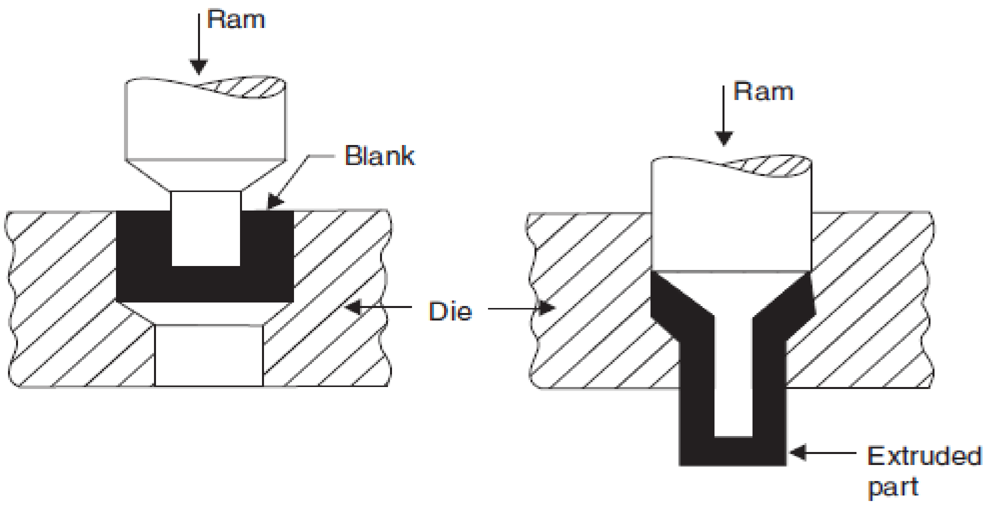
This process is called backward extrusion process as the flow of material is in a direction opposite to the movement of the ram. In the forward extrusion process the flow of material and ram movement Were both in the same direction. The following table compares the forwards (direct) and backwards (Indirect extrusion process).

Comparison between Forward and Backward extrusion

Forward or Direct extrusion	Backward or Indirect extrusion
1. Simple, but the material must slide along the chamber wall. 2. High friction forces must be overcome. 3. High extrusion forces required but mechanically simple and uncomplicated. 4. High scrap or material waste—18–20% on an average.	1. In this case, material does not move but die moves. 2. Low friction forces are generated as the mass of material does not move. 3. 25–30% less extruding force required as compared to direct extrusion. But hollow ram required limited application. 4. Low scrap or material waste only 5–6% of billet weight.

Cold Extrusion Processes

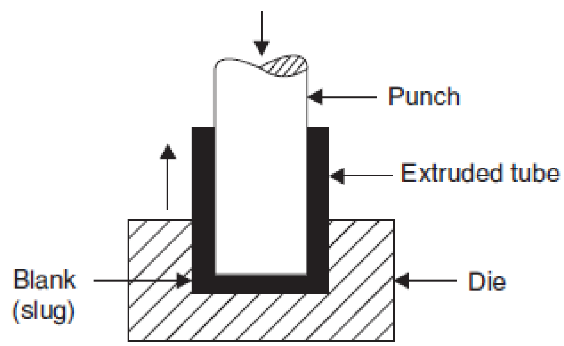
Hooker extrusion process: This process is also known as extrusion down method. It is used for producing small thin walled seamless tubes of aluminium and copper. This is done in two stages. In the first stage the blank is converted into a cup shaped piece. In the second stage, the walls of the cup one thinned and it is elongated. The process can be understood by referring to Figure. This process is a direct extrusion process.



Hooker extrusion

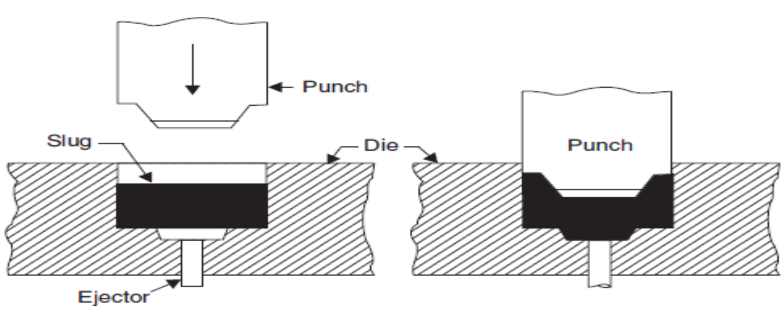
Hydrostatic extrusion: This is a direct extrusion process. But the pressure is applied to the metal blank on all sides through a fluid medium. The fluids commonly used are glycerine, ethyl glycol, mineral oils, castor oil mixed with alcohol etc. Very high pressures are used – 1000 to 3000 MPa. Relatively brittle materials can also be successfully extruded by this method.

Impact extrusion: In this process, which is shown in Figure the punch descends with high velocity and strikes in the centre of the blank which is placed in a die. The material deforms and fills up the annular space between the die and the punch flowing upwards. Before the use of laminated plastic for manufacturing tooth paste, shaving cream tubes etc., these collapsible tubes containing paste were and are still made by this process. Other examples of products made by impact extrusion are light fixtures, automotive parts, and small pressure vessels. Most nonferrous metals can be impact extruded in vertical presses and at production rates as high as two parts per second. This process is actually a backward extrusion process.



Impact extrusion

Cold extrusion forging: This process is depicted in Figure. This is generally similar to the impact extrusion process; but there are two differences: In this process the punch descends slowly. The height of extruded product is short and the side walls are much thicker than the thin walled products produced by the impact extrusion process. In essence, this process is one of



backward extrusion.

Comparison between Hot extrusion and Cold extrusion

Cold extrusion	*Hot extrusion*
1. Better surface finish and lack of oxide layers.	1.Surface is coated with oxide layers. Surface finish not comparable with cold extrusion.
2. Good control of dimensional tolerance—no Machining or very little machining required.	2. Dimensional control not comparable with cold extrusion products.
3. High production rates at low cost. Fit for individual Component production.	3. High production rates but process fit for bulk material, not individual components.
4. Improved mechanical properties due to strain hardening.	4.Since processing is done hot, recrystallisation takes place.
5. Tooling subjected to high stresses.	5. Tooling subjected to high stresses as well as to high temperature. Tooling stresses are however lower than for cold extrusion.
6. Lubrication is crucial.	6. Lubrication is crucial.

EXTRUSION DEFECTS

Sometimes the surface of extruded metal/products develops surface cracks. This is due to heat generated in the extrusion process. These cracks are specially associated with aluminium, magnesium and zinc alloy extrusions. The extruded product can develop internal cracks also. These are variously known as centre burst, centre cracking and arrowhead fracture. There are three principal extrusion defects: surface cracking, pipe, and internal cracking.

Surface Cracking:

If extrusion temperature, friction, or speed is too high, surface temperatures can rise significantly, which may cause surface cracking and tearing. These cracks are intergranular (i.e., along the grain boundaries. and usually are caused by hot shortness . These defects occur especially in aluminum, magnesium, and zinc alloys, although they may also occur in high- temperature alloys. This situation can be avoided by lowering the billet temperature and the extrusion speed. Surface cracking also may occur at lower temperatures, where it has been attributed to periodic sticking of the extruded product along the die land. Because of the similarity in appearance to the surface of a bamboo stem, it is known as a bamboo defect. When the product being extruded temporarily sticks to the die land. The extrusion pressure increases rapidly. Shortly thereafter, the product moves forward again, and the pressure is released. The cycle is repeated continually, producing periodic circumferential cracks on the surface.

Pipe:

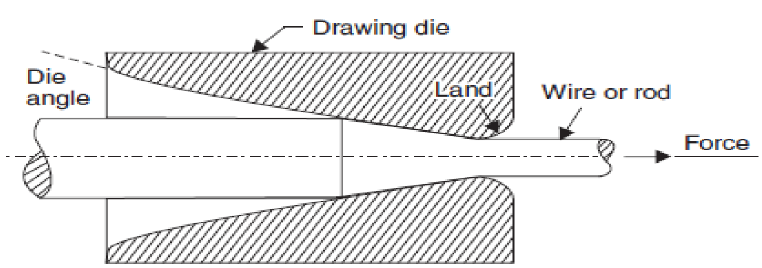
The type of metal-flow pattern in extrusion tends to draw surface oxides and impurities toward the center of the billet-much like a funnel. This defect is known as pipe defect, tailpipe, or fis/atailing. As much as one-third of the length of the extruded product may contain this type of defect and thus has to be cut off as scrap. Piping can be minimized by modifying the flow pattern to be more uniform, such as by controlling friction and minimizing temperature gradients. Another method is to machine the billet's surface prior to extrusion, so that scale and surface impurities are removed. These impurities also can be removed by the chemical etching of the surface oxides prior to extrusion.

