UNIT II
MELTING FURNACES

Before pouring into the mould, the metal to be casted has to be in the molten or liquid state. Furnace is used for carrying out not only the basic ore refining process but mainly utilized to melt the metal also. A blast furnace performs basic melting (of iron ore) operation to get pig iron, cupola furnace is used for getting cast iron and an electric arc furnace is used for re-melting steel. Different furnaces are employed for melting and re-melting ferrous and nonferrous materials.

The following are the factors which are responsible for the selection of furnace

✓ Considerations of initial cost and cost of its operation
✓ Relative average cost of repair and maintenance
✓ Availability and relative cost of various fuels in the particular locality
✓ Melting efficiency, in particular speed of melting
✓ Composition and melting temperature of the metal
✓ Degree of quality control required in respect of metal purification of refining,
✓ Cleanliness and noise level in operation
✓ Personnel choice or sales influence

Heat in a melting furnace is created by combustion of fuel, electric arc, electric resistance, etc. A furnace contains a high temperature zone or region surrounded by a refractory wall structure which withstands high temperatures and being insulating minimizes heat losses to the surroundings. For refining and melting the ferrous and non-ferrous materials, various furnaces are used.

FURNACES FOR MELTING DIFFERENT MATERIAL

1. Grey Cast Iron
   (a) Cupola
   (b) Air furnace (or Reverberatory Furnace)
   (c) Rotary furnace
   (d) Electric arc furnace

2. Steel
   (a) Electric furnaces
   (b) Open hearth furnace

3. Non-ferrous Metals
   (a) Reverberatory furnaces (fuel fired) (Al, Cu)
      (i) Stationary
      (ii) Tilting
   (b) Rotary furnaces
      (i) Fuel fired
      (ii) Electrically heated
   (c) Induction furnaces (Cu, Al)
      (i) Low frequency
      (ii) High frequency.
Some of the commonly used furnaces in foundries are discussed as under.

**CRUCIBLE FURNACES**

Crucible furnaces are small capacity typically used for small melting applications. Crucible furnace is suitable for the batch type foundries where the metal requirement is intermittent. The metal is placed in a crucible which is made of clay and graphite. The energy is applied indirectly to the metal by heating the crucible by coke, oil or gas. The heating of crucible is done by coke, oil or gas.

**Coke-Fired Furnace**
- Primarily used for non-ferrous metals
- Furnace is of a cylindrical shape
- Also known as pit furnace
- Preparation involves: first to make a deep bed of coke in the furnace
- Burn the coke till it attains the state of maximum combustion
- Insert the crucible in the coke bed
- Remove the crucible when the melt reaches to desired temperature

**Oil-Fired Furnace**
- Primarily used for non-ferrous metals
- Furnace is of a cylindrical shape
Advantages include: no wastage of fuel
- Less contamination of the metal
- Absorption of water vapour is least as the metal melts inside the closed metallic furnace

**PIT FURNACE**

Pit furnace is a type of a crucible furnace bath which is installed in the form of a pit and is used for melting small quantities of ferrous and nonferrous metals for production of castings. It is provided with refractory inside and chimney at the top.

Generally coke is used as fuel. It is provided with refractory lining inside and chimney at the top. Natural and artificial draught can be used for increasing the capability towards smooth operation of the furnace. Fig. 2.1 shows the typical pit furnace.

![Fig. 2.1 Pit furnace](image)

**OPEN HEARTH FURNACE**

In open hearth furnace, pig iron, steel scrap etc. are melted to obtain steel. This furnace is widely used in American foundries for steel production. The hearth is surrounded by roof and walls of refractory bricks as shown in Fig. 2.2. The charge is fed through a charging door and is heated to 1650°C mainly by radiation of heat from the burning of gaseous fuels above it. This heat is obtained by the burning of sufficiently pre-heated air and gas.

Such pre-heated air of gas is obtained by passing them though arc shaped hot regenerators at a lower level. This contains fire bricks which are arranged to extract heat from exhaust gases. In the furnace air and fuel are passed through a honeycomb of hot firebrick, called checkers. It preheats the air and fuel so that they are ready for combustion when they enter the hearth. The products of combustion at the same time pass through the checkers at the other end of the furnace. The hot gases heat the checkers. The process then reverses itself, and the newly heated checkers now are used to heat the air and the fuel. It is said as a regenerative process.
The products of combustion after giving up their heat to the checkers pass up through the stack. On firing of coke, the charge is heated. Part of the heat necessary, results from radiation from the low hot roof of the chamber. The furnace is raised bricked in with the charging platform, at the rear, also raised so that the charge may be put into the furnace. The melt is tapped off the front into large ladles. The chemical composition of the end product depends upon the lining, the charge, and the control impurities added during the melt after the melt has been tapped off into the ladle.

