A suitable and workable material possessing high refractoriness in nature can be used for mold making. Thus, the mold making material can be metallic or non-metallic.

For metallic category, the common materials are cast iron, mild steel and alloy steels.

In the non-metallic group molding sands, plaster of paris, graphite, silicon carbide and ceramics are included.

**But, out of all, the molding sand is the most common utilized non-metallic molding material because of its certain inherent properties namely refractoriness, chemical and thermal stability at higher temperature, high permeability and workability along with good strength. Moreover, it is also highly cheap and easily available.**

**REFRACTORY SANDS**

Different types of refractory sands used for molding are:

(i) Silica sand
(ii) Magnesite
(iii) Zircon
(iv) Silimanite
(v) Olivine
(vi) Graphite/carbon

Sand used in foundries must be capable of with-standing very high temperatures and shouldn't collapse under the prevailing load.

Silica sand is mostly used in foundries because of the following.

1. It is a very good refractory material and doesn't fuse or soften even at very high temperatures, i.e. 1650°C, when in contact with molten metal.
2. They can be easily molded into intricate shapes.
3. They have sufficient porosity or permeability and allow easy escape of gases produced by molten metal and other bonding constituent.
4. They can be used repeatedly for making molds after addition of some bonding materials.
5. They are cheap and easily available.
6. They are chemically immune to molten metals.
7. They don't decay. Its main drawback is its high coefficient of thermal expansion (above 560T).

**Sources of Molding Sand Molding**

Sand used in foundries is available in (i) River beds. (ii) Sea. (iii) Deserts. (iv) Lakes.

**Types of Molding Sand**

Depending upon the purity and other constituents present, sand is classified into

(i) Natural sand. (ii) Synthetic sand, (iii) loam sand.

(i) Natural sand:

- Natural sand is directly used for molding and contains 5-20% of clay as binding material.
- It needs 5-8% water for mixing before making the mold. Many natural sands possess a wide working range of moisture and are capable of retaining moisture content for a long time.
Its main drawback is that it is less refractory as compared to synthetic sand.
Many natural sands have weak molding properties. These sands are reconditioned by mixing small amounts of binding materials like bentonite to improve their properties and are known as semi-synthetic sand.

(II) **Synthetic Sands:**
- Synthetic sand consists of silica sand with or without clay, binder or moisture.
- It is a formulated sand i.e. sand formed by adding different ingredients. Sand formulations are done to get certain desired properties not possessed by natural sand.
- These sands have better casting properties like permeability and refractoriness and are suitable for casting ferrous and non-ferrous materials.
- These properties can be controlled by mixing different ingredients.
- Synthetic sands are used for making heavy castings.

(III) **Loam Sand:**
- Loam sand contains many ingredients, like fine sand particles, finely ground refractories, clay, graphite and fiber reinforcements.
- In many cases, the clay content may be of the order of 50% or more.
- When mixed with water, the materials mix to a consistency resembling mortar and become hard after drying.
- Big molds for casting are made of brick framework lined with loam sand and dried.
- Sweeps etc are used for making big castings like big bells by using loam sand.

Refactory sand grains: Sand grain size and shape has a marked effect on the properties of molding sand. The specific surface gives a rough idea of the amount of binder needed for molding sand.

**GRAIN SIZE**
- Many properties of molding sand like permeability, adhesiveness, surface fineness, strength, etc, depend upon the grain size and distribution of sand particles.
- The finer the grain size, the finer is the sand as a whole.
- Finely grained sand gives a good surface finish but possesses low permeability.
- Coarse grained sand gives lesser surface finish but imparts good flow ability, good refractoriness and good permeability.
- The green strength of fine sand is higher than coarse sand for the same quantity of ingredients added to it.

**Foundry Sand Grain Shape:** The grain shape of foundry sand has a marked influence on its properties like flow ability, cohesiveness and strength. Generally, four types of grains are present in foundry sand given as follows.

(I) **Rounded Sand Grains:** Rounded sand grains give poor bonding strength as compared to angular sand grains. Too many smooth and rounded sand grains result in sand wash, sand crack and sand scales. These sands also possess greater flow ability.
(II) **Angular Grains:** These grains are produced by breaking of rocks without movement of particles. These are also formed by frost and glacial action. Angular grains have greater bonding strength, lesser flow ability and low permeability than round grain sands. Angular grains have sharp corners and greater contact surface.

(III) **Sub-angular Grains:** As compared to rounded grains, sub-angular grains possess better strength and lower permeability. In comparison to angular grains, they possess lower strength and better permeability.

(IV) **Compound Grains:** Compound grained sand is formed when two or more sand grains stick together and don't separate either on sawing or washing. These sands are not preferred and used in foundries.

**BINDERS USED IN MOLDING SANDS**

- Binders are added to give cohesion to molding sands.
- Binders provide strength to the molding sand and enable it to retain its shape as mold cavity.
- Binders should be added in optimum quantity as they reduce refractoriness and permeability.
- An optimal quantity of binders is needed, as further increases have no effect on properties of foundry sand.

The following binders are generally added to foundry sand:

1. **Fireclay**
2. **Illite**
3. **Bentonite**
   - Sodium montmorillonite
   - Calcium montmorillonite
4. **Limonite**
5. **Kaolinite**

(i) **Fireclay:** It is usually found near coal mines. For use in the foundry, the hard black lumps of fireclay are taken out, weathered and pulverized. Since the size of fireclay particles is nearly 400 times greater than the size of bentonite particles, they give poor bonding strength to foundry sand.