Internal Cracking:

The center of the extruded product can develop cracks, called center cracking, center-burst, arrowhead fracture. These cracks are attributed to a state of hydrostatic tensile stress at the centerline in the deformation zone in the die, a situation similar to the necked region in a tensile- test specimen . These cracks also have been observed in tube extrusion and in tube spinning

WIRE DRAWING

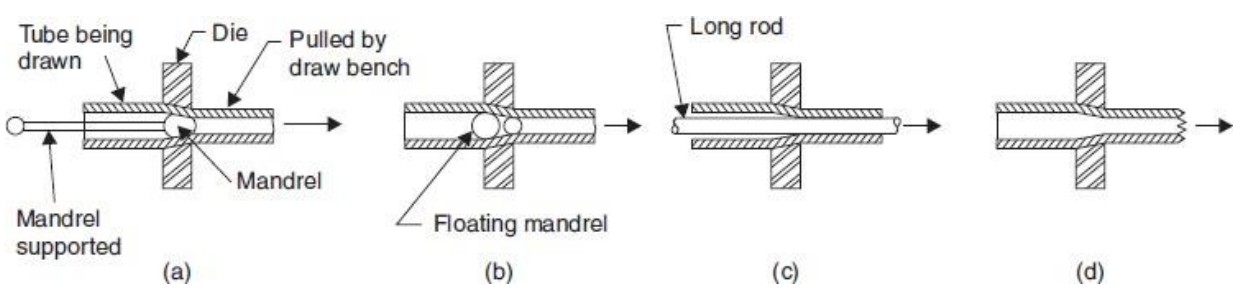
Wire drawing is a simple process. In this process, rods made of steel or non ferrous metals and alloys are pulled through conical dies having a hole in the centre. The included angle of the cone is kept between 8 to 24°. As the material is pulled through the cone, it undergoes plastic deformation and it gradually undergoes a reduction in its diameter. At the same time, the length is increased proportionately. The process is illustrated in Figure



Wire drawing process

The dies tend to wear out fast due to continuous rubbing of metal being pulled through it. Hence they are made of very hard material like alloy steel, tungsten carbide or even diamond. In one pass, the reduction in cross-sectional area achieved is about 25–30%. Hence in a wire drawing plant, the wire has to pass thorugh a number of dies of progressively reducing diameter to achieve the required reduction in diameter. However as the wire passes through dies and undergoes plastic deformation, it gets strain hardened. Its strength increases and capacity to further undergo plastic deformation decreases. Therefore during the entire run of the wire, from time to time, it has to be heated (and cooled) to remove the effect of work-hardening. This process is called “in process annealing”. The aim is to make the material soft and ductile again so that the process of drawing may be smoothly carried out. The metal rods to be drawn into wires must be absolutely clean. If necessary, they are pickled in an acid bath to dissolve the oxide layer present on the surface. Its front end is then tapered down so that it may pass through the hole in the die which is firmly held in the wire drawing machine. The wire is drawn by means of a number of power driven spools or rotating drums. During wire drawing, a great deal of heat is generated due to friction between the wire rod and the die. To reduce friction, dry soap or a synthetic lubricant is used. But despite reducing friction, the dies and drums may have to be water cooled. The preferred material for dies is tungsten carbide but for drawing fine wire, use of ruby or diamond dies is preferred. The drawing machines can be arranged in tandem so that the wire drawn by the previous die may be collected (in coil form) in sufficient quantity before being fed into the next die for further reduction in diameter. As the diameter becomes smaller, the linear speed of wire drawing is increased. The major variable in wire drawing process is (1) Reduction ratio (2) Die angle and (3) Friction. Improper control of these parameters will cause defects in the drawn material. Defects include centre cracking (as in extrusion and for the same reasons) and formation of longitudinal scratches or folds in the material.

TUBE DRAWING



The ‘drawing’ process can also be used for tube drawing. Tube drawing does not mean manufacturing a tube from solid raw material. It means lengthening a tube reducing its diameter. Various arrangements used for tube drawing are shown in Figure.

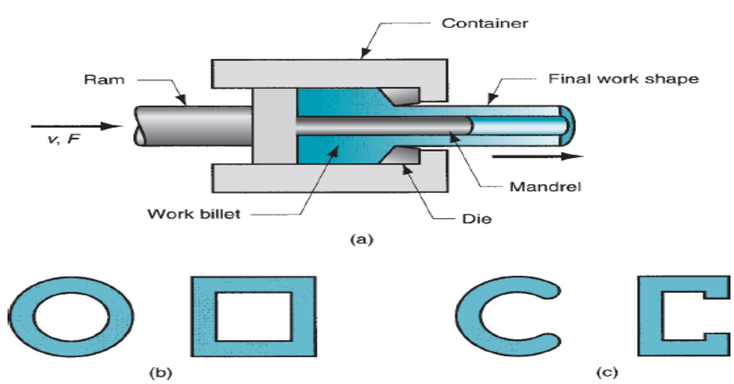
Advantages of the extrusion process:
There are several advantages of the modern extrusion process

1. A variety of shapes are possible, especially with hot extrusion.
2. Grain structure and strength properties are enhanced in cold and warm extrusion.
3. Fairly close tolerances are possible, especially in cold extrusion.
4. Little or no wasted material is created.

However, a limitation is that the cross section of the extruded part must be uniform throughout its length.

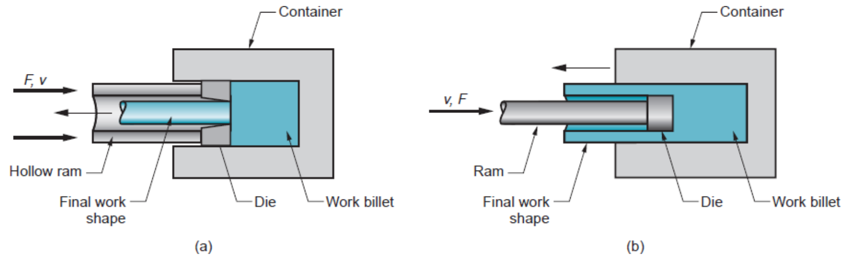
Types of extrusion process:
There are many classifications for the extrusion processes, it may classify depending on the extrusion direction as direct and indirect another classification is by working temperature as cold or warm or hot extrusion.

Direct extrusion (also called forward extrusion) is illustrated in Figure. A metal billet is loaded into a container, and a ram compresses the material, forcing it to flow through one or more openings in a die at the opposite end of the container. As the ram approaches the die, a small portion of the billet remains that cannot be forced through the die opening. This extra portion, called the butt, is separated from the product by cutting it just beyond the exit of the die. One of the problems in direct extrusion is the significant friction that exists between the work surface and the walls of the container as the billet is forced to slide toward the die opening. This friction causes a substantial increase in the ram force required in direct extrusion.
In hot extrusion, the friction problem is aggravated by the presence of an oxide layer on the surface of the billet. This oxide layer can cause defects in the extruded product. To solve these problems, a dummy block is often used between the ram and the work billet. The diameter of the dummy block is slightly smaller than the billet diameter, so that a narrow ring of work metal (mostly the oxide layer) is left in the container, leaving the final product free of oxides.
Hollow sections (e.g., tubes) are possible in direct extrusion by the process setup in.The starting billet is prepared with a hole parallel to its axis .This allows passage of a mandrel that is attached to the dummy block. As the billet is compressed, the material is forced to flow through the clearance between the mandrel and the die opening



(a) Direct extrusion to produce a hollow or semi –hollow cross section;
(b) Hollow
(c) Semi-hollow cross sections.

Indirect extrusion, also called backward extrusion and reverse extrusion, the die is mounted to the ram rather than at the opposite end of the container. As the ram move, the metal is forced to flow through the clearance in a direction opposite to the motion of the ram. Since the billet is not forced to move relative to the container, there is no friction at the container walls, and the ram force is therefore lower than in direct extrusion. Limitations of indirect extrusion are imposed by the lower rigidity of the hollow ram and the difficulty in supporting the extruded product as it exits the die.



Indirect extrusion to produce (a) a solid cross section and (b) a hollow cross section

Indirect extrusion can produce hollow (tubular) cross sections,

There are practical limitations on the length of the extruded part that can be made by this method. Support of the ram becomes a problem as work length increases.

Hot extrusion involves prior heating of the billet to a temperature above (0.5Tm). This reduces strength and increases ductility of the metal, permitting more extreme size reductions and more complex shapes to be achieved in the process. Additional advantages include reduction of ram force, increased ram speed. Cooling of the billet as it contacts the container walls is a problem, and isothermal extrusion is sometimes used to overcome this problem.

Cold extrusion and warm extrusion are generally used to produce discrete parts, often in finished (or near finished) form. Some important advantages of cold extrusion include increased strength due to strain hardening, close tolerances, improved surface finish, absence of oxide layers, and high production rates. Cold extrusion at room temperature also eliminates the need for heating the starting billet.

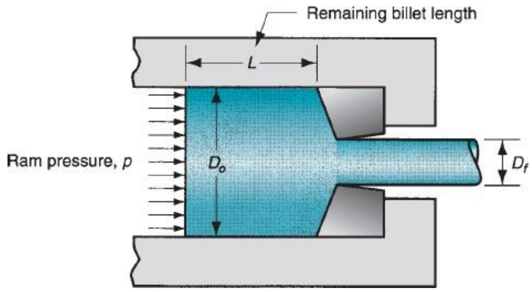
Analysis of extrusion:

Some of the parameters in extrusion. The diagram assumes that both billet and extrudate are round in cross section. One important parameter is the extrusion ratio, also called the reduction ratio. The ratio is defined:

Where rx= extrusion ratio; Ao= cross-sectional area of the starting billet, mm2 (in2); and

Af = final cross-sectional area of the extruded section,mm2 (in2). The ratio applies for both direct and indirect extrusion the value of rx can be used to determine true strain in extrusion, given that ideal deformation occurs with no friction and no redundant work:

Under the assumption of ideal deformation (no friction and no redundant work), the pressure applied by the ram to compress the billet through the die opening depicted in our figure can be computed as follows: Where Yf = average flow stress during deformation, MPa (lb/in2)



Pressure and other variables in direct extrusion.

Friction exists between the die and the work as the billet squeezes down and passes through the die opening. In direct extrusion, friction also exists between the container wall and the billet surface. The following empirical equation proposed by Johnson for estimating extrusion strain (in friction condition):Where ε_x = extrusion strain; and a and b are empirical constants for a given die angle. Typical values of these constants are: a = 0.8 and b = 1.2 to 1.5. Values of a and b tend to increase with increasing die angle.

Indirect extrusion the ram pressure to perform can be estimated based on Johnson's extrusion strain formula as follows: Where is calculated based on ideal strain , rather than extrusion strain

In direct extrusion, the effect of friction between the container walls and the billet causes the ram pressure to be greater than for indirect extrusion, the following formula can be used to compute ram pressure in direct extrusion. Where the term 2L/Do accounts for the additional pressure due to friction at the container billet interface. L is the portion of the billet length remaining to be extruded, and Do is the original diameter of the billet. Note that p is reduced as the remaining billet length decreases during the process.

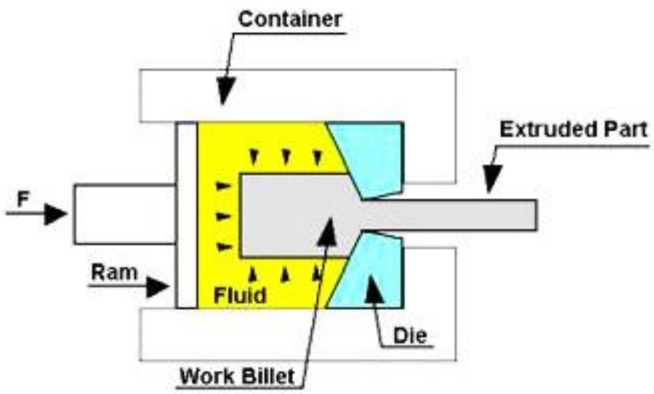
Ram force in indirect or direct extrusion is simply pressure p from, multiplied by billet area A_o and F = ram force in extrusion, N (lb).

