Chapter 2

Metal Casting and Forming

CHAPTER HIGHLIGHTS

Metal Casting

Metal casting is the process of pouring a molten metal in to a mould and allowing it to solidify to produce a desired object.

Most commonly used method of metal casting is sand casting in which a sand mould is used. It is a very old method. Improved methods such as shell moulding, investment casting, die casting, centrifugal casting etc. now find wider application. Various steps in casting are

1. Pattern making
2. Mould and core making
3. Melting and pouring
4. Fettling after solidification
5. Inspection and testing

Pattern Making

Pattern is the replica or full size model of the casting to be made. It is used to give shape to the mould cavity where the poured molten metal solidifies to the desired form and size.

Pattern is generally made using the following materials.

1. Wood
2. Metals
3. Plastics
4. Plasters
5. Wax

Each material has its own advantages and limitations. The required accuracy, strength and life of a pattern depend on the quantity of casting to be produced.

Generally for short run production wood is used as pattern material. For mass production metal patterns are used. Plastics may be used for batch production.

Pattern Allowances

A pattern is generally slightly larger in size compared to the casting due to the various allowances to be provided.

Various allowances are

1. Shrinkage or contraction allowance
2. Machining or finishing allowance
3. Draft or taper allowance
4. Shaking or rapping allowance
5. Distortion or camber allowance

Shrinkage Allowance

Almost all metals shrink or contract on solidification. So to compensate the reduction in size of the casting, size of pattern is to be increased. The allowance provided for this is called shrinkage allowance. Following is the typical values of shrinkage allowances for some of the commonly used metals

Cart iron/		
Malleable iron	:	10 mm/m
Brass, Cu, Al	:	15 mm/m
Steel	:	20 mm/m
Zn, Lead	:	25 mm/m

A 'shrink scale' is a pattern maker's rule using which pattern dimensions, are laid out. Shrink scale is longer than a standard scale by the shrinkage value for the appropriate metal.

Machining or Finishing Allowance

To remove surface roughness and other imperfections and to achieve exact casting dimensions, a casting has to be machined. Therefore to account for this the pattern is to be made sufficiently larger. The allowance provided for this is called machining or finishing allowance.

Draft or Taper Allowance

Draft is the taper provided on the vertical surfaces of pattern for the easy removal of the pattern from the mould with out damaging the edges of the mould around the pattern. Draft is expressed in mm per meter on a side or in degrees. The amount of taper depends on method of moulding, shape and size of pattern and the moulding material.

Shaking or Rapping Allowance

The pattern is to be shaked or rapped for easy withdrawal from the mould. The cavity of the mould is slightly increased by the shaking action. To compensate this the pattern is made slightly smaller than the required size.

Distortion or Camber Allowance

A casting will distort or warp during cooling due to uneven shrinkages due to irregular shape, uneven metal thickness or difference in exposures of the metal surfaces. To allow for this, the shape of the pattern is modified in such a way it bends in the opposite direction of distortion.

Types of Patterns

The type of a pattern to be used depends up on the following points

1. Quantity of casting to be produced
2. Size and complexity of the shape of casting to be produced
3. Moulding method used
4. Surface finish and accuracy required etc

The most common type of patterns are

1. Solid or single piece pattern
2. Split pattern
3. Loose piece pattern
4. Cope and drag pattern
5. Match plate pattern
6. Gated pattern
7. Sweep pattern
8. Segmental pattern
9. Skelton pattern
10. Built up pattern
11. Follow board pattern

Solid or single piece pattern is used either in the drag or in the cope. It is generally used for large castings of simple shape.

All castings, for example spherical shaped, cannot be mould using single piece patterns. So split patterns are used. Split patterns are made in two parts. So that one part will come in the dag and the other part will come in the cope. This facilitates easily removal of the pattern from the mould without damage to the mould.

In loose piece patterns projections or overhanging parts are made as loose pieces which are attached to the main part using wooden dowel pins. After making the mould, the main part of pattern is withdrawn first and then the loose pieces.

Cope and drag pattern is another type of split pattern. The split halves of the pattern are mounted on different plates. The two halves are made separately and then assembled. These are used for very large castings.

Match plate patterns are mostly used in machine moulding and for producing large number of small castings by hand moulding. The pattern halves with gating and runner systems are mounted on opposite sides of one single wooden or metal plate called match plate.

Gated pattern is one or more loose patterns having attached gates and runners. Time required to cut gating system by hand is eliminated. These are used for mass production of small castings.

Sweep patterns are used for symmetrically shaped large castings. A section or wooden board of proper contour is rotated about one edge so that a cavity is made in the moulding material such as loam sand with the desired contour.

Segmental patterns are also known as part patterns. These are used for producing large circular castings such as rings, gears etc. The part pattern is moved about the centre. After ramming one section it is moved to the adjacent section and this is continued to complete the mould.

Skeleton patterns are used for very large castings of simple geometrical shapes. If no. of castings required is small it is not economical to construct solid patterns. Pattern is made of wooden frame and ribs. The frame work is filled with loam sand and rammed. A strike off board known as strickle board is used to give the pattern the desired shape.

Built up patterns are composed of two or more segments made by cutting strips of wood. Pattern for special pulleys are built up type.

Follow board pattern is a wooden board and is used for supporting a pattern which is very thin and fragile. It also helps to establish a parting plane with ease in a pattern that has an irregular shape.

Stop Off

Stop offs are wooden pieces used to reinforce some portion of the pattern which are structurally weak. The cavities formed after moulding due to the stop offs are refilled with sand before pouring molten metal.

Pattern Colour Codes

Colour codes are used in patterns for indicating different surfaces. There is no universally accepted standard colour code. The colour code adopted by most of the foundries are as follows.

Part of the pattern	Colour
1. Surface to be left unmachined	Balck
2. Surface to be machined	Red
3. Coreprints and seats for loose core prints	Yellow
4. Seats for loose pieces	Red strips on yellow background
5. Stop offs or supports	Black strips on yellow

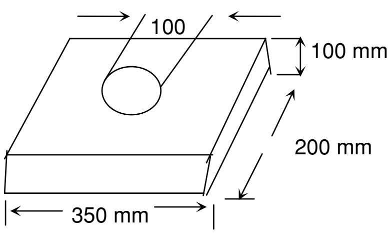
Pattern Design Considerations

A pattern not properly designed will produce only bad castings. The following are some of the factors that must be taken into account while designing a pattern.

1. The pattern should be dimensionally accurate and should have very good surface finish
2. Metallic pattern give good surface finish but are cost compared to wood castings
3. All the pattern allowances should be taken into account
4. In the case of split pattern the parting surface should be such that the larger part of the pattern should be in the drag
5. All sharp corners and edges should be rounded
6. Change in section thickness should be smooth, gradual and uniform
7. Match plate patterns are preferred for machine moulding
8. Jointed cores should be avoided

Solved Examples

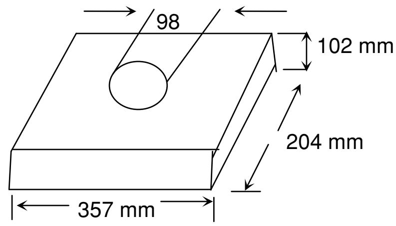
Example 1: Calculate dimensions of the pattern for the casting shown in figure. (Material white cast iron)



Solution: Shrinkage allowance for white cast iron (from tables)

= 20 mm/m
= 0.02 mm/mm
Pattern dimension/mm of casting = 1.02 mm
(for holes = 0.98 mm)

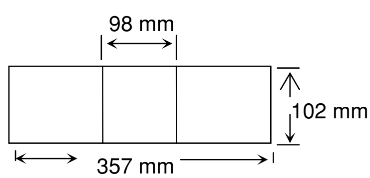
Casting dimension	Pattern dimension
100 mm	100 × 1.02 = 102 mm
200 mm	200 × 1.02 = 204 mm
350 mm	350 × 1.02 = 357 mm
100 mm hole	100 × 0.98 = 98 mm



Pattern dimension Table

Metals/Alloys	Shrinkage allowance (mm/m)
Gray cast iron	10.4
White cast iron	20
Plain carbon steel	20.8
Chromium steel	20
Manganese steel	25–38
Al. alloys	12.5–15
Brass	15.3
Bronze	15.5–20.8
Copper	16
Zinc	24
Magnesium	17

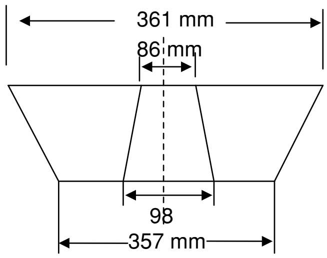
Example 2: Provide draft allowance for the wood pattern in the example 1.



Refer to the tables

Solution: Assume 1° taper for external and 3° taper for internal Draft allowance is provided for the vertical surfaces only

External $102 \times \tan 1° = 1.78$ mm
$\simeq 2$ mm
Internal $= 102 \times \tan 3° = 5.35 \simeq 6$ mm
Outer dimension $= 357 + 2 + 2$
$= 361$ mm
Inner dimension $= 98–12 = 86$ mm



Table

Draft Values for patterns

Pattern materials	Draft (degrees)	
	External surface	Internal surface
Wood	0.25 to 3.00	0.5 to 3.0
Metal	0.35 to 1.50	0.5 to 3.0
Plastic	0.25 to 1.0	0.35 to 2.25

Machining allowances for patterns

Material/alloy	Machining allowances (mm) (on surface)
Cast Iron	
Medium castings	3
Large castings	10
Cast steel	
Medium castings	4.5
Large castings	12
Non-ferrous (brass, bronze, Al)	
Medium castings	1.5
Large castings	5

Example 3: Steel castings are produced from a brass pattern which is to be made from a wooden pattern. If the dimensions of a component part is 80 mm, the corresponding dimension of the wooden pattern considering shrinkage only will be

Solution: Allowance for brass $= 80 \times \frac{15.3}{1000}$

$= 1.224$ mm

Allowance for steel $= 80 \times \frac{20.8}{1000}$

$= 1.664$ mm

Total shrinkage allowance

$= 1.224 + 1.664$

$= 2.888$ mm

$= 2.9$ mm (approx)

Dimension of wooden pattern

$= 80 + 2.9 = 82.9$ mm

Classification of Casting Process

The casting process may be classified in to

1. Expendable mould casting
2. Permanent mould casting
3. Semi-permanent mould casting

In expendable mould casting a refractory material is used as mould material. The mould is to be destroyed for taking out the solidified casting. Sand mould casting is an example. The main draw back of sand mould casting is the poor surface finish of the casting.

Sand Mould Casting

About 80% of the cast products are made using sand mould casting method. Sand moulds are single casting moulds and are completely destroyed for taking out the casting. The moulding material is sand mixed with small quantities of binding materials and additives and water to improve the cohesive strength and mouldability of sand.

Sand moulds are prepared in wooden or metallic boxes called flasks. Depending up on the type of casting there can be one flask or more than one flasks. Two flask system is the most commonly used. In the assembled position, the upper flask is called ‘cope’ and bottom flask is called ‘Drag’. In three flask system, the intermediate or central flask is called the ‘Cheak’

One flask dsign is used in ‘full mould process’ or in pit moulding where it is used as cope, the pit acting as ‘drag’

Cores

Cores are the materials used for making cavities and hollow projections, which cannot normally be produced by pattern alone. Cores are generally made of sand. During casting, cores are surrounded by molten metal and are subjected to severe thermal and mechanical conditions. There fore core sand should be of higher strength than the moulding sand. Core is set in the mould cavity of the prepared mould before closing and pouring. Through holes, recesses, projections, undercuts and internal cavities can be formed using cores.

Types of Cores

Cores can be classified according to the state of the material as

1. Green sand core
2. Dry sand core

Green sand core is formed by the patterns it self when it is being rammed while preparing a green sand mould (Green sand means sand containing moisture) The core is made of the same sand as the moulding sand. Green sand core is weak and can be used only for light castings.

Dry sand core is made separately by core making process of moulding a green core, drying, baking, finishing, coating etc. They are positioned in the mould, after the pattern is taken out before the mould is closed. These are the most commonly used cores.

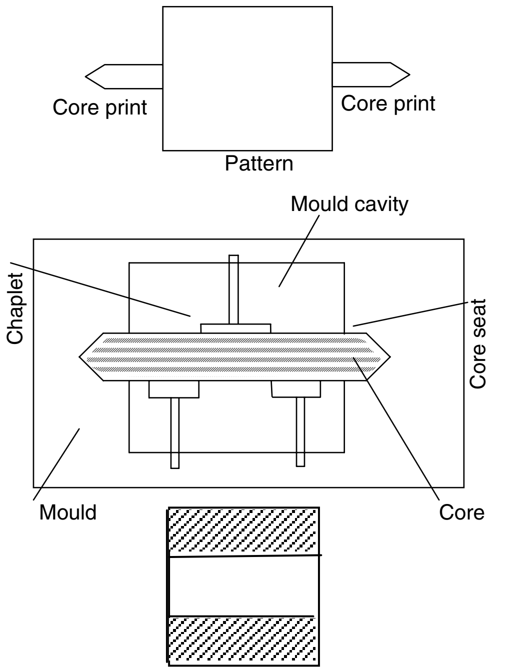
According to the position of the core in the mould, core can be classified as

1. Horizontal core
2. Vertical core
3. Balanced core

4. Hanging core
5. Drop core etc

Coreprints and Coreseats

Coreprints are extra projections provided on the pattern for making depressions in the mould for the placement of the core. The depression made by the coreprint in the mould is called core seat. Cores are placed in the core seats. Coreseats support the core against buoyancy of molten metal. Core prints, though a part of the pattern do not appear on the cast part.