The lining plays a major role in the control of impurities. For magnesite lined furnace, the charge consists of pig iron, limestone, and scrap iron. The limestone forms a slag. This slag and the oxygen in the air combine to remove impurities. The slag reacts with the sulfur and the phosphorus in the metal, while the bubbling air causes oxidation of the carbon and silicon. If too much carbon is present in the melt, iron ore is added. The oxygen from the iron oxide burns out the excess carbon. If the carbon content is too low, pig iron is added. This replenishes the carbon. Other alloying elements like Cr, Ni, Co, W, Mo, V etc. are added as needed.

Ferromanganese may be added to the crucible after tapping. For acid lining furnace, the charge should be scrap iron and low-phosphorus pig iron. Limestone is required to keep the slag fluid. As described above, the basic lining burns phosphorus, silicon, and carbon. The slag is tapped off by the molten metals being allowed to overflow the sides of the crucible into a slag pot. Oxygen is one of the most important elements used in the reduction of the molten metal. Rust, scale, slag, and limestone are some of the sources of oxygen. Oxygen is introduced into the furnace with oxygen lances through the roof of the furnace. Twice
the oxygen input will double the carbon reduction. This increases the steel production of the furnace.
AIR FURNACE

This furnace is also known as puddling or reverbratory furnace. It is used for making wrought iron. Fig. 2.3 shows the construction of this type of furnace.

A furnace or kiln in which the material under treatment is heated indirectly by means of a flame deflected downward from the roof. Reverberatory furnaces are used in copper, tin, and nickel production, in the production of certain concretes and cements, and in aluminum.

Reverberatory furnaces heat the metal to melting temperatures with direct fired wall-mounted burners. The primary mode of heat transfer is through radiation from the refractory brick walls to the metal, but convective heat transfer also provides additional heating from the burner to the metal.

![Fig. 2.3 Air Furnace](image)

**Advantages provided by reverberatory melters:**
- High volume processing rate
- Low operating
- Maintenance costs

**Disadvantages of the reverberatory melters:**
- High metal oxidation rates
- Low efficiencies
- Large floor space requirements

CUPOLA FURNACE

A cupola is a vertical cylindrical furnace equipped with a tapping spout near its base. Cupolas are used only for melting cast irons, and although other furnaces are also used, the largest tonnage of cast iron is melted in cupolas. General construction and operating features of the cupola are illustrated in Fig.

It consists of a large shell of steel plate lined with refractory.

The “charge,” consisting of iron, coke, flux, and possible alloying elements, is loaded through a charging door located less than halfway up the height of the cupola. The iron is usually a mixture of pig iron
and scrap (including risers, runners, and sprues left over from previous castings). Coke is the fuel used to heat the furnace.

Forced air is introduced through openings near the bottom of the shell for combustion of the coke. The flux is a basic compound such as limestone that reacts with coke ash and other impurities to form slag. The slag serves to cover the melt, protecting it from reaction with the environment inside the cupola and reducing heat loss.

As the mixture is heated and melting of the iron occurs, the furnace is periodically tapped to provide liquid metal for the pour.

**Description of Cupola**

- The cupola consists of a vertical cylindrical steel sheet and lined inside with acid refractory bricks. The lining is generally thicker in the lower portion of the cupola as the temperature are higher than in upper portion
- There is a charging door through which coke, pig iron, steel scrap and flux is charged
- The blast is blown through the tuyeres
- These tuyeres are arranged in one or more row around the periphery of cupola
- Hot gases which ascends from the bottom (combustion zone) preheats the iron in the preheating zone
- Cupolas are provided with a drop bottom door through which debris, consisting of coke, slag etc. can be discharged at the end of the melt
- A slag hole is provided to remove the slag from the melt
- Through the tap hole molten metal is poured into the ladle
- At the top conical cap called the spark arrest is provided to prevent the spark emerging to outside

**Operation of Cupola**

The cupola is charged with wood at the bottom. On the top of the wood a bed of coke is built. Alternating layers of metal and ferrous alloys, coke, and limestone are fed into the furnace from the top. The purpose of adding flux is to eliminate the impurities and to protect the metal from oxidation.

Air blast is opened for the complete combustion of coke. When sufficient metal has been melted that slag hole is first opened to remove the slag. Tap hole is then opened to collect the metal in the ladle.
Working of Cupola Furnace

Initially the furnace prop is opened to drop the existing earlier charge residue. The furnace is then repaired using rich refractory lining. After setting the prop in position, the fire is ignited using firewood and then small amount of coke is used to pick fire. The little oxygen is then supplied for combustion. Lime, coke, and metal in balanced proportions are charged through the charging door upon the coke bed and at proper time on starting the blower.