(ii) **Illite:** Illite is found in natural molding sands that are formed by the decomposition of micaceous materials due to weathering. Illite possesses moderate shrinkage and poor bonding strength than bentonite.

(iii) **Bentonite:** It is the most suitable material used in molding sands. Limonite and Kaolinite are not commonly used as binders as they have comparatively low binding properties.
CONSTITUENTS OF MOLDING SAND
The main constituents of molding sand involve silica sand, binder, moisture content and additives.

Silica sand
- Silica sand in form of granular quarts is the main constituent of molding sand having enough refractoriness which can impart strength, stability and permeability to molding and core sand.
- Along with silica small amounts of iron oxide, alumina, lime stone, magnesia, soda and potash are present as impurities.
- The chemical composition of silica sand gives an idea of the impurities like lime, magnesia, alkalis etc. present.
- The presence of excessive amounts of iron oxide, alkali oxides and lime can lower the fusion point to a considerable extent which is undesirable.
- The silica sand can be specified according to the size (small, medium and large silica sand grain) and the shape (angular, sub-angular and rounded).

Moisture
- The amount of moisture content in the molding sand varies generally between 2 to 8 percent.
- This amount is added to the mixture of clay and silica sand for developing bonds.
- This is the amount of water required to fill the pores between the particles of clay without separating them.
- This amount of water is held rigidly by the clay and is mainly responsible for developing the strength in the sand.
- The effect of clay and water decreases permeability with increasing clay and moisture content.
- The green compressive strength first increases with the increase in clay content, but after a certain value, it starts decreasing.

Additives
Additives are the materials generally added to the molding and core sand mixture to develop some special property in the sand. Some common used additives for enhancing the properties of molding and core sands are

(i) Coal dust
Coal dust is added mainly for producing a reducing atmosphere during casting. This reducing atmosphere results in any oxygen in the poles becoming chemically bound so that it cannot oxidize the metal.

(ii) Dextrin
Dextrin belongs to starch family of carbohydrates. It increases dry strength of the molds.

(iii) Pitch
It is distilled form of soft coal. It can be added from 0.02 % to 2% in mold and core sand. It enhances hot strengths, surface finish on mold surfaces.

(iv) Wood flour
This is a fibrous material mixed with a granular material like sand; its relatively long thin fibers prevent the sand grains from making contact with one another. It can be added from 0.05% to 2% in mold and core sand. It increases collapsibility of both of mold and core.

**KINDS OF MOULDING SAND**
Molding sands can also be classified according to their use into number of varieties which are described below.

1) **Green sand**
Green sand is also known as tempered or natural sand which is a just prepared mixture of silica sand with 18 to 30 percent clay, having moisture content from 6 to 8%. The clay and water furnish the bond for green sand. It is fine, soft, light, and porous. Green sand is damp, when squeezed in the hand and it retains the shape and the impression to give to it under pressure. Molds prepared by this sand are not requiring backing and hence are known as green sand molds. This sand is easily available and it possesses low cost. It is commonly employed for production of ferrous and non-ferrous castings.

2) **Dry sand**
Green sand that has been dried or baked in suitable oven after the making mold and cores, is called dry sand. It possesses more strength, rigidity and thermal stability. It is mainly suitable for larger castings. Mold prepared in this sand are known as dry sand molds.

3) **Loam sand**
Loam is mixture of sand and clay with water to a thin plastic paste. Loam sand possesses high clay as much as 30-50% and 18% water. Patterns are not used for loam molding and shape is given to mold by sweeps. This is particularly employed for loam molding used for large grey iron castings.

4) **Facing sand**
Facing sand is just prepared and forms the face of the mold, gives surface finish to casting. It is directly next to the surface of the pattern and it comes into contact molten metal when the mold is poured. Initial coating around the pattern and hence for mold surface is given by this sand. This sand is subjected severest conditions and must possess, therefore, high strength refractoriness. It is made of silica sand and clay, without the use of used sand.

5) **Backing sand**
Backing sand or floor sand is used to back up the facing sand and is used to fill the whole volume of the molding flask. Used molding sand is mainly employed for this purpose. The backing sand is sometimes called black sand because that old, repeatedly used molding sand is black in color due to addition of coal dust and burning on coming in contact with the molten metal.

6) **Parting sand**
Parting sand without binder and moisture is used to keep the green sand not to stick to the pattern and also to allow the sand on the parting surface the cope and drag to separate without clinging.

7) **Core sand**
Core sand is used for making cores and it is sometimes also known as oil sand. This is highly rich silica sand mixed with oil binders such as core oil which composed of linseed oil, resin, light mineral oil and other bind materials.
PROPERTIES OF MOULDING SAND
The basic properties required in molding sand and core sand are described as under.

1) Refractoriness
Refractoriness is defined as the ability of molding sand to withstand high temperatures without breaking down or fusing thus facilitating to get sound casting. It is a highly important characteristic of molding sands. Refractoriness can only be increased to a limited extent. Molding sand with poor refractoriness may burn on to the casting surface and no smooth casting surface can be obtained. The degree of refractoriness depends on the SiO2 i.e. quartz content, and the shape and grain size of the particle. The higher the SiO2 content and the rougher the grain volumetric composition the higher is the refractoriness of the molding sand and core sand. Refractoriness is measured by the sinter point of the sand rather than its melting point.