Hydrostatic Extrusion:

Hydrostatic extrusion is a process in which the billet is completely circumscribed by a pressurized liquid in all the cases, with the exception being the case where billet is in the contact with die. This process can be carried out in many ways including warm, cold or hot but due to the stability of the used fluid, the temperature is limited. Hydrostatic extrusion has to be carried out in a completely sealed cylinder for containing the hydrostatic medium. The fluid may be pressurized in following two ways:

Constant-Rate Extrusion: A ram or plunger is used for pressurizing the fluid in the container.

1. Constant-Pressure Extrusion: A pump with a pressure intensifier is used for pressurizing the fluid, which is then pumped into the container.



Advantages of Hydrostatic Extrusion

1. No friction amidst the container and billet. This minimizes the force requirements, allowing higher reduction ratios, faster speeds, & lower billet temperatures.
2. Friction of the die can be largely reduced by a film of pressurized lubricant amidst the die surface and deforming metal.
3. On applying high pressures, the ductility of material increases.
4. Even flow of material.
5. Large billets & large cross-sections are extruded.
6. Uniform hydrostatic pressure inside the container eliminates the requirement of billets being straightened and extrusion of coiled wire.
7. No billet residue is left on the walls of container.

Disadvantages of Hydrostatic Extrusion

The billets have to be prepared by tapering one end so that it matches the die entry angle. This is essential for forming a seal at the starting of the cycle. Generally, the complete billet is required to be machined for the removal of surface defects.

It can be difficult to contain the fluid, under the effects of high pressures (up to 2 GPa, or 290 ksi).

There are a number of limitations in the hydrostatic extrusion, especially when a large volume of fluid is used in comparison with the billet volume, which is to be extruded. These limitations are as follows:

1. Increased handling for the injection and removal of the fluid for every extrusion cycle.
2. Decreased control of speed of the billet & stopping because of potential.
3. Stick-slip and enormous stored energy in the compressed fluid.
4. Decreased process efficiency in terms of billet-to-container volume ratio.
5. Enhanced complications, when extrusion is done at elevated temperatures.

INTRODUCTION TO RAPID PROTOTYPING

One of the important steps prior to the production of a functional product is building of a physical prototype. Prototype is a working model created in order to test various aspects of a design, illustrate ideas or features and gather early user feed-back. Traditional prototyping is typically done in a machine shop where most of parts are machined on lathes and milling machines. This is a subtractive process, beginning with a solid piece of stock and the machinist carefully removes the material until the desired geometry is achieved. For complex part geometries, this is an exhaustive, time consuming, and expensive process. A host of new shaping techniques, usually put under the title Rapid Prototyping, are being developed as an alternative to subtractive processes. These methods are unique in that they add and bond materials in layers to form objects. These systems are also known by the names additive fabrication, three dimensional printing, solid freeform fabrication (SFF), layered manufacturing etc.

These additive technologies offer significant advantages in many applications compared to classical subtractive fabrication methods like formation of an object with any geometric complexity or intricacy without the need for elaborate machine setup or final assembly in very short time. This has resulted in their wide use by engineers as a way to reduce time to market in manufacturing, to better understand and communicate product designs, and to make rapid tooling to manufacture those products. Surgeons, architects, artists and individuals from many other disciplines also routinely use this technology.

Prototype: It is a model fabricated to prove out a concept or an idea.

Solid Modeling: It’s a branch of CAD that produces 2D or 3D objects in an electronic format.

Definition: Rapid prototyping is basically a additive manufacturing process used to quickly fabricate a model of a part using 3-D CAM data.

OR

It can also be defined as layer by layer fabrication of 3D physical models directly from CAD.

Need for the compression in the product development:
• To increase effective communication.
• To decrease development time.
• To decrease costly mistakes.
• To minimize sustaining engineering changes.
• To extend product life time by adding necessary features & eliminating redundant features early in the design.

Trends in manufacturing industries emphasis the following:
▪ increasing the no of variants of products.
▪ Increase in product complexity.
▪ Decrease in product lifetime before obsolescence.
▪ Decrease in delivery time.
▪ Product development by Rapid prototyping by enabling better communication.

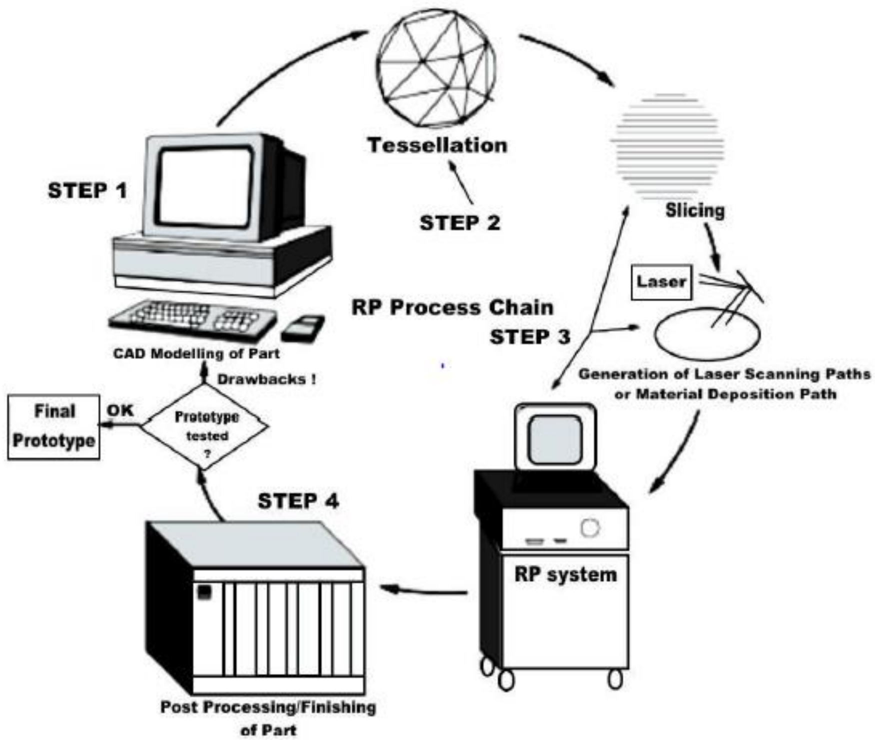
Conventional Machining:
▪ It's not suitable for complex shapes because they are difficult to machine.
▪ Time consuming
▪ Very costly
▪ Tedious or very laborious.
▪ Skilled operator is required.
▪ Accuracy will be less.
▪ Increased product development time.

Pre-processing:- CAD model slicing & setting algorithms applied for various RP systems.

Post-processing:- Cleaning operations required to finish a part after removing it from RP machine.

Materials for Rapid Prototyping:- Paper, Wax, Plastics, Resins, Metallic powders.

Methodology of Rapid Prototyping:
RP in its basic form can be described as the production of three dimensional (3D) parts from computer aided design (CAD) data in a decreased time scale. The basic methodology of all RP process can be summarized as shown in following figure.



Construct a CAD model.
▪ Convert it to STL format.
▪ RP machine processes .STL file by creating sliced layers of model.
▪ First layer of model is created.
▪ Model is then lowered by thickness of next layer.
▪ Process is repeated until completion of model
▪ The model & any supports are removed.
▪ Surface of the model is then finished and cleaned.

(1) **Development of a CAD model**

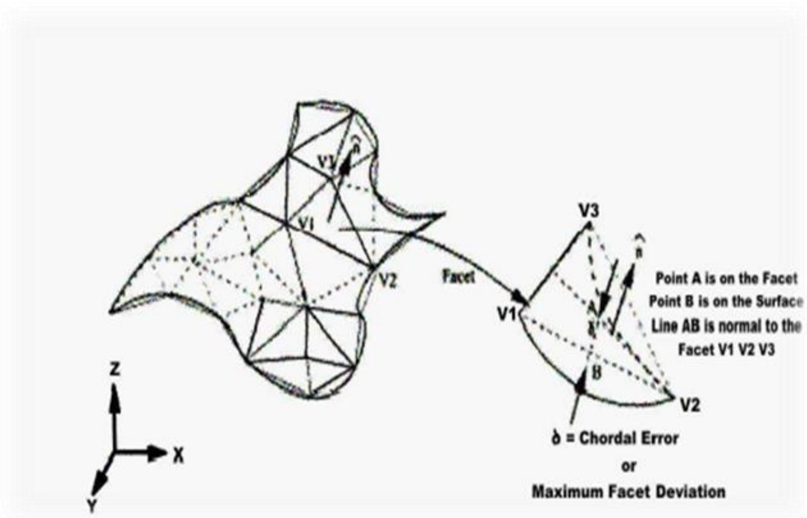
The process begins with the generation CAD model of the desired object which can be done by one of the following ways;

• Conversion of an existing two dimensional (2D) drawing
• Importing scanned point data into a CAD package
• Creating a new part in CAD in various solid modeling packages
• Altering an existing CAD model

RP has traditionally been associated with solid rather than surface modelling but the more recent trends for organic shapes in product design is increasing the need for free flowing surfaces generated better in surface modelling.