Chaplets

Chaplets are metallic supports often kept inside the mould cavity to support the cores. They are made of the same material of the pouring metal. They melt and fuse with the pouring metal during solidification. There are various types of chaptlets such as radiater chaplets, rivaled chaplets, double head chaplets, cast chaplets, sheet metal chaplets etc.

Moulding Materials

Moulding materials may be classified in to two groups– basic and auxiliary

Basic materials include silica sands and binders Auxiliary materials include various additives which impart desired properties to the moulding and core sands.

A moulding sand consists silica sand grains, binder, additives and water. Silica sand grains form the base of the moulding sand. Binder is the bonding agent in a green sand. Most commonly used binder is clay. Clay imparts cohesiveness and plasticity to the moulding sand in the moist state and increase its strength after drying. When moulding sand has proper amount of water added to it to give a high strength with sufficient plasticity it is said to be 'tempered'.

According to the amount of clay present, the moulding sand may be classified as

1. Silica sand: up to 2% clay
2. Lean or weak sand: 2 to 10% clay
3. Moderately strong sand: 10 to 20% clay
4. Strong sand: up to 30% clay
5. Extra strong or loam sand: up to 50% clay

According to the initial conditions and use moulding sand may be classified as

1. Green sand
2. Dry sand
3. Loam sand
4. Facing sand
5. Parting sand
6. Backing sand

Foundry sand containing moisture is known as green sand. Green sand may contain 20 to 30% clay and 6 to 8% water.

Another classification of moulding sand is

1. Natural sand
2. Synthetic sand
3. Chemically coated sand

Natural sand is available from natural deposits. It contains sufficient or slightly more clay content that is required for moulding. So only additives and water need be added.

Relatively clay free sand having specified grain size is mixed with suitable type of clay additives and water to form synthetic sand.

Clean silica grain are coated with a non thermosetting hydrocarbon resin, which acts as a binder to form chemically coated sand.

Binders

Binders used in a foundry may be organic or inorganic. The most common is inorganic binders. Fire clay, Kaolinite, Illite and Bentonite are the clays used in moulding. The basic constituent which gives refractoriness to a clay is alumina, Al_2O_3. Bentonite is the most commonly used clay. As it needs only smaller quantity of water to get sufficient plasticity. Therefore steam generation during casting is less and moulding sand of low porosity or permeability can be used. Other inorganic binders are Portland cement, sodium silicate etc.

Organic binders are most commonly used in core making. Examples are

1. Cereal binders obtained from wheat, corn etc
2. Drying oils such as linseed oil, fish oil, soyabean oils and some mineral oils
3. Pitch and molasses

Additives

Additives are small quantities of special materials added to a moulding sand in order to enhance its existing properties and to impart some special properties.

Sea coal, cereals, sand dust, wood flour, silica flour, fuel oil, Iron oxide, dextrin etc are some of the additives used.

Properties of Moulding Sand

The choice of moulding maerials is based on their processing properties. The properties that are required in moulding materials are

1. **Permeability or porosity**
   The ability of the sand to allow gases from molten metal and steam and water vapours generated in the mould to pass through it is called permiability. It depends on the size and shape of grains, moisture content, degree of ramming etc

2. **Plasticity or flowability**
   It is the property of the moulding sand by which it is able to flow around and over a pattern during ramming and to uniformly fill the flask. Plasticity can be increased by adding clay and water

3. **Adhesiveness**
   The property to adhere with other materials is called adhesiveness. Adhesiveness between moulding sand and the moulding flasks are required during handling of the rammed boxes

4. **Cohesiveness or strength**
   The ability of the sand particles to stick to each other is called cohesiveness. In the absence of this property the mould will break when molten metal is poured. This depends up on grain size of sand and clay content

   Green strength is the strength of the sand in green or moist state.
   Dry strength is the strength of moulding sand in dry condition.
   Hot strength is the strength required to hold the shape of the mould cavity in hot condition. It is above 100°C and the molten metal in the mould is still in liquid state.

5. **Refractoriness**
   The capability of the moulding sand to with stand high temperatures of the molten metal with out fusing is known as refractoriness

6. **Collapsibility**
   It is the ability of the moulding sand to decrease in volume under compressive forces developed by the shrinkage of metal during freezing and subsequent cooling. This is very important for cores. It permits the moulding sand to break easily during its knock out from casting

7. **Fineness**
   Finer mould sand resists metal penetration and produces smooth surface for the casting. But permeability is reduced by fineness

8. Coefficient of expansion of the moulding sands should be less

Forces Acting on the Moulds

When the mould cavity is filled with molten metal it experience high metellelo static pressures and buoyant forces As a result moulds may be distorted or cores may be displaced. The effects of these forces can be eliminated by various methods such as placing weights on cope, clamping cope and drag properly by reinforcing sand mass etc.

The metellostatic force is due to the head acting by the molten metal in the mould cavity

Metallostatic force is given by

$$F_{\mathrm{m}} = Awh$$

Where A = projected area.
w = sp. weight of molten metal
h = head of the molten metal

upward force on core = displaced volume × difference in sp.wt

Example 4: Find the weights that is required to be kept to compensate the force during pouring in casting of a cast iron pipe of 12.5 cm OD and 10 cm ID with a length of 200 cm. The metal head is about 25 cm. While moulding, flask size used for the purpose is 220 × 25 × 20 cm in size. Weight density of core sand is 0.0165 N/cm^3 and that of liquid metal is 0.0771 N/cm^3

Solution: Displaced volume

V = Volume of core in the mould cavity

$$= \frac{\pi}{4}(10)^2 \times 200 = 15708\,\text{cm}^3$$

Upward force on the core

$$= V(w_m - w_c)$$
$$= 15708\ (0.0771 - 0.0165)$$
$$= 951.9\ \text{N}$$

Projected area

$$A = 12.5 \times 200 = 2500\ \text{cm}^2$$

Metallostatic force

$$F_m = Aw_m h$$
$$= 2500 \times 0.0771 \times 25$$
$$= 4818.75\ \text{N}$$

Total upward force = 4818.75 + 951.9 = 5770.65 N

wt of cope

$$= \left[220 \times 25 \times 20 - \frac{\pi}{4}\frac{(12.5)^2}{2} \times 200\right] \times 0.0165$$

$$= 1612.5\ \text{N}$$

Net upward force = 5770.65–1612.5
= 4158.15 N.

So the weight that is required to compensate upward force is approximately 4200 N. To account for the dynamic forces due to change in momentum of the molten liquid an additional 50% wt may be placed.

Total weight = 4200 × 1.5
= 6300 N.

Moulding processes

According to the method used moulding processes can be classified as

1. Bench moulding
2. Floor moulding
3. Machine moulding

Bench moulding is used for preparing small moulds. It is carried out on a bench of convenient height.

In floor moulding, the mould is made in the foundry floor. It is used for making medium and large size castings.

Machine moulding is used in batch and mass production. The moulding production becomes faster and labour is minimised. Moulding machines are classified according to

1. Method of compacting moulding sand and
2. The method of removing the pattern

Squeezer machines, jolt machine and sand slinger comes in the first group.

Straight draw moulding machine and turn over moulding machine are example of second group.

According to the mould materials used moulding process can be classified as

1. Green sand moulding
2. Dry sand moulding
3. Loam sand moulding
4. Metallic moulding or permanent moulding
5. Carbondioxide moulding

Green sand moulding is used for small and medium castings. It is simplest and least expensive and requires less time to prepare.

In dry sand moulding the green sand mould is dried before pouring molten metal. Drying or baking is carried out in ovens. Time for baking depends upon the binders used.

Loam sand moulding is used for large castings. Approximate contour of the casting is made by bricks and other materials and a thick coating of loam sand is given inside. Using a sweep pattern, correct contour of the casting is produced.

In carbondioxide moulding, sand is thoroughly mixed with 3 to 5% sodium silicate liquid base binder (water glass SiO_2 Na_2O) in a muller. Mould is prepared using the sand mixture by machine or hand moulding. Then CO_2 is forced in to the mould at a pressure of about 1.5 Kgf/cm^2 for 10 to 30 seconds.

Sodium silicate reacts with CO_2 to form silica jel

SiO_2 $Na_2O + CO_2 \rightarrow Na_2CO_3 + H_2O + SiO_2$

Carbon dioxide is expected to form a weak acid, which hydrolises the sodium silicate resulting in amorphous silica, which form the bond. The introduction of CO_2 gas starts the reaction by forming hydrated sodium carbonate. This gelling action increases the viscosity of the binder till it becomes solid. The compressive strength of the bond increases due to dehydration.

Melting and Pouring

After the preparation of moulds, molten metal is poured in to the mould to get the casting. Various type of melting furnaces are available for melting metals and alloys. Most commonly used furnaces are,

1. Cupola furnace–for melting cast iron
2. Crucible furnace–for melting non-ferrous metals
3. Electric furnace–for melting steel and special alloy steels

Molten metal is poured into the mould through the gating system.

Gating System

All the passages through which molten metal passes before entering the mould cavity is referred as gating system.

Various elements of a gating system are

1. Pouring basin
2. Sprue
3. Sprue base or well
4. Runner
5. Runner extension
6. Choke
7. Skim bob
8. Gates and/or ingates
9. Riser

Pouring Basin

A pouring basin or cup is a reservoir at the top of the vertical passage (sprue) in the cope, where the molten metal is poured, It is used for maintaining the required flow rate, minimize turbulence and to aid in separating dross and slag from the molten metal before it enter the runner system.

Sprue

It is a vertical passage through the cope and connects the pouring basin to the runner or gate. A straight sprue with sharp corners will cause severe aspiration (air sucking) thereby causing turbulence in the molten metal. If a tapered sprue with round corners and dam type pouring basin are used aspiration and turbulence are negligible.

The molten metal when moving from the top of the cope to parting plane gains in velocity and as a consequence requires smaller area of cross section for the same amount of metal to flow. If straight sprue is used metal flow would not be full at the bottom leading to aspiration.

Equations of continuity can be used to find the exact tapering required. Denoting top and choke by 't' and 'c'.

$$A_t V_t = A_c V_c$$

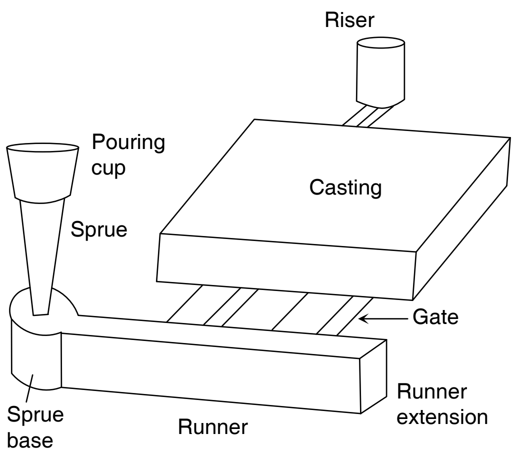
$$\text{or } A_t = A_c \frac{Vc}{V_t}$$

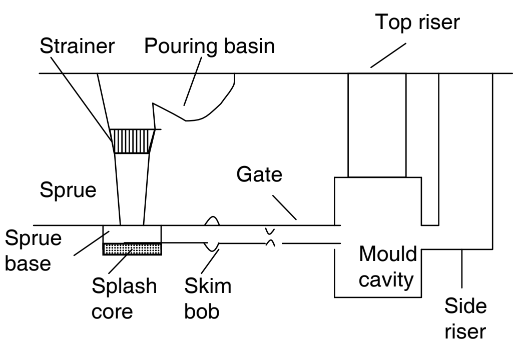
$$\text{But } V = \sqrt{2gh}$$

$$\text{Or } \quad V \alpha \sqrt{h}$$

$$\therefore A_t = A_c \sqrt{\frac{h_c}{h_t}}$$

From the above equation it can be seen that the profile of an ideal sprue is parabolic. But in practice for convenience a straight tapered sprue is used.





Sprue Base or Well

Where the sprue joins the runner an enlargement called sprue base or sprue well is provided. The mollen metal pool formed at the sprue base prevents excessive sand erosion where the molten metal impinges.

Runners

A runner is a horizontal channel which connects the sprue with the gates. It is generally located in the horizontal, parting plane. Generally these are constructed in a trapezoidal cross section. For ferrous metals, generally runner is provided in the cope portion and in gates in the drag portion. This helps to trap the lighter slag and dross flowing with the molten metal.

Runner Extension

The runner is extended a little further after it meets the ingate. The slag flowing with the molten metal is trapped at the runner extension with out going to the ingates.

Skimbob

Skimbob is an enlargement provided in the runner. It's function is to trap impurities such as dross or eroded sand from going in to the mould cavity.

Gates

Gate is a channel which connects runner with the mould cavity. Ingate is the end of the gate where it joins the mould cavity and through which the molten metal is introduced to the mould cavity.

Choke

Choke is that part of the gating system which has the smallest cross sectional area. It helps to lower the flow velocity in the runner, to hold back slag and foreign materials in the runner also minimise the sand erosion.

Gating Ratio

It describes the relative cross sectional area of sprue: total runner area: total gate area.

Depending up on the position of choke, the gating system may be described as

1. Pressurised or choked system
2. Unpressurised or free system

In pressurised system, ingates serve as choke. The total gate area is smaller than the sprue area. So a back pressure is maintained in the system. A gating ratio 2:2:3 indicates a unpressurised gating system.