2) Permeability
It is also termed as porosity of the molding sand in order to allow the escape of any air, gases or moisture present or generated in the mold when the molten metal is poured into it. All these gaseous generated during pouring and solidification process must escape otherwise the casting becomes defective. Permeability is a function of grain size, grain shape, and moisture and clay contents in the molding sand. The extent of ramming of the sand directly affects the permeability of the mold. Permeability of mold can be further increased by venting using vent rods.

3) Cohesiveness
It is property of molding sand by virtue which the sand grain particles interact and attract each other within the molding sand. Thus, the binding capability of the molding sand gets enhanced to increase the green, dry and hot strength property of molding and core sand.

4) Green strength
The green sand after water has been mixed into it, must have sufficient strength and toughness to permit the making and handling of the mold. For this, the sand grains must be adhesive, i.e. they must be capable of attaching themselves to another body and, therefore, and sand grains having high adhesiveness will cling to the sides of the molding box. Also, the sand grains must have the property known as cohesiveness i.e. ability of the sand grains to stick to one another. By virtue of this property, the pattern can be taken out from the mold without breaking the mold and also the erosion of mold wall surfaces does not occur during the flow of molten metal. The green strength also depends upon the grain shape and size, amount and type of clay and the moisture content.

5) Dry strength
As soon as the molten metal is poured into the mold, the moisture in the sand layer adjacent to the hot metal gets evaporated and this dry sand layer must have sufficient strength to its shape in order to avoid erosion of mold wall during the flow of molten metal.

6) Flowability or plasticity
It is the ability of the sand to get compacted and behave like a fluid. It will flow uniformly to all portions of pattern when rammed and distribute the ramming pressure evenly all around in all directions. Generally sand particles resist moving around corners or projections. In general, flow ability increases with decrease in green strength, and, decrease in grain size. The flow ability also varies with moisture and clay content.
7) **Adhesiveness**
It is property of molding sand to get stick or adhere with foreign material such sticking of molding sand with inner wall of molding box.

8) **Collapsibility**
After the molten metal in the mold gets solidified, the sand mold must be collapsible so that free contraction of the metal occurs and this would naturally avoid the tearing or cracking of the contracting metal. In absence of this property the contraction of the metal is hindered by the mold and thus results in tears and cracks in the casting. This property is highly desired in cores.

9) **Miscellaneous properties**
In addition to above requirements, the molding sand should not stick to the casting and should not chemically react with the metal. Molding sand should be cheap and easily available. It should be reusable for economic reasons. Its coefficients of expansion should be sufficiently low.

**SAND TESTING**
- Molding sand and core sand depend upon shape, size composition and distribution of sand grains, amount of clay, moisture and additives.
- The increase in demand for good surface finish and higher accuracy in castings necessitates certainty in the quality of mold and core sands.
- Sand testing often allows the use of less expensive local sands. It also ensures reliable sand mixing and enables a utilization of the inherent properties of molding sand.
- Sand testing on delivery will immediately detect any variation from the standard quality, and adjustment of the sand mixture to specific requirements so that the casting defects can be minimized.

Generally the following tests are performed to judge the molding and casting characteristics of foundry sands:
1. Moisture content Test
2. Clay content Test
3. Chemical composition of sand
4. Grain shape and surface texture of sand.
5. Grain size distribution of sand
6. Refractoriness of sand
7. Strength Test
8. Permeability Test
9. Flowability Test
10. Shatter index Test
11. Mould hardness Test.

**Moisture Content Test**
- The moisture content of the molding sand mixture may determine by drying a weighed amount of 20 to 50 grams of molding sand to a constant temperature up to 100°C in a oven for about one hour.
- It is then cooled to a room temperature and then reweighing the molding sand.
- The moisture content in molding sand is thus evaporated.
- The loss in weight of molding sand due to loss of moisture, gives the amount of moisture which can be expressed as a percentage of the original sand sample.
- The percentage of moisture content in the molding sand can also be determined in fact more speedily by an instrument known as a speedy moisture teller.
This instrument is based on the principle that when water and calcium carbide react, they form acetylene gas which can be measured and this will be directly proportional to the moisture content.

This instrument is provided with a pressure gauge calibrated to read directly the percentage of moisture present in the molding sand.

**Clay Content Test**

- The amount of clay is determined by carrying out the clay content test in which clay in molding sand of 50 grams is defined as particles which when suspended in water, fail to settle at the rate of one inch per min.
- Clay consists of particles less than 20 micron, per 0.0008 inch in dia.

**Grain Fineness Test**

- The AFS Grain Fineness Number (AFS-GFN) is one means of measuring the grain fineness of a sand system.
- GFN is a measure of the average size of the particles (or grains) in a sand sample. The grain fineness of molding sand is measured using a test called sieve analysis.
- The test is carried out in power-driven shaker consisting of number of sieves fitted one over the other.

1. A representative sample of the sand is dried and weighed, then passed through a series of progressively finer sieves (screens) while they are agitated and tapped for a 15-minute test cycle. The series are placed in order of fineness from top to bottom.

2. The sand retained on each sieve (grains that are too large to pass through) is then weighed and recorded.

3. The weight retained on each sieve is carried out through calculations to get the AFS-GFN.

**Refractoriness Test**

- The refractoriness of the molding sand is judged by heating the A.F.S standard sand specimen to very high temperatures ranges depending upon the type of sand.
- The heated sand test pieces are cooled to room temperature and examined under a microscope for surface characteristics or by scratching it with a steel needle.
- If the silica sand grains remain sharply defined and easily give way to the needle. Sintering has not yet set in.
- In the actual experiment the sand specimen in a porcelain boat is placed into an electric furnace. It is usual practice to start the test from 1000°C and raise the temperature in steps of 100°C to 1300°C and in steps of 50° above 1300°C till sintering of the silica sand grains takes place.
- At each temperature level, it is kept for at least three minutes and then taken out from the oven for examination under a microscope for evaluating surface characteristics or by scratching it with a steel needle.
**Strength Test**

This is the strength of tempered sand expressed by its ability to hold a mold in shape. Sand molds are subjected to compressive, tensile, shearing, and transverse stresses. The green compressive strength test and dry compressive strength is the most used test in the foundry.