Air is forced from wind box through tuyers into furnace. The forced air rise upward rough the stack furnaces for combustion of coke. Besides being fuel, the coke supports the charge until melting occurs. On increase of temperature, the lime stone melts and forms a flux which protects the metal against from excessive oxidation. Lime also fuses and agglomerates the coke ash.

The melting occurs and proceeds and molten metal is collected at the bottom. Molten metal may be tapped at intervals before each skimming, or the tap-hole may be left open with metal flowing constantly.
In most cupolas slag is drained from the slag hole at the back of furnace. When metal is melted completely the bottom bar is pulled sharply under the plates and bottom is dropped.

All remaining slag, un-burned coke or molten metal drops from the furnace. When the melt charge has cooled on closing furnace, it is patched and made ready for the next heat.

**ROTARY FURNACE**

Rotary Melting Furnace is a very flexible and universal equipment used for recycling many non-ferrous metals. It is the major lead production technology used in India and many other countries for Secondary Lead Production.

**Characteristics such as:**

- Equipment scalable for installing higher capacities
- Recovers all lead in one production cycle
- Plates & powder from scrap battery as well as slag from Mini Blast Furnace can be used as raw material
- Requires addition of certain consumables
- Can be fired with various fuels
- Generates high Pollution both as Flue Gases & Fugitive Emissions

**Description of Rotary Furnace**

It is a Rotary kiln in the form of a metallic cylinder with conical sides on both ends. Mild steel plate is used for construction of this shell and its thickness varies depending upon the capacity of the equipment. This shell is rotated on its own axis at 1-2 rpm. For this purposes tyres (also called riding rings) are fitted on the shell.

These are fabricated from MS squares or flats, machined for a smooth finish. These tyres ride on steel rollers which are again machined finely. These rollers are fitted on a robust MS structural frame and driven by a gear & motor arrangement. The shell is lined inside with insulation and fire bricks of suitable Alumina content.

Conical ends of the furnace are open on both sides. The furnace is charged with Raw material along with additives from the front end. This side is provided with a movable door on which a burner is mounted. The burner can be a conventional one or a fully automatic one depending upon the fuel used.

At the other end, an exhaust block lined with refractory bricks is provided. A tapping hole is provided in the center of the shell from where molten metal & slag are discharged.

Flue gases generated are sucked from the exhaust block side of the furnace.
MEE54 INDUSTRIAL CASTING TECHNOLOGY

Rotary Furnace

Process:

Rotary Furnace can be obtained directly from scrapped batteries or as slag from Mini Blast Furnace. In case of former, batteries are cut open or broken to segregate lead scrap, plastic and other materials from them; lead scrap in the form of lead powder/plates etc. is charged in the furnace along with a proportionate charge of additives. In the case of latter, slag produced from Mini Blast Furnaces is charged into the Rotary Furnace, again with proportionate additives.

This process is a batch type process. After filling the required quantity of raw material (either manually or mechanically), the lid of the furnace at the front is closed. The burner attached to the moving door is then fired.

Material along with additive chemicals is heated at high temperature inside the furnace. After some time, molten lead is collected at the bottom of the furnace by puncturing the central opening of the Rotary Furnace. Lead is collected either directly into Jumbo Ingot Moulds or in receiving channels from which they are poured into Jumbo Ingot Moulds.

After draining the Furnace of the first batch, production of next batch is undertaken and the Furnace is again charged with raw material. After three such batches, one batch of slag collected in Rotary Furnace is executed.

Advantages

- Recovers 100% lead in the first operation.
- Slag produced is lead free.
- Equipment can be scaled up for higher production capacities.

Disadvantages

- Many chemicals are required for operation.
- High power consumption.
- Difficult to produce low Antimony lead suitable for soft lead purposes.
- Fugitive Emissions need to be captured in addition to flue gases.
- Need skilled operators and careful maintenance
REFRACTORIES FOR MELTING UNITS

Refractories are materials that can withstand high temperatures and resist the action of slags. These materials should not show any sign of fusion below 1580°C because they are used to serve as receptacles for molten metal. Refractories form a vital part of all melting furnaces in foundries. Good refractory materials:

i. Do not fuse and soften at the temperature at which they are used
ii. Are able to withstand thermal shock due to sudden change in temperature
iii. Resist abrasion
iv. Do not get crushed under the heavy pressure of the charge when used at high temperature
v. Have a low thermal coefficient
vi. Are chemically inert and resist corrosion
vii. Do not allow gases to permeate through them and
viii. Have high electrical resistance if used for electric furnaces.