Types of Gates

Gates may be classified as

1. Parting line gate
2. Bottom gate
3. Top gate

In parting line gate, metal enters the mould cavity at the parting line. The gate may contain skimbob, skimming gate, shrink bob and whirl gate. Skimming gate is a vertical passage through the cope: Lighter foreign material is trapped in skimming gate. Shrink bob may be provided if there is a tendency for shrinkage defect near the ingate.

Whirlgate employs centrifugal force to aid the slag come to the centre where it rises up in the skimming gate. A bottom gate is provided in the drag portion of the mould. Metal fills in the bottom first and then rises up steadily in the mould.

In top gate, metal is poured down directly, into the mould cavity. In this, molten metal at the top of the casting is always hot.

Riser

Due to the shrinkage of metal during solidification voids are likely to form in the casting unless additional molten metal is fed in to these places.A reservoir of molten metal is to be maintained from which the metal can flow readily in to the casting when the need arises. These reservoirs are called risers. Riser is a hole cut in cope to prevent the molten metal to rise above the highest point in the casting.

Other functions of the risers are

1. The pourer can see the metal in the mould cavity. If the metal is not seen it indicates that metal is not sufficient or there is some obstruction
2. It gives passage of steam, gas, air etc

Directional Solidification

In a casting all parts do not cool at same rate. Some parts solidify more quickly than others. Due to this cavities are formed at certain regions. This cavities should be filled with the molten metal from the risers. For this to happen, the riser should be the last to solidify. So solidification should progress towards the risers from the filled areas. This is known as directional solidification.

Directional solidification can be achieved by the following methods.

1. Proper designing and positioning of risers
2. Use of padding to increase thickness of certain sections
3. Use of exothermic materials in risers
4. Use of chills in moulds

Gating System Design

Bernoulli's theorem can be applied to the molten metal that folws through the gating system. Ignoring frictional loss, law states that

$$h + \frac{p}{w} + \frac{v^2}{2g} = \text{constant}$$

Where h = potential head, m

p = pressure, Pa

v = liquid velocity, m/s

w = specific weight, N/m^3

g = acceleration due to gravity, 9.81 m/s^2

As the metal enters the pouring basin, it has the highest potential energy with no kinetic or pressure energies. But as the flow proceeds there is frictional head loss and heat loss (heat loss is not represented in the Bernoulli's equation).

The continuity equation which states that

$Q = AV$ = constant can also be applied

(Q = rate of flow m^3/s

A = area of cross section, m^2

V = velocity, m/s)

Pouring Time

The duration of time required for complete filling of a mould with molten metal is termed as pouring time. It depends on the casting material, complexity of casting, section thickness and casting size.

High pouring rate means turbulent flow in the mould and mould erosion. Low pouring rate requires higher pouring temperature. Otherwise the mould cavity may not be filled completely.

Empirical formulae for pouring time for, different casting materials are given below:

1. Grey cast iron, mass less than 450 kg

   Pouring time,

$$t = k\left[1.41 + \frac{T}{14.59}\right]\sqrt{w} \text{ seconds}$$

Where $k = \dfrac{\text{Fluidity of iron in inches}}{40}$

T = average section thickness, mm

W = mass of casting, Kg

2. Grey cast iron, mass greater than 450 Kg

$$t = k\left(1.236 + \frac{T}{16.65}\right) 2\sqrt{w} \text{ secs}$$

3. Steel castings

   $t = (2.4335–0.3953 \text{ Log } w)\ \sqrt{w}$ secs

Choke Area

It is the area at sprue exit. Choke area can be calculated using Bernoullis equation as

$$A = \frac{W}{dtc\sqrt{2gH}}$$

Where A = choke area, mm^2

W = casting mass, Kg

t = pouring time, s

d = density of molten metal Kg/mm^3

g = acceleration due to gravity, mm/s^2

H = effective metal head (sprue height)

C = efficiency factor–a function of gating system used.

H depends on the casting dimensions and the type of gating used. The following relations can be used.

Top gate, $H = h$

Bottom gate, $H = h - \frac{c}{2}$

Parting gate, $H = h - \frac{p^2}{2c}$

Where h = height of sprue
p = height of mould cavity in cope
c = total height of mould cavity

Risering Design

Riser is used to feed the casting during solidification so that no shrinkage cavities are formed. The requirement of risers depends to a great extend up on the type of metal poured and the complexity of casting. Various metals have various volumetric shrinkages.

Grey cast iron some times may have a negative shrinkage. This is because with higher carbon and silicon contents, graphitisation occurs which increases the volume and counter acts the metal shrinkage. Risering is not very critical in these situations. But for metals such as aluminium and steel volumetric contraction is very high and risering is very important.

Riser is also called feed heads. Molten metal rises in the riser after the mould cavity is filled up. They are used in heavy section casting or for high shrinkage alloys.

During casting metal shrinkage occur in three stages,

i) Liquid contraction or shrinkage
ii) Solidification shrinkage
iii) Solid shrinkage

First two are considered for risering purposes.

Riser Location

A riser should be located close to each heavier section. It should be located in such a manner that it is the last portion of the casting to solidify.

Types of Risers

Depending upon the location, a riser can be side riser, top riser and end riser. If it is located between runner and casting it is also called live or hot riser as this contains the hottest metal. Top risers and end risers are also called dead risers as these risers fill up with coldest metal and are likely to solidify before casting. A riser can also be an open riser or blind riser.

Blind Risers

A riser which does not break to the top of the cope and is entirely surrounded by moulding sand is known as blind riser. As the rate of cooling is slower it helps directional solidification. Also only a smaller size is required. It's main draw back is the formation vacuum due to the formation of metal skin on the walls. This hinders the metal feeding. To avoid this a permeable dry sand core is used, connecting it to the mould sand layers.

Shape and Size of Riser

To help directional solidification the risers should loss heat at a slower rate. Amount of heat content is proportional to the volume and rate of heat dissipation depends up on the surface area. Therefore a riser should be designed for a high V/A (Volume/Surface area) ratio for a given size. From this point of view a spherical shape is ideal one as it is having the lowest surface area a for same volume. But risers of spherical shape is difficult to mould. Therefore, a cylindrical shape is preferred. Height of a cylindrical riser is generally taken as $1.5 \times$ diameter of riser.

Riser Size

The solidification time of a casting depends up on the heat in the casting and its dissipation. So it is directly proportional to the volume. And indirectly proportional to the surface area. Based on these facts many relations are available for determining the riser size.

Chvorinov's Rule

Solidification or Freezing Time

$$T = C\left(\frac{V}{SA}\right)^2$$

Where V = volume of casting
SA = surface area of casting
C = constant of proportionality

To achieve directional solidification,

$$\left(\frac{V}{SA}\right)_{\text{Riser}} > \left(\frac{V}{SA}\right)_{\text{Casting}}$$

In practice

$$\left(\frac{V}{SA}\right)_{\text{Riser}} = 1.10 \text{ to } 1.15\left(\frac{V}{SA}\right)_{\text{Casting}}$$

$\left(\frac{V}{SA}\right)$ for the casting is known.

So $\left(\frac{V}{SA}\right)$ for the riser can be calculated. Assuming height to diameter ratio for a cylindrical riser, its size can be determined

Caine's Formula

Caine's method of determining the size of a riser in based on the experimentally determined hyperbolic relationship between relative freezing times and relative volumes of the casting and the riser.

Relative freezing time or freezing ratio,

$$X = \frac{\text{Cooling characteristics of casting}}{\text{Colling characteristics of riser}}$$

$$= \frac{(SA/V)_{\text{Casting}}}{(SA/V)_{\text{Riser}}}$$

Volume ratio,

$$Y = \frac{\text{Volume of riser}}{\text{Volume of casting}}$$

Caine's formula is given as,

$$X = \frac{a}{Y-b} + c$$

Where a = freezing characteristic constant

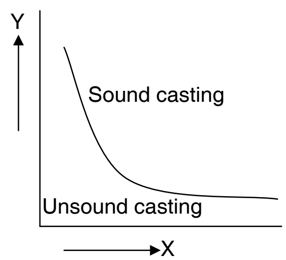
b = Liquid–solid solidification contraction constant

c = Relative freezing rate of riser and casting

Typical values a, b, c for commonly used cast metals are given below.

Cast metals	a	b	c
Steel	0.12	0.05	1.00
Aluminium	0.10	0.06	1.08
Graycast Iron	0.33	0.03	1.00
Cast iron, Brass	0.04	0.017	1.00
Aluminium, Bronze	0.24	0.017	1.00
Silicon Bronze	0.24	0.017	1.00

A typical Caine's hyperbolic curve is as shown in figure



Caine's curves for different cast metals are available in hand books. To find the riser size for a given casting, the riser diameter and height are assumed. Knowing values of a, b, and c, the values of X and Y are calculated. Values of x and Y are plotted on the hyperbolic curve. If the values meet above the curve the assumed size is satisfactory.

Modulus Method

Modulus is the inverse of cooling characteristic

$$\text{i.e, modulus} = \frac{V}{SA}$$

It has been empirically established that if the modulus of the riser exceeds the modulus of casting by a factor 1.2, the feeding solidification would be satisfactory.

It is generally preferable to choose a riser with height to diameter ratio = 1

In such cases, Volume $= \frac{\pi D^3}{4}$

$$\text{Surface area} = \frac{\pi D^2}{4} + \pi D^2$$

$$= \frac{5}{4}\pi D^2$$

$$\text{Modulus of riser, } M_R = \frac{\pi D^3}{4} \Big/ \frac{5\pi D^2}{4} = 0.2D$$

Since $M_R = 1.2Mc$

$D = 6\ Mc$

Thus in this method, calculation of riser size is very much simplified.

Example 5: Optimum pouring time for a casting of cast iron of mass 60 Kg and a section thickness 50 mm is (take fluidity = 22 inches).

Solution: Pouring time $t = k\left(1.41 + {}^{T}\!/\!_{14.59}\right)\sqrt{W}$

$$= \frac{22}{40}\left(1.41 + \frac{50}{14.59}\right)\sqrt{60}$$

$= 20.6$ sec.

Example 6: Determine diameter of the sprue at the exit to fill the mould of a CI casting neglecting flow losses.

Casting weight = 35 Kg

Pouring time = 22 seconds

Density of melt = 7 gm/mm^3

Height of sprue = 60 mm

And top gate.

Solution: Choke area

$$CA = \frac{W}{cdt\sqrt{2gH}}$$

Where W = casting weight = 35 Kg

C = efficiency factor = 0.85 for taper sprue

d = density of melt = 7 gm/cm^3 = 7×10^{-6} kg/mm^3

t = pouring time = 22 seconds

H = effective metal head

= height of sprue for top gate

= 160 mm

$$\therefore CA = \frac{35}{0.85 \times 7 \times 10^{-6} \times 22\sqrt{2 \times 9800 \times 160}}$$

$= 150.99$ mm^2

Diameter at choke area = d

$$\frac{\pi d^2}{4} = 150.99$$

$$d^2 = \frac{150.99 \times 4}{\pi}$$

$d = 13.865$ mm

Example 7: A casting of 200×100×70 mm^3 size solidifies in 10 minutes. Estimate the solidification time for 200×100 ×10 mm^3 casting under similar conditions.

Solution: Solidification time

$$T = k\left(\frac{V}{A}\right)^2$$

Where k = mould constant
V = volume of casting
A = surface area of casting
$V_1 = 200 \times 100 \times 70$ mm^3
$V_2 = 200 \times 100 \times 10$ mm^3
$A_1 = [(20 \times 100) + (100 \times 70) + (70 \times 200)]2$
$A_2 = [(200 \times 100) + (100 \times 10) + (10 \times 200)]2$

$$\frac{t_1}{t_2} = \left(\frac{V_1}{A_1}\right)^2 \Big/ \left(\frac{V_2}{A_2}\right)^2 = \left(\frac{V_1}{V_2}\right)^2 \times \left(\frac{A_2}{A_1}\right)^2$$

$$= \left(\frac{70}{10}\right)^2 \times \left[\frac{(200\times100)+(100\times10)+(10\times200}{(200\times100)+(100\times70)+(70\times200)}\right]^2$$

$$= 49 \times \left(\frac{23000}{4100}\right)^2 = 15.42$$

$$t_2 = \frac{t_1}{15.42} = \frac{10}{15.42} = 0.648 \text{ minutes}$$

Example 8: Calculate the size of a cylindrical riser necessary to feed a steel casting block of dimension 30 × 30 × 5 cm with a side riser, casting poured horizontally into the mould. Assume height = diameter for the riser.

Solution: Volume of casting = 30 × 30 × 5 = 4500 cm^3
Surface area = 2 [30 × 30] +4 [30 × 5]
= 2400 cm^2.

$$\text{Volume of riser} = \frac{\pi D^3}{4}$$

$$\text{Surface area of riser} = \pi D^2 + \frac{\pi D^2}{4} = \frac{5\pi D^2}{4}$$

$$\text{Freezing ratio } X = \frac{2400/4500}{\frac{5\pi D^2}{4} \Big/ \frac{\pi D^3}{4}}$$

$$= 0.1067\,D$$

$$\text{Volume ratio } Y = \frac{0.25\pi D^3}{4500} = 0.0000556 D^3$$

$$\text{Caine's formula } X = \frac{a}{Y-b} + C$$

For steel $a = 0.12$
$b = 0.05$
$c = 1$

Substituting values in the Caine's formula

$$0.1067\text{D} = \frac{0.12}{0.0000556 D^3 - 0.05} + 1$$

$$0.1067 D - 1 = \frac{0.12}{0.0000556\, D^3 - 0.05}$$

$5.93 \times 10^{-6} D^4 - 0.0000556\, D^3$
$- 5.335 \times 10^{-3}\, D + 0.05 = 0.12$
$D^4 – 9.376\, D^3 – 900 D = 11804$
$D = \simeq 16$ cm (By trial).