- **Compression tests**
  - A rammed specimen of tempered molding sand is produced that is 2 inches in diameter and 2 inches in height.
  - The rammed sample is then subjected to a load which is gradually increased until the sample breaks.
  - The point where the sample breaks is taken as the compression strength.

- **Shear tests**
  - The compressive loading system is modified to provide offset loading of the specimen.
  - Under most conditions the results of shear tests have been shown to be closely related to those of compression tests, although the latter property increases proportionately more at high ramming densities.

- **The tensile test**
  - A special waisted specimen is loaded in tension through a pair of grips.

- **The transverse test**
  - A plain rectangular specimen is supported on knife edges at the ends and centrally loaded to fracture.

*Figure: Loading conditions in strength tests for moulding materials. (a) Compression, (b) shear, (c) tension, (d) transverse*
Permeability Test

- Permeability is determined by measuring the rate of flow of air through a compacted specimen under standard conditions.
- A cylinder sand sample is prepared by using rammer and die. This specimen (usually 2 inch dia & 2 inch height) is used for testing the permeability or porosity of molding and the core sand. The test is performed in a permeability meter consisting of the balanced tank, water tank, nozzle, adjusting lever, nose piece for fixing sand specimen and a manometer. The permeability is directly measured.
- Permeability number $P$ is volume of air (in cm$^3$) passing through a sand specimen of 1 cm$^2$ cross-sectional area and 1 cm height, at a pressure difference of 1 gm/cm$^2$ in one minute.

$$P = \frac{Vh}{at}$$

Where, $P$ = permeability
$v$ = volume of air passing through the specimen in c.c.
$h$ = height of specimen in cm
$p$ = pressure of air in gm/cm$^2$
$a$ = cross-sectional area of the specimen in cm$^2$
$t$ = time in minutes.

Shatter Index Test

- In this test, the A.F.S. standard sand specimen is rammed usually by 10 blows and then it is allowed to fall on a half inch mesh sieve from a height of 6 ft.
- The weight of sand retained on the sieve is weighed.
- It is then expressed as percentage of the total weight of the specimen which is a measure of the shatter index.

Mold Hardness Test

- This test is performed by a mold hardness tester.
- The working of the tester is based on the principle of Brinell hardness testing machine.
- In an A.F.S. standard hardness tester a half inch diameter steel hemispherical ball is loaded with a spring load of 980 gm.
- This ball is made to penetrate into the mold sand or core sand surface.
- The penetration of the ball point into the mold surface is indicated on a dial in thousands of an inch.
- The dial is calibrated to read the hardness directly i.e. a mold surface which offers no resistance to the steel ball would have zero hardness value and a mold which is more rigid and is capable of completely preventing the steel ball from penetrating would have a hardness value of 100.
- The dial gauge of the hardness tester may provide direct readings

Compactability and flowability

- The compactability test is widely accepted as both simple to perform and directly related to the behavior of sand in molding, particularly when involving squeeze compaction.
- A fixed volume of loose sand is compacted under standard conditions and the percentage reduction in volume represents the compactability.
SAND CONDITIONING

Natural sands are generally not well suited for casting purposes. On continuous use of molding sand, the clay coating on the sand particles gets thinned out causing decrease in its strength.

Thus proper sand conditioning accomplish uniform distribution of binder around the sand grains, control moisture content, eliminate foreign particles and aerates the sands.

Therefore, there is a need for sand conditioning for achieving better results.

- The foreign materials, like nails, hard sand lumps and metals from the used sand are removed. For removing the metal pieces, particularly ferrous pieces, the sand from the shake-out station is subjected to magnetic separator, which separates out the iron pieces, nails etc. from the used sand.

- Next, the sand is screened in riddles which separate out the hard sand lumps etc. These riddles may be manual as well as mechanical. Mechanical riddles may be either compressed air operated or electrically operated. But the electrically operated riddles are faster and can handle large quantities of sand in a short time.

- After all the foreign particles are removed from and the sand is free from the hard lumps etc., proper amount of pure sand, clay and required additives are added to for the loss because of the burned, clay and other materials. As the moisture content of the returned sand known, it is to be tested and after knowing the moisture the required amount of water is added.

- There are two methods of adding clay and water to sand. In the first method, first water is added to sand follow by clay, while in the other method, clay addition is followed by water. It has been suggested that the best order of adding ingredients to clay bonded sand is sand with water followed by the binders. In this way, the clay is more quickly and uniformly spread on to all the sand grains. An additional advantage of this mixing order is that less dust is produced during the mulling operation.

- Now these things are mixed thoroughly in a mixing muller. The main objectives of a mixing muller is to distribute the binders, additives and moisture or water content uniformly all around each sand grain and helps to develop the optimum physical properties by kneading on the sand grains. Inadequate mulling makes the sand mixture weak which can only be compensated by adding more binder.

- The final step in sand conditioning is the cooling of sand mixture because of the fact that if the molding sand mixture is hot, it will cause molding difficulties.
The mechanism of solidification of metals/alloys and its control for obtaining sound castings is the most important problem of foundry men.