(2) **Generation of Standard triangulation language (STL) file**

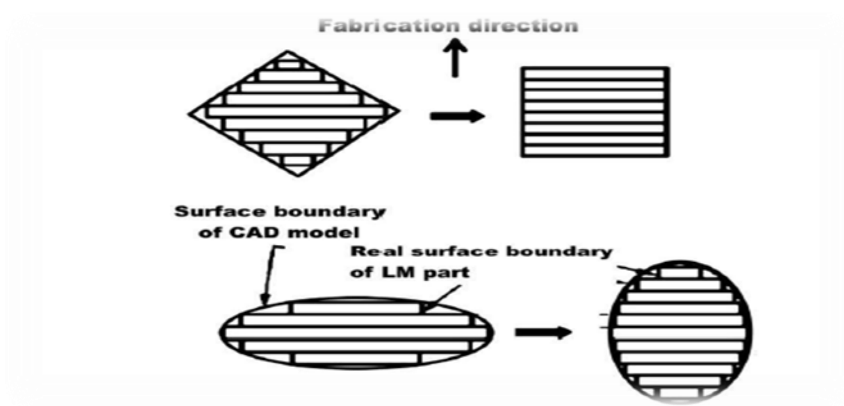
The developed 3D CAD model is tessellated and converted into STL files that are required for RP processes. Tessellation is piecewise approximation of surfaces of 3D CAD model using series of triangles. Size of triangles depends on the chordal error or maximum fact deviation. For better approximation of surface and smaller chordal error, small size triangle are used which increase the STL file size. This tessellated CAD data generally carry defects like gaps, overlaps, degenerate facets etc which may necessitate the repair software. These defects are shown in figure below. The STL file connects the surface of the model in an array of triangles and consists of the X, Y and Z coordinates of the three vertices of each surface triangle, as well as an index that describes the orientation of the surface normal.



Tessellation defects

(3) Slicing the STL file

Slicing is defined as the creating contours of sections of the geometry at various heights in the multiples of layer thickness. Once the STL file has been generated from the original CAD data the next step is to slice the object to create a slice file (SLI). This necessitates the decision regarding part deposition orientation and then the tessellated model is sliced. Part orientation will be showing considerable effect on the surface as shown in the figures.



Effect of Part deposition Orientation

The thickness of slices is governed by layer thickness that the machine will be building in, the thicker the layer the larger the steps on the surface of the model when it has been built. After the STL file has been sliced to create the SLI files they are merged into a final build file. This information is saved in standard formats like SLC or CLI (Common Layer Interface) etc.

(4) Support Structures

As the parts are going to be built in layers, and there may be areas that could float away or of overhang which could distort. Therefore, some processes require a base and support structures to be added to the file which are built as part of the model and later removed.

(5) Manufacturing

As discussed previously, the RP process is additive i.e. it builds the parts up in layers of material from the bottom. Each layer is automatically bonded to the layer below and the process is repeated until the part is built. This process of bonding is undertaken in different ways for the various materials that are being used2 but includes the use of Ultraviolet (UV) lasers, Carbon Dioxide (C) lasers, heat sensitive glues and melting the material itself etc.

(6) Post processing

The parts are removed from the machine and post processing operations are performed sometimes to add extra strength to the part by filling process voids or finish the curing of a part or to hand finish the parts to the desired level. The level of post processing will depend greatly on the final requirements of the parts produced, for example, metal tooling for injection molding will require extensive finishing to eject the parts but a prototype part manufactured to see if it will physically fit in a space will require little or no post processing.

History of RP system

- It started in 1980's
- First technique is Stereo lithography (SLA)
- It was developed by 3D systems of Valencia in California, USA in 1986.
- Fused deposition modeling (FDM) developed by stratasys company in 1988.
- Laminated object manufacturing (LOM) developed by Helisis (USA).
- Solid ground Curing developed by Cubitol corporation of Israel.
- Selective laser sintering developed by DTM of Austin, Texas (USA) in 1989.
- Sanders Model maker developed by Wilton incorporation USA in 1990.
- Multi Jet Modeling by 3D systems.
- 3-D Printing by Solygen incorporation, MIT, USA.

Classification of RP Processes

Here, few important RP processes namely

- Stereo lithography (SLA)

- Laminated Object Manufacturing (LOM)
- Selective Laser Sintering (SLS)
- Fused Deposition Modeling (FDM)
- Solid Ground Curing (SGC)

RAPID TOOLING

Rapid Tooling refers to mould cavities that are either directly or indirectly fabricated using Rapid Prototyping techniques.

Soft Tooling:

It can be used to intake multiple wax or plastic parts using conventional injection moulding techniques. It produces short term production

patterns. Injected wax patterns can be used to produce castings. Soft tools can usually be fabricated for ten times less than a machine tool.

Hard Tooling:

Patterns are fabricated by machining either tool steel or aluminum into the negative shape of the desired component. Steel tools are very expensive yet typically last indefinitely building millions of parts in a mass production environment. Aluminum tools are less expensive than steel and are used for lower production quantities.

Indirect Rapid Tooling:

As RP is becoming more mature, material properties, accuracy, cost and lead time are improving to permitting to be employed for production of tools. Indirect RT methods are called indirect because they use RP pattern obtained by appropriate RP technique as a model for mould and die making.

Role of Indirect methods in tool production:

RP technologies offer the capabilities of rapid production of 3D solid objects directly from CAD. Instead of several weeks, a prototype can be completed in a few days or even a few hours. Unfortunately with RP techniques, there is only a limited range of materials from which prototypes can be made. Consequently although visualization and dimensional verification are possible, functional testing of prototypes often is not due to different mechanical and thermal properties of prototype compared to production part.

All this leads to the next step which is for RP industry to target tooling as a natural way to capitalize on 3D CAD modeling and RP technology. With increase in accuracy of RP techniques, numerous processes have been developed for producing tooling from RP masters. The most widely used indirect RT methods are to use RP masters to make silicon room temperature vulcanizing moulds for plastic parts and as sacrificial models or investment casting of metal parts. These processes are usually known as Soft Tooling Techniques.

Silicon Rubber Tooling:

It is a soft tooling technique. It is a indirect rapid tooling method. Another root for soft tooling is to use RP model as a pattern for silicon rubber mould which can then in turn be injected several times. Room Temperature Vulcanization Silicones are preferable as they do not require special curing equipment. This rubber moulding technique is a flexible mould that can be peeled away from more implicate patterns as suppose to former mould materials. There are as many or more techniques for silicon molding as there are RP processes but the following is the general description for making simple two piece moulds.

First an RP process is used to fabricate the pattern. Next the pattern is fixture into a holding cell or box and coated with a special release agent (a wax based cerosal or a petroleum jelly mixture) to prevent it from sticking to the silicon. The silicon rubber typically in a two part mix is then blended, vacuumed to remove air packets and poured into the box around the pattern until the pattern is completely encapsulated. After the rubber is fully cured which usually takes 12 to 24 hours the box is removed and the mould is cut into two (not necessarily in halves) along a pre determined parting line. At this point, the original pattern is pulled from the silicon mould which can be placed back together and repeatedly filled with hot wax or plastic to fabricate multiple patterns. These tools are generally not injected due to the soft nature of the material. Therefore the final part materials must be poured into the mould each cycle.

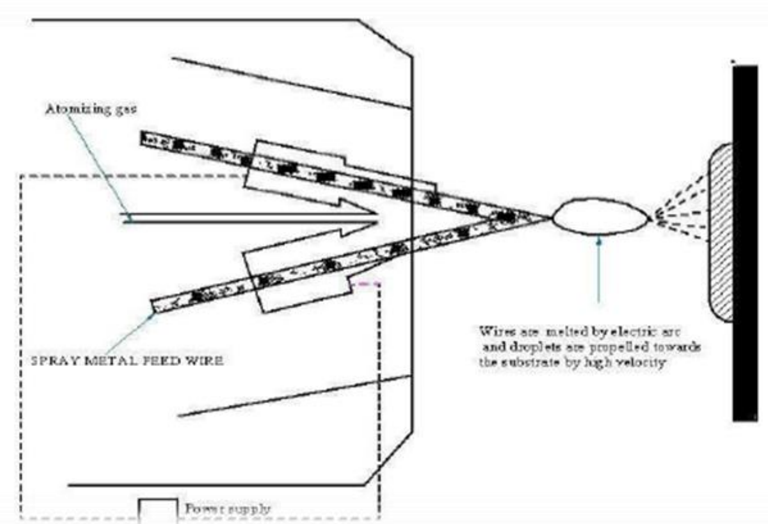
Wire Arc Spray:

These are the thermal metal deposition techniques such as wire arc spray and vacuum plasma deposition. These are been developed to coat low temperature substrates with metallic materials. This results in a range of low cost tools that can provide varying degrees of durability under injection pressures.

The concept is to first deploy a high temperature, high hardness shell material to an RP pattern and then backfill the remainder of the two shell with inexpensive low strength, low temperature materials on tooling channels. This provides a hard durable face that will endure the forces on temperature of injection moulding and a soft banking that can be worked for optimal thermal conductivity and heat transfer from the body.

In Wire Arc Spray, the metal to be deposited comes in filament form. Two filaments are fed into the device, one is positively charged and the other is negatively charged until they meet and create an electric arc. This arc melts the metal filaments while simultaneously a high velocity gas flows through the arc zone and propels the atomized metal particles on to the RP pattern. The spray pattern is either controlled manually or automatically by robotic control. Metal can be applied in successive thin coats to very low temperature of RP patterns without deformation of geometry. Current wire arc technologies are limited to low temperature materials, however as well as to metals available in filament form.

Vacuum Plasma Spray technologies are more suited in higher melting temperature metals. The deposition material in this case comes in powder form which is then melted, accelerated and deposited by plasma generated under vacuum.



Wire Arc Spraying

Epoxy Tools:

Epoxy tools are used to manufacture prototype parts or limited runs of production parts.

Epoxy tools are used as:-

- Moulds for prototype injection
- plastic Moulds for casting
- Compression moulds
- Reaction Injection Moulds

The fabrication of moulds begins with the construction of a simple frame around the parting line of

RP model. Screw gauges and runners can be added or cut later on once the mould is finished. The exposed surface of the model is coated with a release agent and epoxy is poured over the model. Aluminum powder is usually added to epoxy resin and copper cooling lines can also be placed at this stage to increase the thermal conductivity of the mould. Once the epoxy is cured the assembly is inverted and the parting line block is removed leaving the pattern embedded in the side of the tool just cast. Another frame is constructed and epoxy is poured to form the other side of the tool. Then the second side of the tool is cured. The two halves of the tool are separated and the pattern is removed. Another approach known as soft surface rapid tool involves machining an oversized cavity in an Aluminum plate. The offset allows for introduction of casting material which may be poured into the cavity after suspending the model in its desired position and orientation. Some machining is required for this method and this can increase the mould building time but the advantage is that the thermal conductivity is better than for all epoxy models.