Cooling and Solidification

When a molten metal starts to cool and solidify crystals will begin to form independent of one another, at different locations in different orientations within molten mass. The formation of the first tiny particle is called nucleation. With passage of time these tiny particles (crystals) grow in size or grain growth takes place. When the cooling is rapid the pattern of grain/crystal growth is in the shape of radial arms which begin to develop from the various nuclii. As time progresses secondary arms develop at right angles to the radial arm and the process continues. This type of tree like crystals are called 'dentrites'. When cooling is slow equiaxed crystals grow uniformly in all directions. Crystal grows until it comes into contact with adjacent crystal of proper geometrical form and different orientations. The boundary formed between two adjacent crystal line growth because of different orientations of the grains is known as grain boundary

Solidification in a Casting Mould

When molten metal is poured in to a mould solidification will be rapid along the mould walls. In this chill zone, a layer of fine, polly crystalline, equiaxed grains will be produced. As the solidification progress the grains growth will be inwards, towards the centre, their lateral growth reduced due to the early contact made with the adjacent crystals. Here columnar, dentrite crystals are formed leading to the formation of a mushy zone. The width of the mushy zone depends upon the mould material, cooling rate and temperature gradient. As the heat extraction continue through out the mass, simultaneous freezing of the metal at the centre of the mould takes place. Here equiaxed coarse grains are formed. This central zone of equiaxed coarse grain can be extended throughout, without formation of dentrites, by the addition of inoculants (nucleating agents) to the liquid alloy. Ferro-silicon, Ferro-manganese, Ferro-Chromium, Ferro-silicon-chromium etc are the inoculants used.

Types of Solidification

i) Skin forming
Skin forming takesplace when molten metal is solidified in moulds, in the case of pure metals or alloys having eutectic compositions. Since the mould walls are at room temperature, solidification first starts near the

mould walls. The solidification front will move towards centre, and layer by layer solidification takes place

ii) Dantritic growth

Dantritic growth will happen if mushy zone appear during solidifications. Initially solid is nucleated near the boundary and the solidification front moves towards the centre. Solid is also nucleated in the liquid region and the solidification front movement in this case is towards the centre and to the primary dantrite. In this case unidirectional solidification does not takes place. Micro voids are formed at the meeting point of primary and secondary dantrites. These voids cannot be compensated by the riser. This results in defective casting

Segregation

When a liquid alloy metal cools and solidifies the separating out of the constituent elements of different freezing points is called segregation. Various types of segregation are, micro segregation, macro segregation, normal segregation and gravity segregation.

Casting Defects

In a casting various defects may occure due to various reasons. It may be due to improper pattern design, improper mould construction, improper melting practice, improper pouring etc. The defects may be broadly classified as

1. Gas defects
2. Shrinkage cavities
3. Moulding material defects
4. Pouring metal defects
5. Metallurgical defects
6. Moulding and corebox defects

Gas Defects

These are due to lower permeability of the mould. Blow holes and open blows, air inclusions and pinhole porosity etc. come under gas defects.

Blow holes and open blows are spherical, flattened or elongated cavities present inside the casting or on the surface. If they are on the surface they are called open blows. Moisture in the mould will be converted into steam due to the heat of the molten metal. A part of the steam may be entrapped in the casting. This leads to the formation of blow holes. Lower venting and lower permeability of mould also causes formation of blow holes and open blows.

Air Inclusion

Atmospheric and other gases are absorbed by the molten metal at high temperatures in the furnace, during pouring or in the mould. If they are not allowed to escape, they will be trapped inside the casting.

Pinhole Porosity

This is due to the presence of hydrogen in molten metal. During solidification of the molten metal hydrogen leaves the metal causing small diameter and long pinholes.

Shrinkage Cavities

Shrinkage cavities are formed during solidification of the molten metal, if feeding by risers are not proper or if the casting design is not proper.

Moulding Material Defects

Lack of the required properties of moulding materials improper ramming etc will lead to defects such as scabs, swell, runout and drop.

Scab

Scabs are projection formed on the casting. This occurs when a portion of the mould face lifts and metal flows underneath in a thin layer. If it happens due to the expansion of surface layer of sand it is called expansion scab. Scabs occur due to uneven ramming, excess moisture in sand etc,

Run Out

Runout is the escape of molten metal from mould cavity. Faulty moulding flask or faulty mould making may lead to this.

Drop

Drop occurs when cope surface cracks and breaks.Pieces of sand fall into mollen metal. Low green strength of sand, improper ramming of cope etc are the causes.

Cuts or Washes

Cuts or washes appear as low projections and areas of excess metal casused by erosion of moulding sand by the flowing molten metal. It usually occurs with bottom gating castings, when too much metal is made to flow and the moulding sand has insufficient hot strength.

Pouring Metal Defects

Misrun, cold sheet, poured short etc are pouring metal defects.

Misrun

This happens when the metal is unable to fill the mould cavity completely leaving unfilled cavities. This may happen due to lack of fluidity or due to obstruction in flow.

Cold Shut

This is caused when two metal streams coming from different directions while meeting in the mould cavity do not fuse together properly. Due to this, discontinuity or weak spot in the casting is formed.

Too thin sections, improper gating system, slow and intermittant pouring, poor fluidity of metal etc may cause misrun or cold shut.

Poured Short

If the mould cavity is not completely filled due to insufficient metal, this happens.

Metallurgical Defects

Hot Tears

Occur due to hindered contractrion of casting parts immediately after the metal solidification. Main reason is poor casting design.

Hardspots

This happens in metals such as gray cast iron with in sufficient silicon. Such metals may become hardened by the chilling effect of moulding sand. Hardspots make machining of the metal difficult.

Mismatch or Mould Shift

This is due to mismatch of cope and drag flasks at the parting line. The worn out or loose dowels in the pattern halves, inexpert assembly of mould halves etc are reasons. Core shift occurs due to the misalignment of core halves during assembly.

Flashes or Fins

Flashes or fins appear at the mould joints where gaps are formed This may be due to wear or warping or improper fastening of the cope and drag.

Buckles and Rat Tails

Buckle is a broad vee shaped depression appearing on the face of casting. It extends in a fairly straight line across the entire flat surface. It results from the sand expansion carried by the high temperature molten metal, when sand has insufficient hot deformation. It also happens in the design with too large flat surfaces in the mould cavity. Rat tail is a defect similar to buckle, happening due to same reasons, but the shape of the defect is different. Rat tail is not shaped as a broad vee. Buckles are the rat tails which are severe.

Swell

Swell is a slight, smooth bulge appearing on vertical walls of a casting. This is caused by liquid metal pressure at areas of low mould strength, due to improper ramming or too high water content.

Design of Castings

The design of a cast part should be such that the design should ensure high level of its working characteristics such as strength, rigidity, stiffness, lightness and corrosion resistance. Proper attention to design aspects will minimize casting problems and lower the costs.

The design of the casting should be such that it allows directional solidification. Product design should be studied under the following categories.

1. Design for economical moulding
2. Design for elimination of defects
3. Design for features to help handling of castings

The following factors should be taken into account while designing a casting.

1. Function of the casting
2. Selection and optimum use of the casting alloy
3. Strength of the casting
4. Simplification of foundry practices
5. Consideration of safety aspects
6. Economy of production

A few of the rules in design are

1. Stress concentration should be avoided. For thin, sharp corners and frequent use of fillets etc should be avoided
2. All members should have uniform sections as far as possible. Abrupt changes in sections should be avoided
3. Large flat surfaces should be avoided because it is difficult to get true surfaces on large castings
4. Pattern allowances should be provided
5. By providing curved shapes, contraction stresses should be minimized (example- arm of pulleys and wheels)
6. Stiffening members such as webs and ribs should be minimum as these give rise to defects like hot tears and shrinkage
7. Deep and narrow pockets in the casting should be avoided to minimize cleaning costs
8. Vertical walls should be as smooth as possible for easy withdrawals of patterns (markings such as names or numbers etc on vertical walls should be avoided)
9. Tolerance should be provided depending up on the dimensional accuracy desired

Special Casting Processes

Sand casting processes give fairly good results at lowest cost. Main draw back of sand casting is that the moulds are single use types. If in its place a permanent mould could be used there is considerable saving in time and labour cost. Also surface finish and accuracy is poor in the case of sand casting. To overcome this a number of special casting processes are developed. Some of the widely used casting processes are,

i) Shell moulding
ii) Precision investment casting
iii) Permanent mould casting
iv) Die casting
v) Centrifugal casting
vi) Squeeze casting

Shell Moulding

It is a modification of sand moulding process. In this process thin, shell type half moulds are made using a mixture of dry silica sand and phenolic resin.

The sand is mixed with either urea or phenol formaldehyde in a muller and transferred to a dump lox. Pattern made of metal is heated to 205 to 230°C and placed over the dump box and clamped. When the dump box is inverted the sand resin mixture falls over the hot patterns. The resin melts and acts as bond between sand grains at the surface of the pattern. After 30 seconds a hard and thin layer sand is formed over the pattern. Then the dunp box is brought to the original position. The excess sand falls back. Pattern with thin shells is cured at 315°C for 2 minutes. The shell is then ejected by ejector pins and removed. Similarly shell is made for the other half also. These shells are assembled in a flask with backing sand to form the mould.

High dimensional accuracy and good surface finish are the main advantages. The shells can be stored for a long time.

High cost and requirement of specialized equipments are the main disadvantages.

Precision Investment Casting (Lost Wax Method)

The term 'investment' refers to the layer of refractory material with which the pattern in covered to make the mould. Like sand casting method mould is destroyed every time a casting is made.

Shell moulding also is a precision investment casting method, though lost wax method is generally refered as precision investment casting.

In lost wax method a wax pattern is used. Wax pattern is melted from the mould, leaving the cavity.

In this method a master pattern is prepared using steel or brass. Using this pattern split mould is made with bismuth alloy or lead alloy. This mould is used for making wax pattern. Several wax patterns are assembled with necessary gates and risers. This assembly is dipped in a refractory slurry and refractory fine sand is sprinkled over it to ensure smooth surface for the casting. After the primary casting has dried sufficiently a final investment layer consisting of coarser and less expensive slurry is applied. The common refractory used is silica. The binder is of gypsum or water based sodium silicate. After the investment material is set the mould is placed upside down and heated to melt out the wax. The shell produced is used as mould for casting. The final moulds can be made as solid type or shell type. In solid type, the shell is placed in a flask and a hard setting moulding material is poured. For shell type moulding dipping in slurry is continued till sufficient thickness is obtained.

Permanent Mould Casting

In permanent mould casting the mould can be used repeatedly. Permanent moulds are also called dies. In this method gravity feeding of molten metal is used. So this method is also known as gravity diecasting. This method is generally used for non-ferrous metals and alloys such as Al, Mg, Zn, Cu–alloys, Sn, Pb etc. A permanent mould is made up of two parts–one stationary and the other moving. Two common designs are

i) Hinged type or book type
ii) Straight line retractable type

For making hollow portions, cores are to be used. Cores can be made of metal or sand. Metal cores can be used repeatedly. But complex shapes cannot be used. When sand cores are used, the process is called semi–permanent moulding.

Die Casting

Die casting involves the preparation of components by injecting molten metal at high pressure into metallic die. Unlike in permanent mould casting or gravity die casting, metal is fed under pressure. So this process is also called pressure die casting. Narrow sections complex shapes and fine surface details can easily be produced as high pressure is used in this method. The stationary part of the die is called the cover die and moving part is called the ejector die. Lubricant is sprayed on the diecavity manually or by auto lubrication system to avoid sticking of the casting in the die.

Die casting machines are of two types.

1. Hot chamber die casting
2. Cold chamber die casting

In hot chamber die casting machine the melting unit of metal forms an integral part of the machine.

In cold chamber machine metal is melted in a furnace outside and transferred to the cylinder of the machine from where it is forced into the mould by means of the plunger.

Advantages of die casting are,

1. Very high production rates are possible
2. Thin an complex section can be cast
3. Close dimensional control can be maintained

Vacuum Die Casting

Air trapped in the dies when they are closed is a major problem die casting. This also causes a back pressure when moulten metal is injected in to the mould. This problem is solved in vacuum die casting. As air is evacuated after closing the die, metal enters in to the die much faster. As a result fill time is reduced and blisters are avoided.

Low Pressure Die Casting

In low pressure die casting molten metal in a crucible rises to the mould through a riser tube dipped in the molten metal when low pressure in the range of 0.3 to 1.5 bar is applied to the molten metal. Since metal enters the mould slowly compared to die casting with less turbulence the casting quality is improved eliminating the defects.

Centrifugal Casting

In centrifugal casting process, the mould is rotated and the molten metal in the mould is acted up on by the centrigal force. Due to this molten metal is distributed to the periphery of the mould cavity. Centrifugal casting process is classified as

1. True centrifugal casting
2. Semi–centrifugal casting
3. Centrifuging process

In true centrifugal casting process, the axis of rotation of the mould coincides with the axis of casting and due to the centrifugal force molten metal is thrown out uniformly to the periphery of the mould cavity. In this case no core is required for making a concentic hole. Centrifugal casting can be used for the production of cast iron pipes. The finished flask rammed with sand inside, with the required contour and end details, is rotated on rollers. The amount of molten metal poured determines the thickness of the pipe to be cast.