The proper understanding of the solidification mechanism is essential for preventing defects due to shrinkage of the metal.

As soon as the molten metal is poured in a sand mold, the process of solidification starts.

During solidification, cast form develops cohesion and acquires structural characteristics.

The mode of solidification affects the properties of the castings because a casting acquires a metallographic structure which is determined during solidification.

The metallographic structure consists of

- **Grain size, Shape and orientation**
- **Distribution of alloying elements.**
- **Underlying crystal structure and its imperfections.**

Besides structure, the soundness of a casting also depends upon the solidification mechanism.

Soundness implies the degree of true metallic continuity and a casting will be sound if volume shrinkage accompanying the change of state of melt to solid is compensated by liquid metal with the help of riser, etc.

Volume shrinkage or volume contraction occurs during three stages and thus contraction or shrinkage is of three types.

1. **Liquid Contraction (shrinkage):** it occurs when the metal is in liquid state.
2. **Solidification Contraction (shrinkage):** it occurs during the change from liquid (melt) to solid.
3. **Solid Contraction (shrinkage):** it occurs when metal is solid i.e. after solidification. They do not influence shrinkage defects.
Solidification

- In pure metals and eutectic alloys takes place at constant temperature.
- In solid solution alloys proceeds over a temperature range.

Solidification occurs

- By the nucleation of very small crystals.
- Which grow under the thermal and crystallographic conditions existing during solidification.

- **Grain growth** stops when complete melt has been solidified.

- The relative rates and location of nucleation and growth phenomenon within the melt decides final structure of the solid and establishes whether solidification is directional or it takes place in a discrete manner throughout the melt.

Changes that occur are:

i) **Superheat** must be removed from the metal. Super heat is basically that heat which must be removed before solidification begins.

ii) **Latent heat of fusion** is also evolved; this must be transferred to the surrounding mold before complete solidification can be achieved.

iii) Finally solid metal transfers heat to the mold, and then to the atmosphere as it cools to room temperature.

CONCEPT OF SOLIDIFICATION OF METALS

- A metal in molten states possess high energy. As the melt cools, it loses energy to form crystals

- Since heat loss is more rapid near mold walls than any other place, first submicroscopic metal crystallites called nuclei form here.

- Melt experiences difficulty in starting to crystallites if no nuclei in the form of impurities are present to start crystallization.

- However in such conditions melt undercools and thus nuclei or seed crystals form.

- Nuclei formed as above tend to grow at the second stage of solidification.

- The crystal growth proceeds with release of energy at crystal melt interface.
The crystal growth occurs in a dendritic manner.

Dendritic growth takes place by the evolution of small arms on the original branches of individual dendrites.

These solid dendrites give rise to grains.

(a) *Slow cooling* makes the dendrites to grow *long* whereas *fast cooling* causes *short* dendrite growth.

(b) Since eventually dendrites become grains, slow cooling results in large grain structure and fast cooling in small grain structure in the solidified metal.

As solidification proceeds, more and more arms grow on an existing dendrite and also more and more dendrites form until the whole melt is crystallized.

Dendrite arms grow because metal atoms attach themselves to the solid dendrite.

Atoms arrange themselves in a three dimensional pattern which is repeated many times during the crystal growth.

This unit of repetition is called a Unit cell. Unit cells arrange themselves in straight lines.

Straight lines thus formed in geometric pattern at right angles to each other produce dendritic structure.

Dendrite grow outward until they contact the neighboring dendrite and generate grain boundaries i.e. boundaries between crystals or grains

Quiet likely that the dendrite arms become thickened and ultimately a solid crystal or grain may remain with no indication of dendritic growth.
SOLIDIFICATION OF PURE METALS

- Pure metals generally possess:
  - Excellent thermal and electrical conductivity (eg. Cu and Al)
  - Higher ductility, higher melting point, lower yield point and tensile strength
  - Better corrosion resistance as compared to alloys

- Pure metals melt and solidify at a single temperature which may be termed as Melting Point or Freezing Point, it is in solid state.

- Above freezing point the metal is liquid and below freezing point, it is in solid state.

- If number of temperature measurements are taken at different times, while pure metal is cooled under equilibrium conditions from the molten state till it solidifies, a Time-Temperature plot will be obtained.

1. Liquid metal cools from A to B.
2. From B to C, the melt liberates latent heat of fusion; temperature remains constant.
3. The liquid metal starts solidifying at B and it is partly solid at any point between B and C and at C the metal is purely solid.
4. From C to D, the solid metal cools and tends to reach room temperature.
5. The slopes of AB and CD depend upon the specific heats of liquid and solid metals respectively.

If a pure metal cools rapidly or even otherwise when it is very pure and does not contain at all impurity as nucleus to start crystallization.

1. Nucleation of solid does not start at point B (i.e normal solidification temperature) but it does so at C i.e after the liquid metal has supercooled. This phenomenon is known as supercooling or undercooling.
2. Besides pure metals, supercooling may occur in alloys also, eg. Gray cast iron.

Undercooling - The temperature to which the liquid metal must cool below the equilibrium freezing temperature before nucleation occurs.

Recalssence - The increase in temperature of an undercooled liquid metal as a result of the liberation of heat during nucleation.
**Thermal arrest** - A plateau on the cooling curve during the solidification of a material caused by the evolution of the latent heat of fusion during solidification.

**Total solidification time** - The time required for the casting to solidify completely after the casting has been poured.

**Local solidification time** - The time required for a particular location in a casting to solidify once nucleation has begun.