Unfortunately epoxy curing is an exothermic reaction and it is not always possible directly to cast epoxy around a RP model without damaging it. In this case a Silicon RTV Mould is cast from RP pattern and silicon RTV model is made from the mould and is used as pattern for aluminum fill deposited. A loss of accuracy occurs during this succession of reproduction steps. An alternative process is to build an RP mould as a master so that only a single silicon RTV reproduction step is needed because epoxy tooling requires no special skill or equipment. It is one of the cheapest techniques available. It is also one of the quickest. Several hundred parts can be moulded in almost any common casting plastic material.

Epoxy Tools have the following limitations:

- Limited tool life
- Poor thermal transfer
- Tolerance dependent on master patterns
- Aluminum filled epoxy has low tensile strength

3D Keltool Process:

This process is based on metal sintering process. This process converts RP master patterns into production tool inserts with very good definition and surface finish. The production of inserts including the 3D Keltool process involves the following steps

1) Fabricating the master patterns of core and cavity.

2) Producing RTV silicon rubber mould from the pattern.

3) Filling the silicon rubber mould with metal mixtures to produce green parts duplicating the

masters. Metal mixture is powdered steel, tungsten carbide and polymer binder with particle sizes of around 5 mm. Green parts are powdered metal held together by polymer binder.

4) Firing the green parts in a furnace to remove the plastic binder and sintering the metal particles together.

5) Infiltrating the sintered parts (70% dense inserts) with copper in the second furnace cycle to fill the 30% void space.

6) Finishing the core and cavity.

3D Keltool inserts can be built in two materials. Sterlite of A6 composite tool steel. The material properties allow the inserts using this process to withstand more than 10lakh mould cycles.

Direct Tooling:

Indirect methods for tool production necessitate a minimum of one intermediate replication process. This might result in a loss of accuracy and to increase the time for building the tool. To overcome some of the drawbacks of indirect method, new rapid tooling methods have come into existence that allow injection moulding and die casting inserts to be built directly from 3D CAD models.

Classification of Direct Rapid Tooling methods:

Direct Rapid Tooling Processes can be divided into two main groups 1st group:

- It includes less expensive methods with shorter lead times.
- Direct RT methods that satisfy these requirements are called methods for firm tooling or bridge tooling.
- RP processes for firm tooling fill the gap between soft and hard tooling.

2nd group:

- Solutions for hard tooling are based on fabrication of sintered metal steel, iron copper powder inserts infiltrated with copper or bronze.
- It includes RT methods that allow inserts for pre production and production tools to be built.
- These methods come under hard tooling.

Classification of Direct RT methods:

1) Firm Tooling Methods

- Direct AIM
- DTM COPPER PA TOOLING
- DTM SANDFORM TOOLING
- ELECTRO OPTICAL SYSTEM DIRECT CHRONING PROCESS LOM TOOLING IN POLYMER

- 3DP CERAMIC SHELLS.

DIRECT AIM:

Direct Aces Injection Moulds:

Stereolithography is used to produce epoxy inserts for injection mould tools for thermoplastic parts because the temperature resistance of curable epoxy resins available at present is up to 200'C and thermoplastics are injected at temperature as high as 300'C. Specific rules apply to the production of this type of injection moulds.

The procedure detailed in is outlined below:

Using a 3D CAD package, the injection mould is drawn. Runners, fan gates, ejector pins and clearance holes are added and mould is shelled to a recommended thickness of 1.27mm. The mould is then built using accurate clear epoxy solid style on a Stereolithography machine. The supports are subsequently removed and the mould is polished in the direction of draw to facilitate part release. The thermal conductivity of SLA resin is about 300 times lower than that of conventional tool steels (.2002 W/mK for cibatool SL5170 epoxy resin)

To remove the maximum amount of heat from the tool and reduce the injection moulding cycle time, copper water cooling lines are added and the back of the mould is filled with a mixture made up of 30% by volume of aluminum granulate and 70% of epoxy resin. The cooling of the mould is completed by blowing air on the mould faces as they separate after the injection moulding operation.

Disadvantages:

- Number of parts that can be obtained using this process is very dependent on the shape and size of the moulded part as well as skills of good operator who can sense when to stop between cycles to allow more cooling.
- Process is slightly more difficult than indirect methods because finishing must be done on internal shapes of the mould.
- Also draft angles of order up to one and the application of the release agent in each injection cycle are required to ensure proper part injection.
- A Direct AIM mould is not durable like aluminum filled epoxy mould. Injection cycle time is long.

Advantages:

- It is suitable for moulding up to 100 parts.
- Both resistance to erosion and thermal conductivity of D-AIM tools can be increased by deposition of a 25micron layer of copper on mould surfaces.

MODULE-V
FORGING

COURSE OUTCOMES (COs):

At the end of the course students are able to:		
Course Outcomes		Knowledge Level (Bloom's Taxonomy)
CO8	**Classify** the various forging techniques based on functionality, cost and time in development of critical products.	Understand
CO9	**Evaluate** the appropriate manufacturing process parameters, for effective optimization of prototype / products.	Apply

PROGRAM OUTCOMES (POs):

Program Outcomes (POs)		Strength	Proficiency Assessed by
PO 2	**Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.	3	CIE/Quiz/AAT
PO 3	**Design/development of solutions:** Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.	2	Seminar/ conferences/ Research papers

Forging is a basic process in which the work piece is shaped by compressive forces applied through various dies and tooling. It is one of the oldest and most important metalworking operations used to make jewelry, coins, and various implements by hammering metal with tools made of stone. Forged parts now include large rotors for turbines; gears; bolts and rivets; cutlery); hand tools; numerous structural components for machinery, aircraft and railroads and a variety of other transportation equipment.

Simple forging operations can be performed with a heavy hammer and an anvil, as has been done traditionally by blacksmiths. However, most forgings require a set of dies and such equipment as a press or a powered forging hammer.

Forging may be carried out at room temperature (cold forging) or at elevated temperatures (warm or hot forging) depending on the homologous temperature. Cold forging requires higher forces (because of the higher strength of the work piece material), and the work piece material must possess sufficient ductility at room temperature to undergo the necessary deformation without cracking. Cold-forged parts have a good surface finish and dimensional accuracy. Hot forging requires lower forces, but the dimensional accuracy and surface finish of the parts are not as good as in cold forging. Forgings generally are subjected to additional finishing operations, such as heat treating to modify properties and machining to obtain accurate final dimensions and a good surface finish. These finishing operations can be minimized by precision forging, which is an important example of net-shape or near-net-shape forming processes. As we shall seen components that can be forged successfully also may be manufactured economically by other methods, such as casting, powder metallurgy, or machining. Each of these will produce a part having different characteristics, particularly with regard to strength, toughness, dimensional accuracy, surface finish, and the possibility of internal or external defects.

In forging the material is deformed applying either impact load or gradual load. Based on the type of loading, forging is classified as hammer forging or press forging. Hammer forging involves impact load, while press forging involves gradual loads.

Based on the nature of material flow and constraint on flow by the die/punch, forging is classified as open die forging, impression die forging and flashless forging.

Types of Forging Processes

There are basically three methods (or processes) to make a forged part.

1. Impression Die Forging
2. Cold Forging
3. Open Die Forging
4. Seamless Rolled Ring Forging

Impression Die Forging

Impression die forging pounds or presses metal between two dies (called tooling) that contain a precut profile of the desired part. Parts from a few ounces to 60,000 lbs. can be made using this process. Some of the smaller parts are actually forged cold.

Process Operations

Graphical depiction of process steps:

- Still Graphic
- Animated Sequence
- Video
- Process Capabilities

Commonly referred to as closed-die forging, impression-die forging of steel, aluminum, titanium and other alloys can produce an almost limitless variety of 3-D shapes that range in weight from mere ounces up to more than 25 tons. Impression-die forgings are routinely produced on hydraulic presses, mechanical presses and hammers, with capacities up to 50,000 tons, 20,000 tons and 50,000 lbs. respectively.

As the name implies, two or more dies containing impressions of the part shape are brought together as forging stock undergoes plastic deformation. Because metal flow is restricted by the die contours, this process can yield more complex shapes and closer tolerances than open-die forging processes. Additional flexibility in forming both symmetrical and non- symmetrical shapes comes from various preforming operations (sometimes bending) prior to forging in finisher dies.

Part geometry's range from some of the easiest to forge simple spherical shapes, block-like rectangular solids, and disc-like configurations to the most intricate components with thin and long sections that incorporate thin webs and relatively high vertical projections like ribs and bosses. Although many parts are generally symmetrical, others incorporate all sorts of design elements (flanges, protrusions, holes, cavities, pockets, etc.) that combine to make the forging very non-symmetrical. In addition, parts can be bent or curved in one or several planes, whether they are basically longitudinal, equidimensional or flat.

Most engineering metals and alloys can be forged via conventional impression-die processes, among them: carbon and alloy steels, tool steels, and stainless, aluminum and copper alloys, and certain titanium alloys. Strain-rate and temperature-sensitive materials (magnesium, highly alloyed nickel-based superalloys, refractory alloys and some titanium alloys) may require more sophisticated forging processes and/or special equipment for forging in impression dies.

Forging is a manufacturing process involving the shaping of metal using localized compressive forces. The blows are delivered with a hammer (often a power hammer) or a die. Forging is often classified according to the temperature at which it is performed: cold forging (a type of cold working), warm forging, or hot forging (a type of hot working). For the latter two, the metal is heated, usually in a forge. Forged parts can range in weight from less than a kilogram to hundreds of metric tons. Forging has been done by smiths for millennia; the traditional products were kitchenware, hardware, hand tools, edged weapons, and jewellery. Since the Industrial Revolution, forged parts are widely used in mechanisms and machines wherever a component requires high strength; such forgings usually require further processing (such as machining) to achieve a finished part. Today, forging is a major worldwide industry.

PRINCIPLE OF FORGING PROCESSES:

Forging is one of the oldest known metalworking processes. Traditionally, forging was performed by a smith using hammer and anvil, though introducing water power to the production and working of iron in the 12th century allowed the use of large trip hammers or power hammers that exponentially increased the amount and size of iron that could be produced and forged easily. The smithy or forge has evolved over centuries to become a facility with engineered processes, production equipment, tooling, raw materials and products to meet the demands of modern industry.