The mechanical properties of centrifugally cast objects are better compared to the other processes because impurities such as slag and oxides get segregated towards the centre. This can be removed easily by machining.

In semi–centrifugal casting the mould is rotated about the vertical axis and metal is poured in to central sprue where it first enters the hub and then moves outwards to the periphery by centrifugal force. If central hole is required, a core is to be provided. Rotating speed is lesser than that is true centrifugal casting. For high rates of production, moulds can be stacked one over the other and molten metal can be fed through a common central sprue.

Centrifuging process is similar to semi–centrifugal casting process. Metal is fed through a central sprue and the mould is rotated. The main difference is that in the case of centrifuging the axis of the mould is not same as axis of rotation. Here identical small moulds are arranged in a circle which are connected through radial gates from the central sprue.

Continuous Casting

Continuous casting process consists of pouring into a short vertical metal die or mould at a controlled rate, cooling the melt rapidly and withdrawing the solidified product in a continuous length from the bottom at a rate consistent with the pouring rate. Using continuous casting process, slabs, billets and blooms can be directly cast with going through the rolling of ingot in various stages to obtain the products. The skin formed in the water cooled mould is further solidified by intensive cooling with water sprays as the casting moves forward.

Squeeze Casting

In squeeze casting the casting is solidified under high pressure. The product quality is greatly improved. Shrinkage cavities, dissolved gases etc are eliminated at high pressures. It is a combination of casting and forging. Molten metal is poured in to a die. Pressure is applied on this metal with a punch which is having the inner contour of the product.

Metal Forming Processes

Metal forming processes or mechanical working processes are based on permanent changes in the shape of body or plastic deformation under the action of external forces. Mechanical working processes include rolling, forging, extrusion, drawing and sheet metal working. Sheet metal working is also known as press working. The stresses induced in the part are greater than the yield strength but less than the fracture strength except in sheet metal operations. In sheet metal operations such as shearing, piercing, blanking etc stress induced are greater than or equal to the fracture strength.

Machining or metal cutting operations are not included in the forming processes. In machining operations material is removed from the part in the form of chips. But in mechanical forming processes there is no material loss.

Recrystallisation Temperature

During deformation, metal flows plastically and the shapes of grains are changed. If the deformation is carried out at high temperature, new grains are formed in the metal. The process of formation of new grains is known as recrystallisation. The temperature at which formation of new grains is complete is known as recrystallisation temperature. Plastic deformations of a metal above the recrystallisation temperature but below the melting temperature is known as **hot working**. And plastic deformation below the recrystallisation temperature is known as **cold working**.

Under the action of heat and force, atoms reach high energy level, new crystals starts forming during the recrystallisation. Recrystallisation destroys old grain structure deformed by mechanical working and entirely new crystals, which are strain free are formed. Recrystallisation temperature is defined as the approximate minimum temperature at which complete recrystallisation of a cold worked metal occurs with in a specified time.

Recrystallisation temperature generally varies between one third and half the melting point for most of the metals.

For lead and tin minimum recrystallisation is below the room temperature. For Cadmium and Zinc it is at the room temperature For iron it is 450°C.

Cold Working

Advantages

1. Strength and hardness of the metal is increased due to strain hardening.
2. As no oxides are formed on the surface, good surface finish is obtained.
3. Dimensional accuracy achieved is better.
4. It is easier to handle cold parts and is economical for smaller sizes.

Disadvantages

1. The amount of deformation that can be given is limited due to the higher yield strength and also due to strain hardening.
2. Brittle materials cannot be cold worked.
3. Possibility of crack formation and propagation is great.

Hot Working

Advantages

1. Since there is no strain hardening any amount of working can be imparted.
2. Even brittle materials can be hot worked.
3. Only lesser force is required for hot working.
4. A favourable grain size can be attained, at controlled working conditions. So better mechanical properties can be achieved.
5. Blow holes and porosities are eliminated by welding action at high temperature and pressure.

Disadvantages

1. Some metals cannot be hot worked because of their brittleness at high temperature.
2. Poor surface finish due to scaling.
3. Because of thermal expansion dimensional accuracy is hard to achieve.
4. Handling and maintaining of hot metal is difficult and troublesome.
5. Surface decarbonisation in steels reduces strength and hardness of the surface.

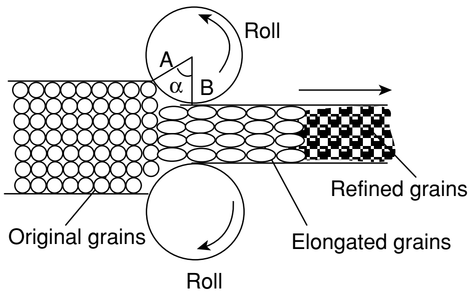
Rolling

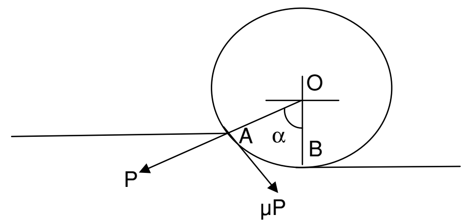
The process of shaping metals and alloys into finished or semi finished conditions passing between circular or contoured rotating cylinders (rolls) is called rolling. The metal is drawn in to the opening between rolls by frictional forces between metal and roll surface. The work piece is subjected to high compressive forces and is plastically deformed.

Rolling is done in both hot and cold. The starting material is cast ingots. These are rolled to blooms, billets and slabs initially and then hot rolled to plates, sheets, rods etc.

In the rolling process the metal is passed through two rolls rotating in opposite directions at a uniform peripheral speed. The space between the rolls can be adjusted to obtain the desired thickness of the rolled product. The work piece comes out of the rolls with reduced thickness, but its width and length is increased.

In the rolling process, because of the squeezing, the grains are elongated in the direction of rolling and the velocity of metal is higher than that at the entry. After the stress zone, the elongated grains start refining in the case of hot rolling. The elongated grains remains as it is the case of cold rolling.





The metal contacts each of the rolls along the arc AB. The angle (α) made by the arc at the centre of the roll is called angle of bite or angle of contact. At the moment of bite two forces act on the metal, normal force P and tangential force μP, where μ is the coefft of friction. If the horizontal component of the resultant normal force P and frictional force μP is directed in the direction of rotation, the work piece will be dragged in the same direction. In the limiting case,

$$\mathrm{P}\sin\alpha = \mu P \cos\alpha$$

$$\text{Or } \mu = \tan\alpha$$

$$\text{Or } \alpha = \tan^{-1}\mu$$

If α is greater than $\tan^{-1}\mu$, the work piece will not be passing through the rolls, without aid of external forces.

In hot rolling the primary purpose is to reduce the section. So the value α and hence μ will be maximum. The roll surface can be roughened to increase the value of μ. This process is called ‘ ragging.’ In the case of cold rolling, rolling loads are high and value of μ will be smaller.

During the plastic deformation of metal it can be assumed that the volume passing per unit time constant. So it can be stated that

$$V_0\, h_0\, b_0 = V_1\, h_1 \text{and } b_1$$

where V, h and b are velocity, height and breadth respectively.

But $b_0 \simeq b_1$

So $V_1 = V_0 \dfrac{h_0}{h_1}$

As $h_0 > h_1$, $V_1 > V_0$

If V_r is the velocity of the roll $V_1 > V_r > V_0$

$\dfrac{V_1 - V_r}{V_r} \times 100$ is called forward ship

and $\dfrac{V_r - V_0}{V_r} \times 100$ is called backward ship

In the deforming area between the rolls velocity of metal is changing from V_0 to V_1. At a particular section this equal to V_r, the velocity of roll. This section is called neutral or no slip section.

Other parameters are

Absolute draught $\Delta h = h_0 – h_1$ mm

Relative draught $\dfrac{\Delta h}{h_0} \times 100$

Absolute elongation $\Delta l = L_1 – L_0$ mm

Coefficient of elongation $= \dfrac{L_1}{L_0}$

Absolute spread $= b_1 - b_0$ mm

% of cold work $= \dfrac{A_0 - A_1}{A_0} \times 100$

where A = area of cross section.

It can be shown that $\cos\alpha = 1 - \dfrac{\frac{h_0 - h_1}{2}}{R}$

or $\cos\alpha = 1 - \dfrac{\Delta h}{D}$

where α = angle of contact

D = diameter of the roll

Maximum possible draught $\Delta h_{max} = \mu^2 R$

Where $R = \dfrac{D}{2}$

Rolling Mills

A set of rolls assembled in a housing is called a rolling stand. A rolling mill may contain one or more rolling stands. A rolling mill is a place where metal rolling is done on rolls and other auxiliary operations are performed.

Classification of Rolling Mills

1. Classification based on number of rolls in the stand
2. Based on products rolled
3. Based on arrangement of rolling stands

Based on no. of rolls in the roll stand it can be two high, three high, four high, multi roll universal rolling mill and planetary rolling mills.

Based on products, it can be blooming and slabbing mills, billet mills, rail and structural mills, rod mills, plate and sheet mills, seamless tube mills etc.

Based on arrangement of rolling stands, it can be looping mills cross country mills, continuous mills etc.

Roll Passes

Bars, rods and special purpose sections (I beam, channels, rails etc) are rolled between grooved rolls. The grooves cut on mating rolls will form passes through which the metal is passed to get the required cross section. Before getting the final stage the work passes through many passes. Roll passes are classified as

1. Break down or roll down or roughing passes
2. Leader passes
3. Finishing passes

Break down passes are intended to reduce the cross sectional area.

Leader passes gradually brings the cross section near to the final shape.

Finishing pass is for the final or the required cross section.

Rolling Defects

Defects found in rolling process are

1. Wavy edges
2. Spread
3. Crocodile neck
4. Surface defects
5. Edge cracks

Wavy edges result from roll bending. The strip becomes thinner along edges corresponding to the centre thickness. As free expansion is restrained, buckling occurs. If the width to thickness ratio of plates and sheets are smaller, width increases considerably in the roll gap. This is called spreading.

If the plate is weak at the centre, sheet bifurcates into two causing neck formation. This is called crocodile neck. Presence of impurities such as scale, rust, dirt in hot bloom, billets or slabs causes surface defects in the rolled products. Limited ductility of the metal or uneven deformation at edges will cause edge cracks.

Example 9: A stock of thickness 30 mm is to be rolled to 10mm in a single stage. Calculate the minimum diameter of the rolls, if the maximum angle of bite is 40°C. Find also the required coefficient of friction.

Solution: $\Delta h = h_1 – h_2$

30–10 = 20 mm

$\alpha = 40°$

$$\text{Cos }\alpha = 1 - \frac{\Delta h}{D}$$

$$\text{Cos } 40 = 1 - \frac{20}{D}$$

$$\frac{20}{D} = 1 - \cos 40$$

$$= 0.234$$

$$D = \frac{20}{0.234} = 85.49 \text{ mm}$$

Example 10: A sheet of 4 mm thickness is rolled with 300 mm diameter rolls to reduce the thickness without any change in its width. The friction coefficient at the work roll interface is 0.1. Calculate the minimum possible thickness of the sheet that can be produced in a single pass.

Solution: Given,

$$h_i = 4 \text{ mm}$$

$$R = \frac{300}{2} = 150\text{m}$$

$$\mu = 0.1$$

$$h_i – h_{\min} = \text{maximum draft} = \mu^2 R$$

$$= (0.1)^2 \times 150 \text{ mm} = 1.5$$

$$h_{\min} = h_i – 1.5$$

$$= 4 – 1.5 = 2.5 \text{ mm.}$$

Forging

Forging is the process of shaping a material under compressive forces in dies by plastic deformation normally after heating. The material is heated to a temperature at which its elastic properties entirely disappear and obeys the laws of plastic flow, following the directions of least resistance when deformed under pressure.

Forging enhances mechanical properties of metals and improves the grain flow due to which strength and toughness of the forged component is increased.

Forging temperature of some common metals are given below.

Material	Forging starting	Temperature finishing
Mild steel	1300	800
Wrought iron	1275	900
Medium carbon steel	1250	750
High carbon steel	1150	825
Copper, brass, bronze	950	600
Al and Mn Alloys	500	350

Basic Forging Operations

1. **Upsetting**: Upsetting is the process of increasing the cross sectional area of the stock at the expense of its length by application force in the direction of its length axis.
2. **Drawing down**: Drawing down is the operation of reducing thickness of the stock to increase its length. Force is applied in a direction perpendicular to the length axis. Thickness is reduced at the end of the stock. Also known as cogging.
3. **Fullering** is the operation reducing thickness of a stock between ends, at a central place. This is done with the help of tools called fullers.
4. **Edging or rolling operation** is to distribute the metal longitudinaly from a thick portion to a portion where material is deficient.
5. **Heading** is an upsetting operation where thickness is increased only at on end.
6. **Blocking** It is a forging operation in which the work piece is obtained its general shape, prior to its final shape.
7. **Piercing** is the operation done with the help of punch to obtain blind or through holes in the metal.
8. **Punching** is the operation of shearing out a slug in a forging to produce a hole.
9. **Swaging** is the operation of reducing the cross sectional area of a circular piece. by rotating it and giving fast impact blows. Bending, flattening, cutoff coining etc are other forging operations.

Forging Processes

Forging processes can be classified in to two groups.

1. Open die forging
2. Closed die forging

Open Die Forging

In open die forging the work piece is struck or pressed between two flat surfaces. This process is used when the components to be forged are only a few. Flat–die forging is another name of open die forging. Open die forging can be further classified as

1. Hand forging
2. Power forging
3. Hammer forging
4. Press forging

Hand forging or Smith forging is usually done in a blacksmith's hearth with the help of small hammers and anvil, to produce small number of light forgings.