- When pure metals (and some eutectic alloys) are allowed to solidify in a mold, the portion of molten metal next to the mold wall begins to solidify.
- The metal solidifies in the form of a solid skin and then the liquid metal tends to freeze onto it.
- The solid skin progresses towards the center of the mold from all the mold walls.
- As the successive layers of molten metal build up in the form of solid skin or as the solid metal wall thickness increases, the liquid level in the mold falls because of solidification shrinkage.
SOLIDIFICATION OF AN ALLOY

➢ The alloys normally solidify in a temperature range

NUCLEATION

➢ Nucleation is the beginning of a phase transformation
➢ Nucleation is marked by the appearance in the molten metal of tiny regions called nuclei of the new phase which grow to solid crystals (by further deposition of atoms) until the transformation is complete.

➢ Nucleation may involve
  • The assembly of proper kinds of atoms
  • Structural change into one or more unstable intermediate structures
  • Formation of critical sized particle (i.e nuclei) of the new (i.e solid) phase
1) HOMOGENOUS or SELF NUCLEATION
- Formation of a critically sized solid from the liquid by the clustering together of a large number of atoms at a high undercooling (without an external interface).
- Homogenous nucleation is one occurring in perfectly homogeneous materials such as pure liquid metals.
- Nucleation of the super cooled grains depends upon two factors:

**Factor A**
1. The free energy available from the solidification process; which depends upon the volume of the particle formed.
2. The replacement of old phase (i.e molten metal) by the new (i.e solid) phase accompanies a free energy decrease per unit volume and this contribute to the stability of the region (new phase).
3. In case of spherical particle, if the temperature is suddenly dropped below the freezing point, the free energy change per unit volume of metal transformed (i.e solidified) will be

\[ \frac{4}{3} \pi r^3 \Delta G^v \]

and it is negative (because free energy decreases); \( r \) is the radius of the particle.

**Factor B**
1. The second factor is the energy required to form a liquid-solid interface.
2. Particles formed, in the melt have some surface area. Solid-liquid phases possess a surface in between the two. Such a surface has a positive free energy per unit area associated with it.
3. The creation of a new interface (surface) is associated with free energy increase proportional to the surface area of the particle and this free energy increase is equal to

\[ 4\pi r^2 \gamma \]

Thus total free energy change for a particle of radius \( r \),

\[ \Delta G_T = -\frac{4}{3} \pi r^3 \Delta G^v + 4\pi r^2 \gamma \]
- As the particle radius increases, the free energy also increases till the particle grows to a critical radius and thereafter an increase in particle radius accompanies with decrease in free energy and so much so that the free energy becomes negative also.

- Particles having radius less than the critical radius tend to redissolve and thus lower the free energy. Such particles are known as EMBRYOS.

- Particles having radius greater than the critical radius tend to grow and also lower the free energy. Such particles are known as NUCLEI.

- The critical particle size must be created before the nucleus is stable for a particular supercooling temperature.

\[ r^* = \frac{-2\gamma T_m}{\Delta H_s \Delta T} \]

Where:
- \( r^* \) = critical radius
- \( \gamma \) = surface free energy
- \( T_m \) = melting temperature
- \( \Delta H_s \) = latent heat of solidification
- \( \Delta T = T_m - T \) = supercooling

Note: \( \Delta H_s \) = strong function of \( \Delta T \)
\( \gamma \) = weak function of \( \Delta T \)

\[ r^* \text{ decreases as } \Delta T \text{ increases} \]

For typical \( \Delta T \) \( r^* \text{ ca. } 100\text{Å} \)

**Numericals**

Calculate the size of the critical radius of atoms in the critical nucleus when solid copper forms by homogeneous nucleation

\[ \Delta T = 236^\circ C \quad T_m = 1085 + 273 = 1358 \text{ K} \]
\[ \Delta H_f = 1628 \text{ J/cm}^3 \]
\[ \sigma_{sl} = 177 \times 10^{-7} \text{ J/cm}^2 \]
\[ r^* = \frac{2\sigma_{sl} T_m}{\Delta H_f \Delta T} = \frac{(2)(177 \times 10^{-7})(1358)}{(1628)(236)} = 12.51 \times 10^{-8} \text{ cm} \]
2) HETEROGENEOUS NUCLEATION

- Heterogeneous nucleation occurs at surfaces, imperfections, severely deformed regions, etc. which lowers the critical free energy.
- In molten metals (castings) usually foreign particles are present as impurities which lower the liquid solid interface energy and help in nucleation and thereby reduce the amount of undercooling needed to actuate nucleation.
- The basic requirement for heterogeneous nucleation lies in the ability of the liquid metal to wet the foreign particles.

A solid forming on an impurity can assumed the critical radius with a smaller increase in the surface energy. Thus, heterogeneous nucleation can occur with relatively low undercoolings

- After the initial nuclei are formed.
  1. More solid may be deposited upon the first nuclei or
  2. More nuclei may form, or
  3. A different phase may occur in the melt.
- There is either very little or no supercooling at all in heterogeneous nucleation.

GROWTH

- Growth follows nucleation.
- Growth process determines the final crystallographic structure of the solid.
- The mode of growth of individual grains as well as the general mass of the solid depends upon the thermal conditions prevalent in the solidification zone and the constitution of the alloy.
- Growth may be defined as the increase of the nucleus in size.
- The nuclei grow by additions of atoms.
- The nuclei reduce their total free energy by continuous growth
- During growth, material is transferred by diffusion.
  a) Through the old phase (i.e. liquid metal)
  b) Across the liquid-solid interface.
  c) Into the nucleus
- Growth starts on the grains already formed.
- The growth is controlled by the rate of heat transfer from the casting, since there is a temperature gradient towards the casting surface, the growth occurs in a direction opposite to heat flow, i.e towards the center of the melt.