In modern times, industrial forging is done either with presses or with hammers powered by compressed air, electricity, hydraulics or steam. These hammers may have reciprocating weights in the thousands of pounds. Smaller power hammers, 500 lb (230 kg) or less reciprocating weight, and hydraulic presses are common in art smithies as well. Some steam hammers remain in use, but they became obsolete with the availability of the other, more convenient, power sources.

TYPES FORGING:

When forging, an initially simple part- a billet, is plastically deformed between two dies to obtain the desired final configuration. For understanding and optimization of forging operations, it is useful to classify this process in a systematic way.

a) Cold forging:

Forging is carried out at or near room temperature (below the recrystallization temp.) of the metal. Carbon and standard alloy steels are most commonly cold forged. Cold forging is generally preferred when the metal is already a soft, like aluminum. This process is usually less expensive than hot forging and the end product requires little or no finishing work. Cold forging is also less susceptible to contamination problems, and the final component features a better overall surface.

Advantages:

Production rates are very high with exceptional die life, Improves mechanical properties, Less friction between die surface and work piece, Lubrication is easy, No oxidation

Disadvantages:

Residual stress may occur, Heavier and more powerful equipment is needed, stronger tooling is required, Tool design and manufacturing are critical.

b) Warm forging:

The temperature range for the warm forging of steel runs from above room temperature to below the recrystallization temperature. Compared with cold forging, warm forging has the potential advantages of: Reduced tooling loads, reduced press loads, increased steel ductility, elimination of need to anneal prior to forging, and favorable as-forged properties that can eliminate heat treatment.

In warm forging, the billet is heated below the recrystallization temperature, up to 700 to 800^0C for steels, in order to lower the flow stress and the forging pressures.

Advantages:

High production rates, excellent dimensional tolerances and surface finish for forged parts, significant savings in material and machining, Favorable grain flow to improve strength, Greater toughness of the forged part.

c) Hot forging (most widely used):

Forging is carried out at a temperature above the recrystallization temperature of the metal. The recrystallization temperature is defined as the temperature at which the new grains are formed in the metal. This kind of extreme heat is necessary in avoiding strain hardening of the metal during deformation.

Advantages:

High strain rates and hence easy flow of the metal, recrystallization and recovery are possible, forces required are less.

Disadvantages:

Lubrication is difficult at high temperatures, oxidation and scaling occur on the work piece, poor surface finish, less precise tolerances, possible warping of the material during the cooling process.

Metal or alloy	Temperature Range (^{0}C)
Aluminum alloys	400 – 550
Magnesium alloys	250 – 350
Copper alloys	600 – 900
Carbon and Low-alloy steels	850 – 1150
Martensitic stainless steels	1100 – 1250
Austenitic stainless steels	1100 – 1250
Titanium alloys	700 – 950
Iron-base superalloys	1050 – 1180
Cobalt-base superalloys	1180 – 1250
Tantalum alloys	1050 – 1350
Molybdenum alloys	1150 – 1350
Nickel-base superalloys	1050 – 1200
Tungsten alloys	1200 – 1300

OPEN DIE FORGING: In this, the work piece is compressed between two platens. There is no constraint to material flow in lateral direction. Open die forging is a process by which products are made through a series of incremental deformation using dies of relatively simple shape. The top die is attached to ram and bottom die is attached to the hammer anvil or press bed. Metal work piece is heated above recrystalline temp from 1900 to 2400^{0}c.Most open die forging are produced on flat dies. Convex surface dies and concave surface dies are also used in pairs or with flat dies.

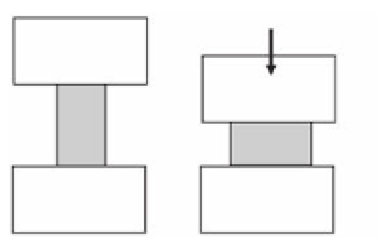
Open die forging is classified into three main types, namely, cogging, fullering and edging. **Cogging: Cogging** (also called as drawing out) consists of a sequence in which the thickness of an ingot is reduced to billet or blooms by narrow dies. **Fullering and Edging** operations are done to reduce the cross section using convex shaped or concave shaped dies. Material gets distributed and hence gets elongated and reduction in thickness happens. **Upsetting** is an open die forging in which the billet is subjected to lateral flow by the flat die and punch. Due to friction the material flow across the thickness is non-uniform. Material adjacent to the die gets restrained from flowing, whereas, the material at center flows freely. This causes a phenomenon called barreling in upset forging.

Open-die forging is also known as smith forging. In open-die forging, a hammer strikes and deforms the work piece, which is placed on a stationary anvil.Open-die forging gets its name from the fact that the dies (the surfaces that are in contact with the work piece) do not enclose the work piece, allowing it to flow except where contacted by the dies. Therefore, the operator needs to orient and position the work piece to get the desired shape. The dies are usually flat in shape, but some have a specially shaped surface for specialized operations. For example, a die may have a round, concave, or convex surface or be a tool to form holes or be a cut-off tool. Open-die forgings can be worked into shapes which include discs, hubs, and blocks, shafts (including step shafts or with flanges), sleeves, cylinders, flats, hexes, rounds, plate, and some custom shapes. Open-die forging lends itself to short runs and is appropriate for art smiting and custom work. In some cases, open-die forging may be employed to rough-shape to prepare them for subsequent operations. Open-die forging may also orient the grain to increase strength in the required direction.

Advantages of open-die forging

- Reduced chance of voids
- Better fatigue resistance
- Improved microstructure
- Continuous grain flow
- Finer grain size
- Greater strength

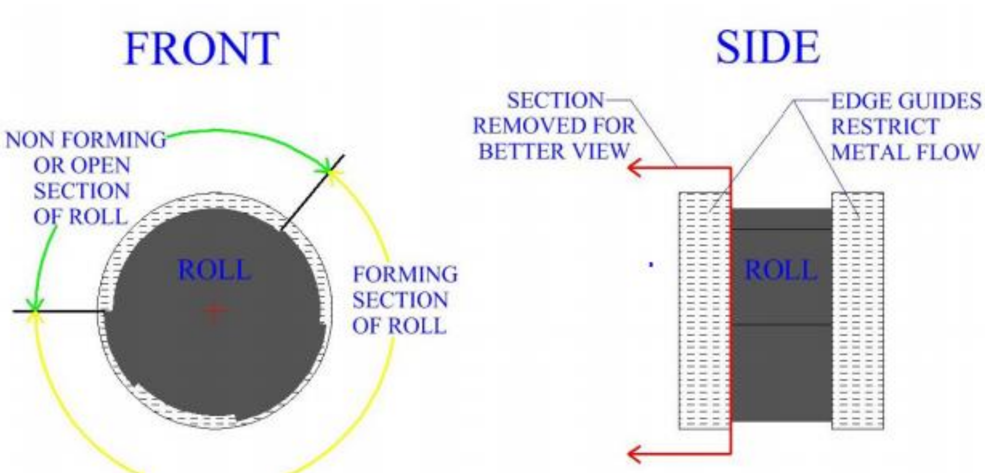
"Cogging" is the successive deformation of a bar along its length using an open-die drop forge. It is commonly used to work a piece of raw material to the proper thickness. Once the proper thickness is achieved the proper width is achieved via "edging"."Edging" is the process of concentrating material using a concave shaped open-die. The process is called "edging" because it is usually carried out on the ends of the work piece. "Fullering" is a similar process that thins out sections of the forging using a convex shaped die. These processes prepare the work pieces for further forging processes.



Open die forging

ROLL FORGING

Roll forging or roll forming is a forging technique that utilizes opposing rolls to shape a metal part. Even though roll forging uses rolls in order to accomplish the deformation of the material, it is classified as a metal forging process and not a rolling process. More similarly to metal forging than metal rolling, it is a discrete process and not a continuous one. Roll forging is usually performed hot. The precisely shaped geometry of grooves on the roll, forge the part to the required dimensions. The forging geometry of the rolls used to forge metal parts is only present over a portion of the roll's circumference. Only part of a full revolution of a roll is needed to forge the work piece. Typically in manufacturing industry, the forging geometry on the rolls may occupy from one quarter to three quarters of the roll's circumference.

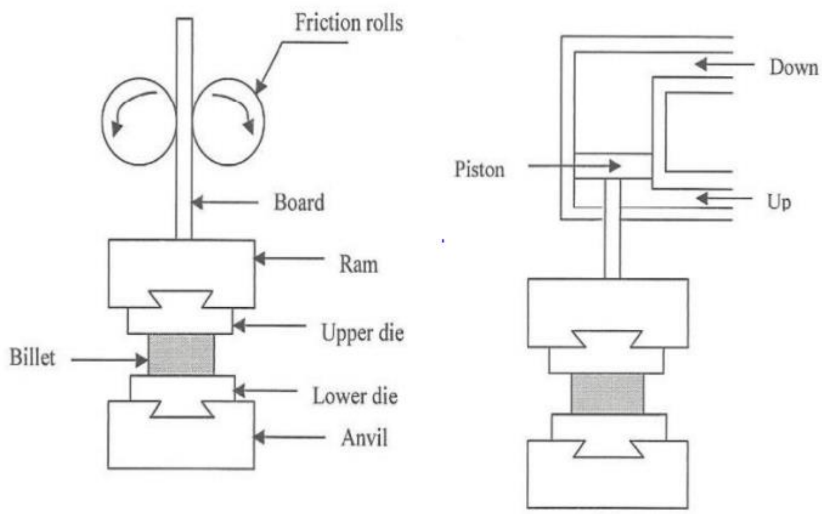


FORGING HAMMERS:

Types according to forging equipments Forged components are shaped either by a hammer or press. Forging on the hammer is carried out in a succession of die impressions using repeated blows. The quality of the forging, and the economy and productivity of the hammer process depend upon the tooling and the skill of the operator. In press forging, the stock is usually hit only once in each die impression and the design of each impression become more important while operator skill is less critical. The continuous development of forging technology requires a sound and fundamental understanding of equipment capabilities and characteristics. The equipment i.e. presses and hammers used in forging, influences the forging process, since it affects the deformation rate and temperature conditions, and it determines the rate of production. The requirements of a given forging process must be compatible with the load, energy, time, and accuracy characteristics of a given forging machine affects the deformation rate and temperature conditions, and it determines the rate of production. The requirements of a given forging process must be compatible with the load, energy, time, and accuracy characteristics of a given forging machine.