Power forging is used for producing large components which cannot be forged by hand. Machines which work on forging by blow are called hammers; while those working by pressure are called presses. Hammers can be mechanical, pneumatic, steam or air hammers.

Closed Die Forging

In closed die forging cavities or impressions are cut in the die block, where metal is forced to take the final shape. The dies can be single impression type or multi impression type.

Impression-die forging is used to make complex shapes of products with greater accuracy. After forging the product should be trimmed to remove flashes.

Types of Forging

The four types of forging methods generally used are

1. Smith forging
2. Drop forging
3. Press forging
4. Machine forging

In drop forging closed type dies and drop hammers are used. Using drop hammers repeated blows are given to the material in the die cavity.

In press forging the dies are similar to that of drop forging. But instead of repeated blows by hammer a single continuous squeezing action is given to the material by means of hydraulic presses. Because of the continuous action the material gets uniformly distributed through the cavity.

Machine forging is also known as upset forging as the operation involved is upsetting. Upsetting machines are also called upsetters. Upsetters were originally developed for making bolt heads in a continuous fashion. Now gear blanks, shafts, axles and similar parts are also produced using machine forging. Upsetting machines are generally horizontal acting.

Defects in Forged Parts

Defects may occur in forged parts due to various factors such as forging process, improper heating, incorrect die design, uneven cooling after forging etc. Defects are similar to those in casting. These are mismatch, scale pits, cold shuts or Laps, unfilled section, cracks, fins and rags etc.

Example 11: In an open die forging a disc of 250 mm diameter and 60 mm height is compressed without any barelling effect. The final diameter of the disc is 450 mm. The true strain is

Solution: $\frac{\pi}{4} D_1^2 L_1 = \frac{\pi}{4} D_2^2 L_2$

$$(250)^2 \times 60 = (450)^2 \times L_2$$
$$\therefore L_2 = 18.5 \text{ mm}$$

Change in length

$$= L_1 – L_2$$
$$= 60–18.5 = 41.5 \text{ mm}$$

$$\text{Strain} = \frac{L_1 - L_2}{L_2} = \frac{41.5}{18.5} = 2.24$$

True strain $= L_n (1 + \varepsilon)$
$= L_n (1 + 2.24) = 1.176.$

Extrusion

Extrusion is the process by which a block of metal is reduced in cross section by forcing it to flow through a die orifice under high pressure. High pressure is applied by hydraulic press or mechanical press.

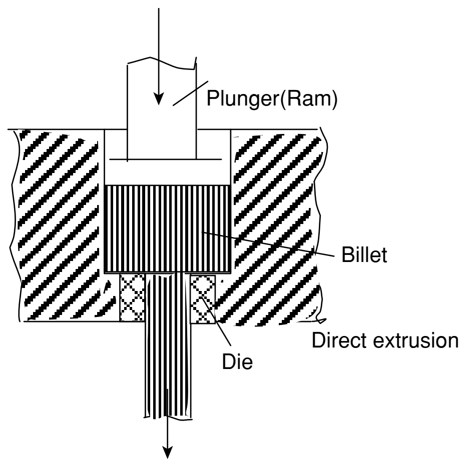
Extrusion process can be hot extrusion or cold extrusion depending up on the temperature at which the extrusion is done.

Based on the direction of flow of metal and application of force extrusion can be classified as

1. Direct or forward extrusion
2. Indirect or backward extrusion
3. Impact extrusion
4. Side extrusion
5. Tube extrusion

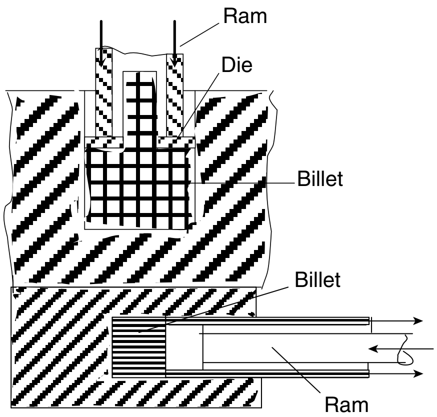
Direct or Forward Extrusion

In this case the billet is placed inside the container and force through the die with the help of pressure applied by a hydraulic driven ram.



Indirect or Backward Extrusion

It is similar to the direct extrusion except that the extruded part is forced through the ram stress. The deformed metal flows through the die opening in the direction opposite to that of ram motion.



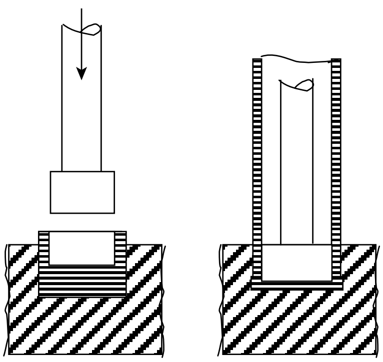
In indirect extrusion, the billet inside the cylinder has no relative motion with the cylinder. So there is no friction between cylinder and billet. Therefore power required for indirect extrusion is less compared to direct extrusion. But the long hollow ram is required and this limits the loads that can be applied.

Impact Extrusion

It is a cold extrusion process used for soft metals (like aluminium). It can be backward or forward. In backward impact extrusion, metal flows in reverse direction of the plunger. The flowing metal is guided only initially. Afterwards it moves by its on inertia. Impact extrusion is carried out at higher speeds. The punch strikes a single blow with considerable force causing the metal to squirt up against the punch.

Application of impact extrusion process are in the manufacture of collapsible tubes for tooth paste, ointments, shell cases, causes etc.

Combined forward and backward extrusion can be used to produce complex shapes. In the same stroke of the plunger backward and forward extrusion happens.



Backward impact extrusion

Side Extrusion

In side extrusion the movement of the material is in a direction perpendicular to that of the ram motion. In this case the force required is very high and therefore mostly used for non-ferrous metals or highly plastic materials.

Tube Extrusion

Extrusion is one of the methods for producing seamless tubes. It is a form of direct extrusion but a mandrel is used to form the inside of the tube. After placing the billet inside the cylinder, die containing the mandrel is pushed through it. When force is applied on the press stem it advances extruding the metal through the die and around the mandrel forming the seam less tube.

Hydrostatic Extrusion

Hydrostatic extrusion is a cold extrusion process, in which billet is surrounded by a working fluid, which is pressurised by ram. To provide the extrusion force. Friction between billet and container is elimimated in this case and this makes it possible to extrude very long billets.

Extrusion ratio is defined as the ratio of cross sectional area of the bullet to the cross sectional area of the product.

Extrusion Pressure

Estimation of extrusion pressure in many cases is done with the help of empirical relation ships. One such relation for calculating maximum pressure of backward extrusion of carbon steel is

$$P = T\left[3.45\ln\frac{A_0}{A_b} + 1.15\right]\text{kw/mm}^2$$

Where T = upper yield point, kN/mm^2

A_0 = cross sectional area of extruded component

A_b = cross sectional area of billet

The above expression is valid for extrusion ratios varying from 1.65 to 4.25 using billets with 0.6 length to diameter ratio.

Another expression for extrusion force is

$$\text{Extrusion force} = kA_1 \ln\left(\frac{A_1}{A_f}\right)$$

Where k = extrusion constant

A_1 = initial area of cross section

A_f = final area of cross section

Drawing of Wire, Rod and Tube

Drawing is a cold working process, used to reduce the diameter of wires, rods and tubes by drawing through a tapered hole in a die.

Wire is made by cold drawing of hot rolled wire rod through one or more dies. Metals blow 16 mm diameter are handled in coil form. The end of the rod or wire to be drawn is made pointed by swaging or hammering so that it freely enters the die orifice and sticks out behind the die. This end is gripped by jaws of a gripper and pulled. Under the tensile force material inside die undergoes deformation and its cross sectional area is reduced.

In rod drawing the product is to be straight. Maximum length of the rod that can be drawn depends upon the maximum travel of the carriage which the pulls the rod through the die. Before drawing the rod is to be cleaned to remove scales etc. This is done by acid pickling. After pickling the metal is washed well and conditioned by sulling, coppering, phosphating, liming etc to have to have proper lubrication.

In sulling or yellowing the blank is given a thin coating of iron hydroxide $Fe(OH)_3$, which combines with lime to serve as a filler for the lubricant. Phosphating consists of applying coating of phosphates of Mn, Fe or Zn. Lubricant sticks to the phosphates coatings. In coppering the metal is dipped in a weakly acidified solution of copper sulphate. In liming the metal is dipped in a boiling lime solution. Acid remains are neutralized by liming and forms as a carrier for lubricant. Before drawing the metal is dried above 100°C. A suitable lubricant is applied on the dry surface. Drawing lubricants used are mineral and vegetable oils, animal fats, graphite, certain emulsions etc. Considerable heat is generated during drawing. Water is circulated around the die to remove heat.

Tube drawing also is similar to the other drawing processes. The main difference is that a mandrel is used to form the internal hole.

Degree of Drawing

Degree of drawing is measured as the reduction of area (RA), which is the ratio of the difference in cross sectional area before and after drawing to the initial cross sectional area.

$$\text{i.e. } RA = \frac{D_i^2 - D_0^2}{D_i^2} = 1 - \left(\frac{D_0}{D_i}\right)^2$$

Defects in Wire Drawing

In wire drawing operations the following defects are observed

1. Bulge formation
2. Internal cracks
3. Surface defects
4. Seams

Bulge formation occurs infront of the die due to high die angle and low reduction.

Internal cracks or central burst occur due to increase in die angle or increase in the amount of impurities. It decreases with increasing drawing ratio and friction.

Surface defects occur due to inadequate lubrication and improper selection of drawing methods.

Longitudinal scratch or fold in materials is called seams.

Drawing Force

Force required for drawing under frictionless conditions is given by the following expression.

$$F = Y_{av} A_f \ln\left(\frac{A_o}{A_f}\right)$$

where A_0 = original area of cross section of the wire or rod

A_f = final area of cross section

Y_{av} = average true stress of the material in die gap

Maximum reduction in diameter

$$R = 1 - \left(\frac{D_f}{D_o}\right)^2 = 1 - \left(\frac{1}{1+B}\right)^{1/B}$$

Where D_f = final diameter

D_0 = original diameter

$$B = \frac{\mu}{\tan\alpha}$$

where μ = coefficient of friction

α = semi die angle

Hot Drawing and Cupping

This is another method of producing seamless tubes and cylinders. A thick metal blank of circular shape is hot pierced by a hydraulically operated plunger to form a cup shaped product first. This is drawn through a series of dies by pushing with plungers to reduce diameter and increase the length. This method is generally used for producing thick walled cylindrical products.

Exercise

Practice Problems I

1. A rectangular block of dimensions 100 × 50 × 20 mm is to be made from cast iron by casting process. For this a wooden pattern is to be made treating 20 mm as vertical. Assuming a machining allowance of 2 mm, shrinkage allowance of 2% and a draft allowance of 1°, find the bottom dimensions and height of the pattern in mm.
(A) 55.9 × 106.9, 25.3
(B) 55.9 × 106.9, 24.5
(C) 55.1 × 106.1, 25.3
(D) 55.1 × 106.1, 24.5

2. The top diameter of a down sprue is 20 mm. Its length is 180 mm. Liquid metal in the pouring up is maintained up to 60 mm height. For ensuring flow with out aspiration, the diameter of down sprue at lower end will be
(A) 16.26 mm (B) 14.15 mm
(C) 12.38 mm (D) 15.92 mm

3. A 350 mm thick slab is to be cold rolled using rolls of 650 mm diameter. If coefficient of friction is 0.08, the maximum possible reduction in mm thickness will be
(A) 1.18 (B) 2.28
(C) 1.32 (D) 2.08

4. Large size bolt heads are produced by
(A) Swaging (B) Roll forging
(C) Upset forging (D) Tumbling

5. Seamless tubes in mass production are manufactured by
(A) Rolling (B) Spinning
(C) Welding (D) Extrusion

6. Needle is produced by
(A) Forging (B) Machining
(C) Extrusion (D) Swaging

7. Frictional force between billet and die is more in the case of
(A) Direct extrusion
(B) Indirect extrusion
(C) Impact extrusion
(D) Hydrostatic extrusion

8. Out of the following the metal that cannot be forged is
(A) Wrought iron
(B) Mild steel
(C) Cast iron
(D) High carbon steel

9. Wire cannot be hot rolled commercially/economically smaller than about a diameter of
(A) 10 mm (B) 5 mm
(C) 15 mm (D) 2 mm

10. Out of the following which one is not connected with tube making
(A) Hot cupping
(B) Pilgering
(C) Three-roll piercing
(D) Rotary swaging

11. By a 10 ton press, it is meant that
(A) The weight of press is 10 ton
(B) It can handle work weighing up to 10 ton
(C) It can exert force up to 10 ton
(D) Turn over per day is 10 mton

12. Skelton patterns are generally used for
(A) Small castings
(B) Non-ferrous castings
(C) Large castings
(D) Hollow castings

***Direction for question 13 and 14*:** A metal strip is to be rolled from initial thickness of 4 mm to a final rolled thickness of 3 mm in a single pass rolling mill having rolls of 300 mm diameter. The strip is 450 mm wide. The average coefficient of friction in the roll gap is 0.08. Assume plane strain flow stress of 140 MPa for the metal and negligible spreading.