Development of the ingot structure of a casting during solidification: (a) Nucleation begins, (b) the chill zone forms, (c) preferred growth produces the columnar zone, and (d) additional nucleation creates the equiaxed zone
CASTING DEFECTS

- Any unwanted deviation from the desired requirements in a cast product results in a defect.
- Some defects in the cast products are tolerable while others can be rectified by additional processes like welding etc.
- Modern foundries have sophisticated inspection equipment can detect small differences in size and a wide variety of external and even internal defects. For example, slight shrinkage on the back of a decorative wall plaque is acceptable whereas similar shrinkage on a position cannot be tolerated. No matter what the intended use, however, the goal of modern foundries is zero defects in all castings.
- The following are the major defects which are likely to occur in sand castings:

MIS RUN

Misrun is a casting defect which occurs due to
(a) insufficient fluidity of the molten metal
(b) absorption of gases by the liquid metal
(c) improper alignment of the mould flasks

REMEDIES

1. Increase metal and/or mold temperature
2. Increase head pressure and/or rate of pour; avoid splashing
3. Improve gating to enhance mold fill
4. Modify alloy composition to enhance fluidity
5. Insulates the mold or use an insulating refractory
6. Increase permeability by using coarse refractory flour

COLD SHUT

A cold shut is caused when two streams while meeting in the mold cavity, do not fuse together properly thus forming a discontinuity in the casting. When the molten metal is poured into the mold cavity through more-than-one gate, multiple liquid fronts will have to flow together and become one solid. If the flowing metal fronts are too cool, they may not flow together, but will leave a seam in the part. Such a seam is called a cold shut.

CAUSES

1. Poor pouring practice.
2. Improper gating.
3. Low shell permeability.
4. Low metal or mold temperature.
5. Low metal fluidity.

REMEDIES

1. Increase metal and/or mold temperature
2. Increase head pressure and/or rate of pour; avoid splashing
3. Improve gating to enhance mold fill
4. Modify alloy composition to enhance fluidity
5. Insulates the mold or use an insulating refractory (alumina bubbles)
6. Increase permeability by using coarse refractory flour
MOLD SHIFT
The mold shift defect occurs when cope and drag or molding boxes have not been properly aligned.

REMEDIES
1. Change worn out pins and bushes.
2. Mount the pattern correctly.

SHRINKAGE CAVITIES
These are caused by liquid shrinkage occurring during the solidification of the casting. To compensate for this, proper feeding of liquid metal is required. For this reason risers are placed at the appropriate places in the mold. Sprues may be too thin, too long or not attached in the proper location, causing shrinkage cavities. It is recommended to use thick sprues to avoid shrinkage cavities.

REMEDIES
1. Lower the pouring temperature.
2. Use risers to feed heavy sections and ensure that they are filled with hot metal. If using open risers, use feeding flux, if using blind risers use feeding cores. Embody chills where a heavy section or bots cannot be fed directly with a riser.

PIN HOLES
Formation of many small gas cavities at or slightly below surface of casting

CAUSES
1. Wrong type of metal.
2. Incorrect gating system.
4. Cold metal.

REMEDIES
1. Control atmosphere
2. Vacuum
3. Gases with less solubility
4. Proper venting to let gases out
5. Proper design of runners and gates to
6. Avoid turbulence

HOT TEARS
Hot tearing / hot cracking / hot shortness / hot brittleness is one of the most serious defects which a casting can suffer.
Irregularly shaped fracture in a casting resulting from stresses set up by steep thermal gradient within the casting during solidification.
APPEARANCE:

[1] Its form is that of ragged, branching crack.
[4] Failure surface is heavily oxidized.
[5] Its location is often at a hot spot, and where contraction strains from adjoining extensive thinner sections are concentrated.
[6] The defect is highly specific to certain alloys; other alloys are virtually free from this problem.

CAUSE OF HOT TEARING

1. Thermal contraction.
2. Liquid film distribution.
3. Liquid pressure drop.
4. Bad casting design.
5. Shell too strong.
7. Fast cooling rate.

REMEDIES

1. Change casting design.
2. Use coarser refractory flour, reduce viscosity, increase slurry refractory load.
3. Modify the gating and/or chemistry of the alloy.
4. Reduce the cooling rate by insulating the mold or using insulating refractories.

SCABS

A rough piece of metal left on the casting when the molten metal eroded the sand. Usually occurs in the drag. The defect can usually be removed from the casting leaving a solid wall, but it may result in sand inclusions elsewhere in the casting.

CAUSES

1. Uneven ramming.
2. Incorrect gating.
3. Improper dried mould.
4. High clay content in molding sand.

REMEDIES

1. Ram more evenly.
2. Gate so that an even flow of metal is obtained over surface of mould.
3. Avoid too rapid drying and allow time for heat to penetrate through the mold.

SLAG INCLUSIONS

A defect in metal intermediate and finished products made primarily by rolling or forging. Slag inclusions are elongated accumulations of nonmetallic inclusions, from several millimeters to several centimeters in length; they usually form in the metal during pouring. They are arranged in the direction of the predominant flow of the metal upon deformation (mainly, on the surface of the metal or in the adjacent layers).
CAUSES
1. Dirty metal.
2. Incorrect gating.