HAMMER FORGING:

The most common type of forging equipment is the hammer and anvil. The hammer is the least expensive and most versatile type of equipment for generating load and energy to carry out a forging process. This technology is characterized by multiple impact blows between contoured dies. Hammers are primarily used for hot forging. There are basically two types of anvil hammers: Gravity-drop hammers and power drop hammers. In a simple gravity-drop hammer, the upper ram is connected to a board (board-drop hammer), a belt (belt-drop hammer), a chain (chain-drop hammer),or a piston (oil-, air-, or steam-lift drop hammer).The ram is lifted to a certain height and then dropped on the stock placed on the anvil. During the down stroke, the ram is accelerated by gravity and builds up the blow energy. The upstroke takes place immediately after the blow. The operation principle of a power-drop hammer is similar to that of an airdrop hammer. In the down stroke, in addition to gravity, the ram is accelerated by steam, cold air, or hot air pressure. In the power-drop hammer, the acceleration of the ram is enhanced with air pressure applied on the top side of the ram cylinder. Figure 3 shows mechanical board hammer- It is a stroke restricted machine. Repeatedly the board (weight) is raised by friction rolls and is dropped on the die. Its rating is in the terms of weight of the ram and energy delivered. Figure 4 shows steam hammer- It uses steam in a piston and cylinder arrangement. It has greater forging capacity. It can produce forgings ranging from a few kgs to several tones. It is preferred in closed-die forging.



PRESS FORGING:

In press forging, the metal is shaped not by means of a series of blows as in hammer forging, but by means of a single continuous squeezing action. There are two main types: mechanical and hydraulic presses. Mechanical presses function by using cams, cranks and/or toggles to produce a preset (a predetermined force at a certain location in the stroke) and reproducible stroke. Due to the nature of this type of system, different forces are available at different stroke positions. Mechanical presses are faster than their hydraulic counterparts (up to 50 strokes per minute).Their capacities range from 3 to 160 MN

(300 to 18,000 short tonsforce).Hydraulic presses use fluid pressure and a piston to generate force. Figure 5 shows hydraulic press. It is a load restricted machine. It has more of squeezing action than hammering action. Hence dies can be smaller and have longer life than with a hammer. Features of Hydraulic Press: Full press load is available during the full stroke of the ram, ram velocity can be controlled and varied during the stroke, it is a slow speed machine and hence has longer contact time and hence higher die temperatures, the slow squeezing action gives close tolerance on forgings, initial cost is higher compared to hammers.

ROTARY FORGING:

Components weight reduction is top priority for many metal formed parts. Together with LABEIN Teklanika, DENN is providing solutions to this issue. We apply the rotary forging process to manufacture components, which exceed the forming suitability of conventional processes. The rotary forging process offers the advantage of combining an incremental process with the end product properties provided by conventional forging. Rotary forging is an incremental manufacturing process characterized by its combination of two actions, rotational and an axial compression movement, for precise component forming that can be carried out cold or hot. Parts manufacture by this process are wheel performs, gears, discs, rings, etc.. This technology enables greater use to be made of materials, minimizing (in some cases eliminating) machining and welding operations. Rotary forging requires less force, between 5% to 20% of conventional forming presses, due to reduction in contact and friction; resulting in smaller presses and simpler tools. Rotary forging machines (presses)

- High flexibility (small modifications allow new geometries)
- Lower tooling costs, less number of tooling changes and shaping stages
- Very high dimensional precision (near net shape)
- Reduction / elimination of burrs• High finish quality (elimination of cracks)
- Hardening of the material and optimized grained structure
- Minimizing / elimination of machining and welding operations

Forging defects:

Though forging process give generally prior quality product compared other manufacturing processes. There are some defects that are lightly to come a proper care is not taken in forging process design.

A brief description of such defects and their remedial method is given below.

• (A): Unfilled Section: In this some section of the die cavity are not completely filled by the flowing metal. The causes of this defect are improper design of the forging die or using forging techniques.

(B): Cold Shut: This appears as a small crack at the corners of the forging. This is caused Manley by the improper design of die. Where in the corner and the fillet radius are small as a result of which metal does not flow properly into the corner and the ends up as a cold shut.

(C): Scale Pits: This is seen as irregular depurations on the surface of the forging. This is primarily caused because of improper cleaning of the stock used for forging. The oxide and scale gets embedded into the finish forging surface. When the forging is cleaned by pickling, these are seen as depurations on the forging surface.

(D): Die Shift: This is caused by the miss alignment of the die halve, making the two halve of the forging to be improper shape.

(E): Flakes: These are basically internal ruptures caused by the improper cooling of the large forging. Rapid cooling causes the exterior to cool quickly causing internal fractures. This can be remedied by following proper cooling practices.

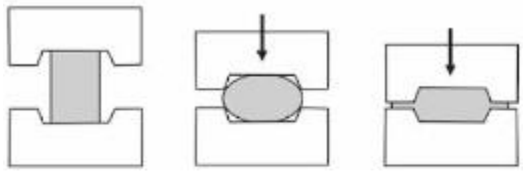
(F): Improper Grain Flow: This is caused by the improper design of the die, which makes the flow of the metal not flowing the final interred direction.

IMPRESSION DIE FORGING

Here half the impression of the finished forging is sunk or made in the top die and other half of the impression is sunk in the bottom die. In impression die forging, the work piece is pressed between the dies. As the metal spreads to fill up the cavities sunk in the dies, the requisite shape is formed between the closing dies. Some material which is forced out of the dies is called “flash”. The flash provides some cushioning for the dies, as the top strikes the anvil. The flash around the work piece is cut and discarded as scrap. For a good forging, the impression in the dies has to be completely filled by the material. This may require several blows of the hammer, a single blow may not be sufficient.

CLOSED DIE FORGING

Closed die forging is very similar to impression die forging, but in true closed die forging, the amount of material initially taken is very carefully controlled, so that no flash is formed. Otherwise, the process is similar to impression die forging. It is a technique which is suitable for mass production.



Closed die forging

DROP FORGING

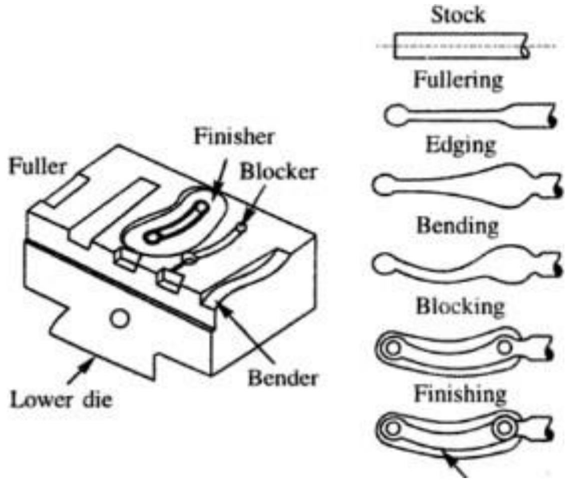
Drop forging utilizes a closed impression die to obtain the desired shape of the component. The shaping is done by the repeated hammering given to the material in the die cavity. The equipment used for delivering the blows are called drop hammers.

Drop forging die consists of two halves. The lower half of the die is fixed to the anvil of the machine while the upper half is fixed to the ram. The heated stock is kept in the lower die. While the ram delivers four to five blows on the metal, in quick succession so that the metal spread and completely fills the die cavity. When the two die halves closed the complete cavity is formed.

The **die impressions** are machined in the die cavity, because of more complex shapes can be obtained in drop forging, compared to smith forging. However too complex shape with internal cavities, deep pockets, cannot be obtained in drop forging. Due to limitation of withdrawal of finished forging from die. The final shape desired in drop forging cannot be obtained directly from the stock in the single pass. Depending upon the shape of the component, the desired grain flow direction and the material should be manipulated in a number of passes. Various passes are used are

Fullering impression: Since drop forging involves only a reduction in cross section with no upsetting, the very first step to reduce the stock is fullering.The impression machined in the die to achieve this is called fullering impression.

Edging impression: Also called as preform. This stage is used to gather the exact amount of material required at each cross-section of the finished component. This is the most important stage in drop forging.



Bending impression:

This is required for those parts which have a bend shape. The bend shape can also be obtained without the bending impressions. Then the grain flow direction will not follow the bend shape and thus the point of bend may become weak. To improve the grain flow, therefore a bending impression is incorporated after edging impression.

Blocking impression:

It is also called as semi finishing impression. Blocking is a step before finishing. In forging, it is difficult for the material to flow to deep pockets, sharp corners etc. Hence before the actual shape is obtained, the material is allowed to have one or more blocking impressions where it requires the shape very near to final one. The blocking impression is characterized by large corner radii and fillet but no flash.

Finishing impression:

This is the final impression where the actual shape required obtained. In order to ensure that the metal completely fills the die cavity, a little extra metal is added to the stock. The extra metal will form the flash and surround the forging in the parting plane.

Trimming:

In this stage the extra flash present around the forging is trimmed to get the forging in the usable form.

PRESS FORGING

Press forging dies are similar to drop forging dies as also the process. In press forging the metal is shaped not by means of a series of blows as in drop forging, but by means of a single continuous squeezing action. This squizing is obtained by means of hydraulic presses. Because of continuous action of the hydraulic presses, the material gets uniformly deformed throughout the entire depth. More hammer force is likely to be transmitted to the machine frame in drop forging where in press forging it is absorbed fully by stock. The impression obtained in press forging is clean compared to that of jarred impression which is like in drop forged component. The draft angle in press forging is less than in drop forging. But the press capacity required for deforming is higher and as a result the smaller sized component only are press forged in closed impression dies. The presses have capacities ranging from 5MN to 50 MN for normal application For special heavy duty application, higher capacity press of order 150 MN are required.

To provide the necessary alignment the two halves, die post are attached to the bottom die so that the top die would slide only on the post and thus register the correct alignment. This ensures better tolerance for press forged components.