13. The average roll gap pressure will be
(A) 161. 56 M Pa (B) 157. 23 M Pa
(C) 169. 33 M Pa (D) 152. 88 M Pa

14. The roll separating force will be
(A) 836.7 kN (B) 832.5 kN
(C) 810.8 kN (D) 890.6 kN

15. A grey cast iron casting is to be made using a wooden pattern. The shrinkage allowance allowed on the wooden pattern should be
(A) 10 mm/m (B) 16 mm/m
(C) 26 mm/m (D) 20 mm/m

16. Chills are used in casting moulds to
(A) Reduce the freezing time
(B) Achieve directional solidification
(C) Reduce hot tear
(D) Improve surface finish

17. Upsetting is a process of
(A) Increasing cross section of a bar
(B) Reducing cross section of a bar
(C) Bending of a bar
(D) Joining two pieces of bars

18. Collapsible tubes are made by
(A) Cold extrusion forging
(B) Impact extrusion
(C) Forward hot extrusion
(D) Backward hot extrusion

19. A two–high rolling mills consists of
(A) Two rolling stands at different heights
(B) Two rollers of equal diameter rotating in same direction
(C) Two rollers of equal diameter rotating in opposite directions
(D) One set of rolls with two back up rolls

20. Mandrel is used in tube drawing
(A) To form the internal hole
(B) To give good surface finish
(C) To aid in pulling of the tube.
(D) To provide lubrication

Practice Problems 2

1. A pattern maker's shrinkage rule considers
(A) All pattern allowances
(B) Only shrinkage allowance
(C) All materials to be cast
(D) All materials of the pattern

2. Property of sand due to which a great amount of steam and other gases are released is called
(A) Collapsibity
(B) Permeability
(C) Cohesiveness
(D) Flowabilitry

3. When a hole or cavity to be cored is not in line with the parting suface, the core to be used is

(A) Horizontal core (B) Vertical core
(C) Drop core (D) Balanced core

4. Maximum possible draft in cold rolling of a sheet increases with

(A) Increase in coefficient of friction
(B) Decrease in coefficient of friction
(C) Decrease in radius of roll
(D) Not related to radius of role

5. In a 4 high rolling mill there are four rolls out of which

(A) One is working roll and 3 are backing up rolls
(B) Two are working rolls and two are backing up rolls
(C) Three are working rolls and one is backing up roll
(D) All four rolls are working rolls

6. Metal extrusion process is generally used for producing

(A) Uniform solid sections only.
(B) Uniform hollow section only
(C) Uniform solid and hollow sections
(D) Varying solid and hollow sections

7. A solid cylinder of diameter 100 mm and height 50 mm is forged between two frictionless flat dies to a height of 25 mm. The percentage change in diameter is

(A) 35.6 (B) 41.4
(C) 43.7 (D) 38.8

8. Cold working of metals is carried out

(A) Below lower critical temperature
(B) Below upper critical temperature
(C) Below recrystallization temperature
(D) Below 15°C

9. Fullers are used

(A) For finishing flat surfaces
(B) For necking down a piece of work
(C) For punching a hole
(D) Bending of a bar

10. Thick walled cylinder can be produced by

(A) Hot drawing
(B) Hot extrusion
(C) Cold drawing
(D) Continuous drawing

11. In a foundry, two castings of same weight and material due to be produced. One is cube shaped and the other is cylindrical shaped with a length to diameter ratio of 0.5. Cooling time ratio of cylindrical and cubical casting is

(A) 0.95 (B) 1.05
(C) 1.15 (D) 1.22

12. A 200 mm long down sprue has an area of cross section 600 mm^2 where pouring basin meets the sprue. A constant head of molten metal is maintained by the pouring basin. The molten metal flow rate is 6×10^5 mm^3/s. Considering the end of the down sprue to be open to atmosphere and an acceleration due to gravity of 10^4 mm/s^2, the area of down sprue in mm^2 at its end (avoiding aspiration effect) should be

(A) 310.3 mm^2 (B) 281.2 mm^2
(C) 290.7 mm^2 (D) 268.3 mm^2

13. A cubical casting of side 45 mm undergoes 3.5%, 4.5% and 5% volume shrinkage, during liquid state, phase transformation and solid state respectively, while cooling. The volume of metal compensated from the riser is

(A) 9.5% (B) 8.5%
(C) 8% (D) 13%

14. In a rolling process a sheet of 30 mm thickness is rolled to 25 mm thickness. Roll is of diameter 700 mm. and it rotates at 100 rpm. The roll strip contact length will be

(A) 48.5 mm (B) 38.7 mm
(C) 41.9 mm (D) 36.3 mm

15. A brass billet is to be extruded from its initial diameter of 100 mm to final diameter 60 mm. The working temperature is 700°C and the extrusion constant is 250 MPa. The force required for extrusion is

(A) 12.97 kN (B) 11.46kN
(C) 16.92 kN (D) 10.13 kN

16 In a wire drawing operation, diameter of a steel wire is reduced from 12 mm to 10 mm. The mean flow stress of the material is 400 Mpa. The ideal force, ignoring friction and redundant work is

(A) 12.97 kN (B) 11.46 kN
(C) 16.92 kN (D) 10.13 kN

Direction for questions 17, 18 A cylindrical billet of 100 mm diameter is forged from 60 mm height at 1000°C. The material has a constant flow stress of 80 MPa

17. Find the work of deformation in Nm.

(A) 31400 (B) 30210
(B) 25120 (D) 28105

18. If a 10 kN drop hammer is used to complete the reduction in one blow, what will be the height of the fall?

(A) 2.51 m (B) 2.82 m
(C) 3.14 m (D) 2.73 m

19. A mould has down sprue whose length is 25 cm and cross sectional area at the base 1.5 cm^2. The down sprue feeds a horizontal runner leading to mould cavity of volume 1500 cm^3. The time required to fill the mould cavity will be

(A) 3.61 sec (B) 5.05 sec
(C) 4.51 sec (D) 5.81 sec

20. In a rolling operation a 25 mm thick plate of width 100 mm is reduced to 20 mm thickness. Roller radius is 300 mm and rotational speed is 10 rpm. The average flow stress for the material is 300 MPa. The power required for rolling operation in kw is approximately

(A) 365 (B) 472
(C) 343 (D) 387

21. A cubic casting of 60 mm side undergoes volumetric solidification shrinkage and volumetric solid contraction 3% and 5% respectively no riser is used. The side of the cube after the solidification and contraction will be (assume uniform cooling in all direction
(A) 58.98 mm (B) 59.65 mm
(C) 59.32 mm (D) 58.39 mm

22. During hot working of metals
(A) Porosity of metal is largely eliminated
(B) Grain structure of the metal is refined
(C) Mechanical properties are improved due to refinement of grains
(D) All of the above

23. Structurals of sections such as rails, angles, I–beam etc are made by
(A) Hot rolling (B) Hot drawing
(C) Hot piercing (D) Hot extrusion

24. Forging temperature of medium carbon steel is approximately
(A) 950°C to 1300°C
(B) 750°C to 1250°C
(C) 800°C to 1100°C
(D) 900°C to 1250°C

25. Pressing a hot metal inside a chamber and forcing it out by high pressure through an orifice to form a product is called
(A) Hot drawing
(B) Pressing
(C) Extrusion
(D) Hot piercing

26. Metal patterns are generally used for
(A) Small castings
(B) Medium castings
(C) Complicated castings
(D) Mass productions of castings

27. As per the general colour code, surface to be left un machined is marked on a pattern by
(A) Red colour (B) Black colour
(C) Yellow colour (D) Blue colour

28. Mass of a grey cast iron casting is 20 Kg and its average section thickness is 15 mm. Fluidity of iron is 28 inches. Optimum pouring time for the casting is
(A) 7.63 sec (B) 8.58 sec
(C) 9.32 sec (D) 6.75 sec

29. In the case of a pressurized gating system
(A) A sprue base area is the smallest
(B) Runner cross section area is the smallest.
(C) Ingate area is the smallest.
(D) Ingate area is the largest.

30. The term 'shape factor' is used in
(A) Riser design
(B) Pouring time calculation
(C) Pattern design
(D) Core design

Previous Years' Questions

1. Misrun is a casting defect which occurs due to **[2004]**
(A) Very high pouring temperature of the metal
(B) Insufficient fluidity of the molten metal
(C) Absorption of gases by the liquid metal
(D) Improper alignment of the mould flasks

2. Gray cast iron blocks 200 × 100 ×10 mm are to be cast in sand moulds. Shrinkage allowance for pattern making is 1%. The ratio of the volume of pattern to that of the casting will be **[2004]**
(A) 0.97 (B) 0.99
(C) 1.01 (D) 1.03

3. In a rolling process, sheet of 25 mm thickness is rolled to 20 mm thickness. Roll is of diameter 600 mm and it rotates at 100 rpm. The roll strip contact length will be **[2004]**
(A) 5 mm (B) 39 mm
(C) 78 mm (D) 120 mm

4. Match the following: **[2004]**

Product	Process
P. Molded luggage	1. Injection molding
Q. Packaging	2. Hot rolling containers for liquid
R. Long structural shapes	3. Impact extrusion
S. Collapsible tubes	4. Transfer molding
	5. Blow molding
	6. Coining

(A) P-1 Q-4 R-6 S-3
(B) P-4 Q-5 R-2 S-3
(C) P-1 Q-5 R-3 S-2
(D) P-5 Q-1 R-2 S-2

5. Match the items of List I (Equipment) with the items of List II (Process) and select the correct answer using the given codes. **[2005]**

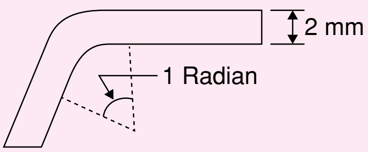
List (Equipment)	List (Process)
P – Hot chamber machine	1. Cleaning
Q – Muller	2. Core making
R – Dielectric baker	3. Die casting
S – Sand blaster	4. Annealing
	5. Sand mixing

(A) P – 2 Q – 1 R – 4 S – 5
(B) P – 4 Q – 2 R – 3 S – 5
(C) P – 4 Q – 5 R – 1 S – 2
(D) P – 3 Q – 5 R – 2 S – 1

6. A mould has a downsprue whose length is 20 cm and the cross sectional area at the base of the downsprue is 1 cm^2. The down sprue feeds horizontal runner leading into the mould cavity of volume 1000 cm^3. The time required to fill the mould cavity will be **[2005]**

(A) 4.05 s (B) 5.05 s
(C) 6.05 s (D) 7.25 s

7. A 2 mm thick metal sheet is to be bent at an angle of one radian with a bend radius of 100 mm. If the stretch factor is 0.5, the bend allowance is **[2005]**



(A) 99 mm (B) 100 mm
(C) 101 mm (D) 102 mm

8. An expendable pattern is used in **[2006]**

(A) Slush casting
(B) Squeeze casting
(C) Centrifugal casting
(D) Investment casting

9. In a sand casting operation, the total liquid head is maintained constant such that it is equal to the mould height. The time taken to fill the mould with a top gate is t_A. If the same mould is filled with a bottom gate, then the time taken is t_B. Ignore the time required to fill the runner and frictional effects. Assume atmospheric pressure at the top molten metal surfaces. The relation between t_A and t_B is: **[2006]**

(A) $t_B = \sqrt{2}\ t_A$ (B) $t_B = 2t_A$
(C) $t_B = \dfrac{t_A}{\sqrt{2}}$ (D) $t_B = 2\sqrt{2}\ t_A$

10. A 4 mm thick sheet is rolled with 300 mm diameter rolls to reduce thickness without any change in its width. The friction coefficient at the work–roll interface is 0.1. The minimum possible thickness of the sheet that can be produced in a single pass is: **[2006]**

(A) 1.0 mm (B) 1.5 mm
(C) 2.5 mm (D) 3.7 mm

11. In a wire drawing operation, diameter of a steel wire is reduced from 10 mm to 8 mm. The mean flow stress of the material is 400 MPa. The ideal force required for drawing (ignoring friction and redundant work) is: **[2006]**

(A) 4.48 kN (B) 8.97 kN
(C) 20.11 kN (D) 31.41 kN

12. Which of the following engineering materials is the most suitable candidate for hot chamber die casting? **[2007]**

(A) Low carbon steel (B) Titanium
(C) Copper (D) Tin

13. Volume of a cube of side 'I' and volume of a sphere of radius 'r' are equal. Both the cube and the sphere are solid and of same material. They are being cast. The ratio of the solidification time of the cube to the same of the sphere is **[2007]**

(A) $\left(\dfrac{4\pi}{6}\right)^3\left(\dfrac{r}{l}\right)$ (B) $\left(\dfrac{4\pi}{6}\right)\left(\dfrac{r}{l}\right)^2$
(C) $\left(\dfrac{4\pi}{6}\right)^2\left(\dfrac{r}{l}\right)^3$ (D) $\left(\dfrac{4\pi}{6}\right)^2\left(\dfrac{r}{l}\right)^4$

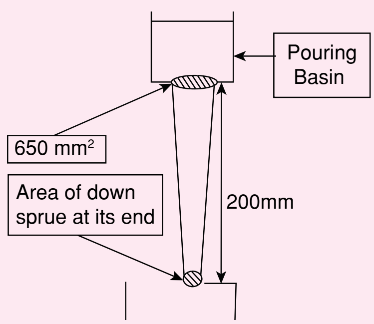
14. In open-die forging, a disc of diameter 200 mm and height 60 mm is compressed without any barreling effect. The final diameter of the disc is 400 mm. The true strain is **[2007]**

(A) 1.986 (B) 1.686
(C) 1.386 (D) 0.602

15. The thickness of a metallic sheet is reduced from an initial value of 16 mm to a final value of 10 mm in one single pass rolling with a pair of cylindrical rollers each of diameter of 400 mm. The bite angle in degree will be **[2007]**