REMEDIES
1. Remove all slag from meal before pouring. Thicken slag with sand before skimming.
2. Incorporate skim gates or strainer cores or filters in running system. Keep runner bush full whilst pouring.

BLOW HOLES
Blow-holes and pinholes are produced because of gas entrapped in the metal during the course of solidification. Blowholes are smooth-walled cavities, essentially spherical in shape.

CAUSES
1. Low vent on molding or core sand.
2. Hard ramming.
3. High moisture content.
5. Insufficient venting in cores.
6. Too low a pouring temperature.

REMEDIES
1. Increase vents area.
2. Avoid excess ramming.
3. Reduce oil in sand.
4. Ensure vents are clear.
5. Increase pouring temperature.
6. Reduce moisture to minimum.

BULGING
Slab bulging is an undesirable casting defect consisting in the formation of a large swell in the cast shell.

CAUSE
1. Firing/pouring temperature too high.
2. Refractoriness character is insufficient.
3. Metal dissipation insufficient.

REMEDIES
1. Lower firing/pouring temperature.
2. Prefer high refractory materials.
3. Remove thermal insulation.
CASTING FETTLING (CLEANING) OPERATION

The foundry Cleaning is collection processes where castings are ‘finished’ to meet the customer’s specifications.

Shakeout
- The solidified metal component is removed from its mold, where the mold is sand based; this can be done by shaking or tumbling.
- This frees the casting from the sand, which is still attached to the metal runners and gates - which are the channels through which the molten metal traveled to reach the component itself.

Degating
- Degating is the removal of the heads, runners, gates, and risers from the casting.
- Runners, gates, and risers may be removed using cutting torches, bandsaws or ceramic cutoff blades.
- For some metal types, and with some gating system designs, the sprue, runners and gates can be removed by breaking them away from the casting with a sledge hammer or specially designed knockout machinery.
- The gating system required to produce castings in a mold yields leftover metal, including heads, risers and sprue, that can exceed 50% of the metal required to pour a full mold. Since this metal must be remelted as salvage, the yield of a particular gating configuration becomes an important economic consideration when designing various gating schemes, to minimize the cost of excess sprue, and thus melting costs.

Surface cleaning
- After degating, sand or other molding media may adhere to the casting.
- To remove this, the surface is cleaned using a blasting process.
- This means a granular media will be propelled against the surface of the casting to mechanically knock away the adhering sand.
- The media may be blown with compressed air, or may be hurled using a shot wheel.
- The media strikes the casting surface at high velocity to dislodge the molding media (for example, sand, slag) from the casting surface.
- Numerous materials may be used as media, including steel, iron, other metal alloys, aluminum oxides, glass beads, walnut shells, baking powder among others.
- The blasting media is selected to develop the color and reflectance of the cast surface.
- Terms used to describe this process include cleaning, bead blasting, and sand blasting.
- Shot peening may be used to further work-harden and finish the surface.

Finishing
- The final step in the process usually involves grinding, sanding, or machining the component in order to achieve the desired dimensional accuracies, physical shape and surface finish.
- Removing the remaining gate material, called a gate stub, is usually done using a grinder.
- After grinding, any surfaces that require tight dimensional control are machined. Many castings are machined in CNC milling centers. The reason for this is that these processes have better dimensional capability and repeatability than many casting processes.
- More and more the process of finishing a casting is being achieved using robotic machines which eliminate the need for a human to physically grind or break parting lines, gating material or feeders.
Simulation is the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behavior of the system or of evaluating various strategies (within the limits imposed by a criterion or set of criteria) for the operation of the system.

In foundries use of simulation software is increasing due to the fact of pre evaluation of the casting behavior. Foundry simulation software is a graphical modeling and solidification simulation package for analyzing casting behavior and predicting casting defects. It uses digital simulation of liquid metal behavior during pouring and subsequent freezing to predict defects in castings, well before any shop floor work commences.

Foundries that use simulation software avoid costly design mistakes and dramatically shorten development cycles. There are some software packages mainly for design of gating and risering systems which also includes Weight Estimation, Modulus Estimation, Feeding Distance Estimation, Riser Size Calculation, Riser Neck Design, Horizontal Gating, Filter Calculation, Interactive Gating, Metallurgical Calculation, Disamatic gating, Velocity-based gating, Centrifugal slag trap, Mold weighting, Alloy Database Editor etc.

The foundry can enter their best practice by means of a learning function, which updates the database for methods and alloy factors based on actual results. The specific knowledge in a foundry can thereby be accumulated.

Benefits:

- Shorten Lead Times
- Help Solve Problems
- Optimize Existing Jobs
- Train Employees
- Improve Customer Relations
- Attract More Jobs Through Improved Market Image

Example:

SOLIDCAST® is a PC-based software tool that simulates the pouring of hot metal of virtually any casting alloy into sand, shell, investment or permanent molds, and the subsequent solidification and cooling process.

SOLIDCAST® uses the mathematical models of heat transfer calculation, combined with a unique tracking of volumetric changes in the metal, to predict the temperature and volume changes in a casting as it is poured, solidified and cooled. This combined thermal-volumetric approach has proven to be an extremely accurate method of predicting various casting problems, including micro- and macro-porosity, hot spots and other defects.

Casting Process Modeling is a mathematical way to let the computer predict (simulate) what will happen when a casting is poured on the shop floor.

Virtually anything that can be modified in the foundry can be simulated using Casting Process Modeling. Simulation allows you to fine tune your casting process in much less time, and without the waste of expensive materials, than shop floor trials.