FORGING DEFECTS

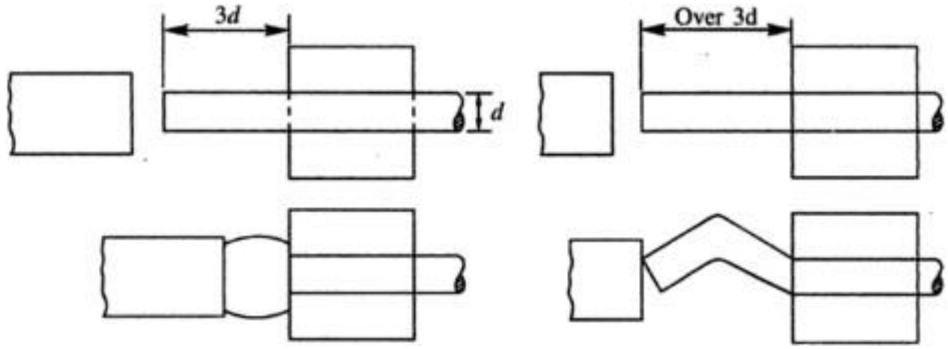
The common forging defects can be traced to defects in raw material, improper heating of material, Faulty design of dies and improper forging practice. Most common defects present in forgings are:

- Laps and Cracks at corners or surfaces lap is caused due to following over of a layer of material over another surface. These defects are caused by improper forging and faulty die design.
- Incomplete forging—either due to less material or inadequate or improper flow of material.
- Mismatched forging due to improperly aligned die halves.
- Scale pits—due to squeezing of scales into the metal surface during hammering action.
- Burnt or overheated metal—due to improper heating.
- Internal cracks in the forging which are caused by use of heavy hammer blows and improperly heated and soaked material.
- Fibre flow lines disruption due to very rapid plastic flow of metal.

UPSET FORGING DIE DESIGN

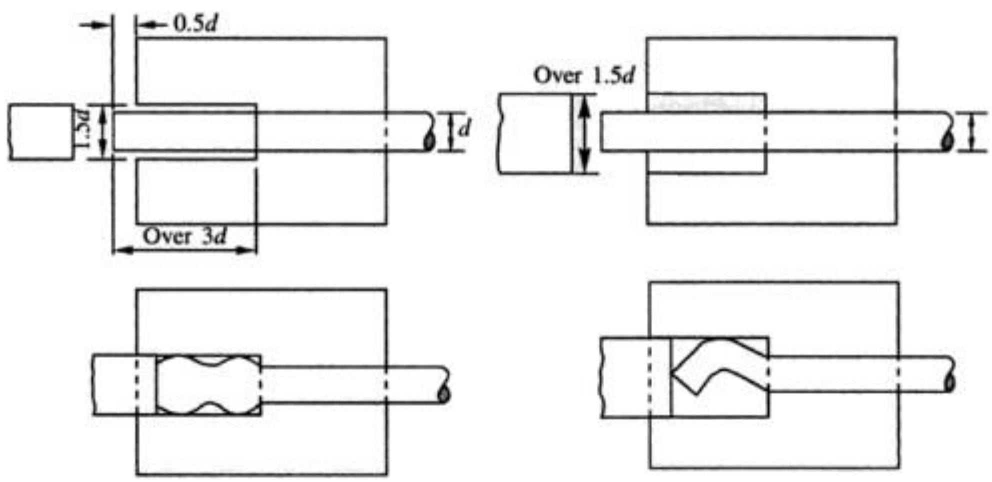
In upset forging there is no reduction in cross section and stock length chosen is smallest area of cross section. Here very negligible flash is provided. Depending upon the shape of upsetting ,the number of passes or blows in the dies are to be designed. The amount of upsetting done in a single stage is limited. Three rules are to be followed for safe amount of upsetting.

1. Maximum length of unsupported stock can be gathered or upset in a single pass. It is not more than three times the stock diameter. Beyond the length material is likely to buckle.
   Under axial upsetting load than be upset as shown below in figure



(a) Stock upset (b) Stock buckle

2. If the stock longer than three times the diameter is to be upset in a single blow, then the following conditions should be complied. The die cavity should not be wider than 1.5 times the stock diameter and the free length of the stock outside the die should be less than half the stock diameter. If these conditions are not complied, the stock would bend.



3. For upsetting the stock which is longer than three times the diameter and the free length of stock outside the die is up to 2.5 times the diameter, the following conditions should be satisfied. The material is to be confined into a conical cavity made in punch with the mouth diameter not exceeding 1.5 times the stock diameter and bottom size being 1.25 times the stock diameter. Also the necessary

that the heading tool recess be not less than two thirds the length of the work ing stock or not less than the working stock minus 2.5 times the stock diameter

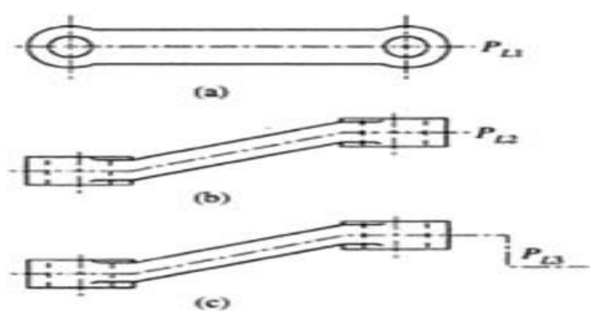
FORGING DESIGN

It is necessary to design the shape of forging to be obtained from the die.

Parting Plane

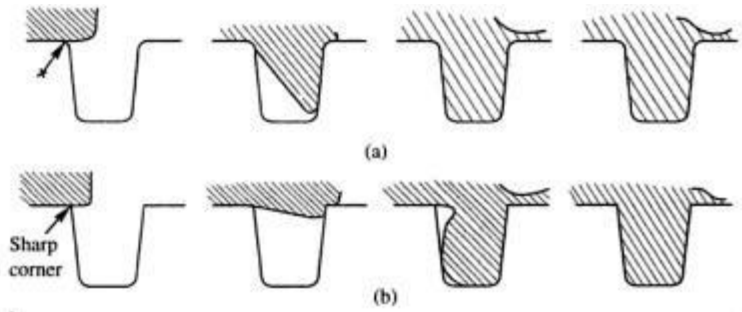
A Parting plane is the plane in which the two die halves of forging meet. It could be a simple plane ar irregularly bent, depending upon the shape of forging. The choice of proper parting plane greatly influences the cost of the die as well as the grain flow in the forging.

In any forging, the parting plane should be largest cross sectional area of forging, since it is easier to spread the metal than to force it into deep pockets. A flat parting plane is more economical. Also the parting plane chosen in such a way that the amount of material is located in each of the two die haves so that no deep die cavities are required It may be required to put more metal into the top die half since metal would flow more readily in the top half than in the bottom half.



Fillet and corner radii

Forging involves the flow of metal in an orderly manner. Therefore it is necessary to provide a streamlined path for the flow of metal so that defects free forging are produced. When two or more surface met a corner is produced which restrict the flow of metal.Therfore these corners are to be rounded off to improve the flow of metal. Fillets are for rounding the internal angles where corner is that of the external angles.



Effect of edge radius on floe metal

Allowance

Shrinkage allowance

The forging are generally made at room temperature of 1150 to 1300^0c.At this temperature, the material gets expanded and when it is cooled to the atmospheric temperature, it dimension would be reduced. It is very difficult to control the temperature at which forging process would be complete, therefore to precisely control the dimensions.

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Shrinkage allowance

Length or width, mm	*Commercial + or − mm*	*Close + or − mm*
up to 25	0.08	0.05
26 to 50	0.15	0.08
51 to 75	0.23	0.13
76 to 100	0.30	0.15
101 to 125	0.38	0.20
126 to 150	0.45	0.23
Each additional 25	add 0.075	0.038
For example 400	1.200	0.830

Die wear allowance

The die wear allowance is added to account for the gradual wear of the die which takes place with the use of die.

Die wear tolerance

Net mass of forging (kg)	*Commercial + or − (mm)*	*Close + or − (mm)*
up to 0.45	0.80	0.40
0.46 to 1.35	0.88	0.45
1.36 to 2.25	0.95	0.48
2.26 to 3.20	1.03	0.53
3.21 to 4.10	1.11	0.55
4.11 to 5.00	1.18	0.60
Each additional 1 add	0.083	0.041
For example 15.00	2.010	1.010

Finish allowance

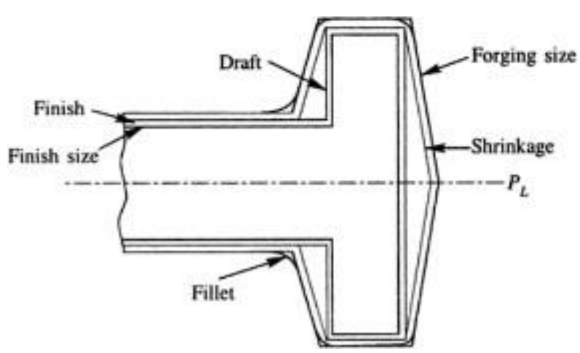
Matching allowance is to be provided on various forged surfaces which need to be further machined. The amount of allowance to be provided should account for the accuracy, the depth of the decarburized layer. Also the scale pits that are likely to form on the component should also be removed by machining.

Finish allowance for drop forgings

Greatest dimension (mm)	*Minimum allowance per surface (mm)*
up to 200	1.5
201 to 400	2.5
401 to 600	3.0
601 to 900	4.0
above 900	5.0

Finish allowance for upset forgings

Greatest diameter (mm)	*Minimum allowance per surface (mm)*
up to 50	1.5
51 to 200	2.5
above 200	3.0



Allowances shown on forged component

Stock

Drop forging do not get upset and therefore the stock size to be chosen depends upon the largest cross sectional area of the component. To get the stock size the flash allowance is to be provided over and above the stock volume. The stock to be used either round, rectangular or any other cross section depending upon the nature of component. Having decided on the cross section of the stock, and from the total volume of the component and the flash, it is possible to find the length of the stock. The stock of the die is to be moved from one impression to other and hence a tong hold is provided in addition to the length of the stock.