(A) 5.936 (B) 7.936
(C) 8.936 (D) 9.936

16. A 200 mm long down sprue has an area of cross-section of 650 mm^2 where the pouring basin meets the down sprue (i.e., at the beginning of the down sprue). A constant head of molten metal is maintained by the pouring basin. The molten metal flow rate is 6.5 × 10^5 mm^3/s. Considering the end of down sprue to be open to atmosphere and an acceleration due to gravity of 10^4 mm/s^2, the area of the down sprue in mm^2 at its end (avoiding aspiration effect) should be **[2007]**



(A) 650.0 (B) 350.0
(C) 290.7 (D) 190.0

17. While cooling, a cubical casting of side 40 mm undergoes 3%, 4% and 5% volume shrinkage during the liquid state, phase transition and solid state, respectively. The volume of metal compensated from the riser is **[2008]**
(A) 2% (B) 7%
(C) 8% (D) 9%

18. In a single pass rolling operation, a 20 mm thick plate with plate width of 100 mm, is reduced to 18 mm. The roller radius is 250 mm and rotational speed is 10 rpm. The average flow stress for the plate material is 300 MPa. The power required for the rolling operation in kW is closest to **[2008]**
(A) 15.2 (B) 18.2
(C) 30.4 (D) 45.6

19. Two streams of liquid metal, which are not hot enough to fuse properly, result into a casting defect known as **[2008]**
(A) Cold shut (B) Swell
(C) Sand wash (D) Scab

20. Match the items in Column I and Column II. **[2009]**

Column I	Column II
(P) Metallic chills	(1) Support for the core
(Q) Metallic chaplets	(2) Reservoir of the molten metal
(R) Riser	(3) Control cooling of critical sections
(S) Exothermic padding	(4) Progressive solidification

(A) P-1, Q-3, R-2, S-4
(B) P-1, Q-4, R-2, S-3
(C) P-3, Q-4, R-2, S-1
(D) P-4, Q-1, R-2, S-3

21. In a gating system, the ratio 1: 2: 4 represents **[2010]**
(A) Sprue base area: runner area: ingate area
(B) Pouring basin area: ingate area: runner area
(C) Sprue base area: ingate area: casting area
(D) Runner area: ingate area: casting area

22. The maximum possible draft in cold rolling of sheet increases with the **[2011]**
(A) Increase in coefficient of friction
(B) Decrease in coefficient of friction
(C) Decrease in roll radius
(D) Increase in roll velocity

23. Green sand mould indicates that **[2011]**
(A) Polymeric mould has been cured
(B) Mould has been totally dried
(C) Mould is green in colour
(D) Mould contains moisture

24. A cubic casting of 50 mm side undergoes volumetric solidification shrinkage and volumetric solid contraction of 4% and 6% respectively. No riser is used. Assume uniform cooling in all directions. The side of the cube after solidification and contraction is. **[2011]**
(A) 48.32 mm (B) 49.90 mm
(C) 49.94 mm (D) 49.96 mm

25. A solid cylinder of diameter 100 mm and height 50 mm is forged between two frictionless flat dies to a height of 25 mm. The percentage change in diameter is **[2012]**
(A) 0 (B) 2.07
(C) 20.7 (D) 41.4

26. In a single pass rolling process using 410 mm diameter steel rollers, a strip of width 140 mm and thickness 8 mm undergoes 10% reduction of thickness. The angle of bite in radians is **[2012]**
(A) 0.006 (B) 0.031
(C) 0.062 (D) 0.600

27. A cube shaped casting solidifies in 5 min. The solidification time in min for a cube of the same material, which is 8 times heavier than the original casting, will be **[2013]**
(A) 10 (B) 20
(C) 24 (D) 40

28. In a rolling process, the state of stress of the material undergoing deformation is **[2013]**
(A) Pure compression
(B) Pure shear
(C) Compression and shear
(D) Tension and shear

29. An aluminium alloy (density 2600 kg/m^3) casting is to be produced. A cylindrical hole of 100 mm diameter and 100 mm length is made in the casting using sand core (density 1600 Kg/m^3). The net buoyancy force (in newton) acting on the core is _____ **[2014]**

30. With respect to metal working, match Group A with Group B: **[2014]**

Group A	Group B
(P) Defect in extrusion	(I) Alligatoring
(Q) Defect in rolling	(II) Scab
(R) Product of skew rolling	(III) Fish tail
(S) Product of rolling through cluster mill	(IV) Seamless tube
	(V) Thin sheet with tight tolerance
	(VI) Semi-finished balls of ball bearing

(A) P - II, Q - III, R - VI, S – V
(B) P - III, Q - I, R - VI, S - V
(C) P - III, Q - I, R - IV, S - VI
(D) P - I, Q - II, R - V, S - VI

31. A mild steel plate has to be rolled in one pass such that the final plate thickness is $2/3^{rd}$ of the initial thickness, with the entrance speed of 10 m/min and roll diameter of 500 mm. If the plate widens by 2% during rolling, the exit velocity (in m/min) is ____ **[2014]**

32. Match the casting defects (Group A) with the probable causes (Group B): **[2014]**

Group A	Group B
P: Hot tears	1. Improper fusion of two streams of liquid metal
Q: Shinkage	2. Low permeability of the sand mould
R: Blow holes	3. Volumetric contraction both in liquid and solid stage
S: Could Shut	4. Differential cooling rate

(A) P-1, Q-3, R-2, S-4 (B) P-4, Q-3, R-2, S-1
(C) P-3, Q-4, R-2, S-1 (D) P-1, Q-2, R-4, S-3

33. The hot tearing in a metal casting is due to **[2014]**
(A) High fluidity
(B) High melt temperature
(C) Wide range of solidification temperature
(D) Low coefficient of thermal expansion

34. In a rolling process, the maximum possible draft, defined as the difference between the initial and the final thickness of the metal sheet, mainly depends on which pair of the following parameters? **[2014]**

(P) Strain
(Q) Strength of the work material
(R) Roll diameter
(S) Roll velocity
(T) Coefficient of friction between roll and work

(A) Q, S (B) R, T
(C) S, T (D) P, R

35. A cylindrical riser of 6 cm diameter and 6 cm height has to be designed for a sand casting mould for producing a steel rectangular plate casting of 7 cm × 10 cm × 2 cm dimensions having the total solidification time of 1.36 minute. The total solidification time (in minute) of the riser is _____ **[2014]**

36. Match the following products with preferred manufacturing processes: **[2015]**

	Product		Process
P	Rails	1	Blow molding
Q	Engine crankshaft	2	Extrusion
R	Aluminium channels	3	Forging
S	PET water bottles	4	Rolling

(A) P–4, Q–3, R–1, S–2
(B) P–4, Q–3, R–2, S–1
(C) P–2, Q–4, R–3, S–1
(D) P–3, Q–4, R–2, S–1

37. The solidification time of a casting is proportional to $\left(\frac{V}{A}\right)^2$, where V is the volume of the casting and A is the total casting surface area losing heat. Two cubes of same material and size are cast using sand casting process. The top face of one of the cubes is completely insulated. The ratio of the solidification time for the cube with top face insulated to that of the other cube is: **[2015]**

(A) $\frac{25}{36}$ (B) $\frac{36}{25}$
(C) 1 (D) $\frac{6}{5}$

38. In a slab rolling operation, the maximum thickness reduction (Δh_{max}) is given by $\Delta h_{max} = \mu^2 R$, where R is the radius of the roll and μ is the coefficient of friction between the roll and the sheet. If $\mu = 0.1$, the maximum angle subtended by the deformation zone at the centre of the roll (bite angle in degrees) is ______. **[2015]**

39. A cube and a sphere made of cast iron (each of volume 1000 cm^3) were cast under identical conditions. The time taken for solidifying the cube was 4s. The solidification time (in s) for the sphere is ______. **[2015]**

40. In a two-stage wire drawing operation, the fractional reduction (ratio of change in cross-sectional area to initial cross-sectional area) in the first stage is 0.4. The fractional reduction in the second stage is 0.3. The overall fractional reduction is: **[2015]**
(A) 0.24 (B) 0.58 (C) 0.60 (D) 1.00

41. The strain hardening exponent n of stainless steel SS 304 with distinct yield and UTS values undergoing plastic deformation is **[2015]**
(A) $n < 0$ (B) $n = 0$
(C) $0 < n < 1$ (D) $n = 1$

42. In full mould (cavity–less) casting process, the pattern is made of: **[2015]**
(A) Expanded polystyrene (B) Wax
(C) Epoxy (D) Plaster of Paris

43. In a rolling operation using rolls of diameter 500 mm, if a 25 mm thick plate cannot be reduced to less than 20 mm in one pass, the coefficient of friction between the roll and the plate is _____. **[2015]**

44. Ratio of solidification time of a cylindrical casting (height = radius) to that of a cubic casting of side two times the height of cylindrical casting is ____.

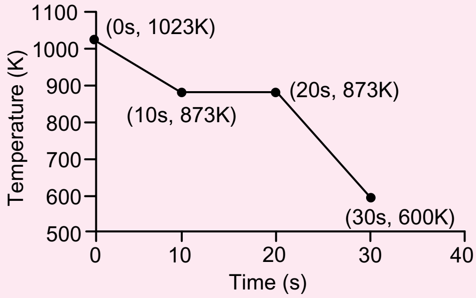
45. The dimensions of a cylindrical side riser (height = diameter) for a 25 cm × 15 cm × 5 cm steel casting are to be determined. For the tabulated shape factor values given below as follows, the diameter of the riser (in cm) is ______. **[2015]**

Shape factor	2	4	6	8	10	12
Riser Volume/ Casting volume	1.0	0.70	0.55	0.50	0.40	0.35

(A) 150 (B) 200
(C) 100 (D) 125

46. The part of a gating system which regulates the rate of pouring of molten metal is: **[2016]**
(A) pouring basin (B) runner
(C) choke (D) in gate

47. Heat is removed from a molten metal of mass 2 kg at a constant rate of 10 kW till it is completely solidified. The cooling curve is shown in the figure.



Assuming uniform temperature throughout the volume of the metal during solidification, the latent heat of fusion of the metal (in kJ/kg) is ________. **[2016]**

48. A cylindrical job with diameter of 200 mm and height of 100 mm is to be cast using modulus method of riser design. Assume that the bottom surface of cylindrical riser does not contribute as cooling surface. If the diameter of the riser is equal to its height, then the height of the riser (in mm) is **[2016]**
(A) 150 (B) 200
(C) 100 (D) 125

49. A 300 mm thick slab is being cold rolled using roll of 600 mm diameter. If the coefficient of friction is 0.08, the maximum possible reduction (in mm) is ________. **[2016]**

50. Gray cast iron blocks of size 100 mm × 50 mm × 10 mm with a central spherical cavity of diameter 4 mm are sand cast. The shrinkage allowance for the pattern is 3%. The ratio of the volume of the patter to volume of the casting is _______. **[2016]**

51. Equal amounts of a liquid metal at the same temperature are poured into three moulds made of steel, copper and aluminum. The shape of the cavity is a cylinder with 15 mm diameter. The sizes of the moulds are such that the outside temperature of the moulds do not increase appreciably beyond the atmospheric temperature during solidification. The sequence of solidification in the mould from the fastest to slowest is

(Thermal conductivities of steel, copper and aluminum are 60.5, 401 and 237 W/m-K, respectively Specific heats of steel, copper and aluminum are 434, 385 and 903 J/kg-K, respectively. Densities of steel, copper and aluminum are 7854, 8933 and 2700 kg/m^3, respectively.) **[2016]**
(A) Copper–Steel–Aluminum
(B) Aluminum–Steel–Copper
(C) Copper–Aluminum–Steel
(D) Steel–Copper–Aluminum

Answer Keys

Exercises

Practice Problems 1

1. D	**2.** B	**3.** D	**4.** C	**5.** D	**6.** D	**7.** A	**8.** C	**9.** B	**10.** D
11. C	**12.** C	**13.** A	**14.** D	**15.** C	**16.** B	**17.** A	**18.** B	**19.** C	**20.** A

Practice Problems 2

1. B	**2.** B	**3.** C	**4.** A	**5.** B	**6.** C	**7.** B	**8.** C	**9.** B	**10.** A
11. B	**12.** D	**13.** C	**14.** C	**15.** B	**16.** B	**17.** A	**18.** C	**19.** C	**20.** A
21. D	**22.** D	**23.** A	**24.** B	**25.** C	**26.** D	**27.** B	**28.** A	**29.** C	**30.** A

Previous Year's Questions

1. B	**2.** A	**3.** B	**4.** B	**5.** D	**6.** B	**7.** C	**8.** D	**9.** B	**10.** C
11. B	**12.** D	**13.** D	**14.** C	**15.** D	**16.** C	**17.** B	**18.** None	**19.** A	**20.** D
21. A	**22.** A	**23.** D	**24.** A	**25.** D	**26.** C	**27.** B	**28.** C	**29.** 7 to 8	**30.** B

31. 14.6 to 14.8 **32.** B **33.** C **34.** B **35.** 2.5 to 4.5 **36.** B **37.** B
38. 5.6 to 5.8 **39.** 6.0 to 6.3 **40.** B **41.** C **42.** A **43.** 0.10 to 0.15
44. 0.5 to 0.6 **45.** 10.5 to 10.7 **46.** C **47.** 50 **48.** A **49.** 1.9 – 1.94 mm
50. 1.08 to 1.10 **51.** C