In actual practice, no refractories fulfil all these requisites, but there are some materials that satisfy many of the conditions.

Refractory materials are classified as acid, basic, or neutral, according to their reactivity with acidic or basic slags formed in the furnaces.

Acid Refractories

Acid refractories are those that are not attacked by acid slags. The common acid refractory materials are silica and fire clay. Silica, in the pure state, fuses at a temperature of 1710°C; when heated in contact with some basic material, it forms a silicate.

Silica bricks are hard and refractory and can withstand 3 kg/cm² load at 1600°C. The thermal shock resistance is low and a tendency to spall is shown during rapid fluctuations of temperature. Fire clays are composed of hydrated aluminium silicate (A12O3 2SiO2 2H₂O).

The properties of fire clay bricks differ markedly due to variations in chemical composition. The thermal expansion of these bricks is low, but the resistance to spalling is high. The fusion temperature is well over 1700°C, but, under load conditions, it gets lowered (1380°C under about 1.5 kg/cm²).

The general requirements of fire bricks, classified into two types as per IS: 1871-1958, are as shown in Table below.

<table>
<thead>
<tr>
<th>Property</th>
<th>Type I</th>
<th>Type II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyrometric cone equivalent, minutes</td>
<td>30 minutes</td>
<td>31 minutes</td>
</tr>
<tr>
<td>(ASTM Cone No.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apparent porosity (% max.)</td>
<td>25</td>
<td>22</td>
</tr>
<tr>
<td>Cold crushing strength (kg/cm², min.)</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Permanent linear change after reheating (% max.)</td>
<td>For 5 hrs at 1350°C ± 1.0</td>
<td>For 2 hrs at 1400°C ± 0.5</td>
</tr>
</tbody>
</table>
**Basic Refractories**

Basic refractories are those that do not react with basic slags. They are suitable for lining furnaces operating on the basic slag practice. Common basic refractories are magnesite, chrome-magnesite and dolomite. Magnesite has a high fusion point of 2800°C and good resistance to the corrosive action of basic slags. Magnesite bricks have poor thermal shock resistance and low resistance to abrasion whereas chrome-magnesite bricks have superior refractoriness under load and better thermal shock resistance.

These consist of 20-30% MgO and 70-80% chromite. Both magnesite and chrome-magnesite bricks are expensive and are used only where slags are highly basic in nature. Dolomite, a double carbonate of calcium and magnesium (CaCO$_3$ MgCO$_3$), serves as a cheaper substitute for magnesite. Stabilized dolomite, which consists of 3CaO-SiO$_2$ and MgO, is a better refractory than ordinary dolomite as it is not over prone to expansion and cracking.

Bauxite (Al$_2$O$_3$-3H$_2$O) is also highly refractory when pure and is basic in nature. Its utility is, however, limited owing to the presence of many impurities which lower its refractory value.

**Neutral Refractories**

Neutral refractories neither react with acid nor with basic slags and they permit the use of both acid and basic processes on the same lining. Common neutral refractory materials are carbon, graphite, chromite, and sillimanite. Carbon bricks do not form a liquid phase on heating and thus retain strength at high temperatures.

Their resistance to thermal shock is high and the coefficient of thermal expansion low. They are not melted by molten metal and slag. The oxidation in air as well as in other oxidising gases is rather high at temperatures above 1400°C.

Chromitc bricks are manufactured from chromite ore, which is composed of 32% FeO and 68% Cr$_2$O$_3$. The fusion temperature of chromite bricks is about 2180°C.

Sillimanite contains 63% Al$_2$O$_3$ and 37% SiO$_2$. Its fusion temperature is 1900°C. It has a low coefficient of thermal expansion, and good resistance to abrasion, spalling and corrosive action of slags. The strength retained at high temperature is also fairly high.

Zircon, composed of 100% zirconium oxide, is also suitable as neutral refractory.

Neutral refractories, though ideal in properties, are very expensive and their use is therefore limited to special applications.

**Selection of Refractory Materials for Different Furnaces**

1. Cupola:

   In the hearth area of the cupola, refractory lining is in contact with molten metal, slag, and relatively static coke. The effect of abrasion is therefore not serious, but the lining is prone to the chemical attack of slag. In the melting zone, the lining encounters high temperature and chemical reactions, and thermal shock too as cold air rushes through the opening when the base is dropped.
The choice of refractories in the hearth and melting areas depends on slag practice. Acid slag practice requires a lining of fire bricks, silica, or alumina. Basic slag practice needs magnesite, chrome-magnesite, or burnt dolomite lining; carbon lining is also used occasionally. Lining in the charging zone is not subject to high temperature or attack by the action of slag, but it withstands severe abrasion when the charge moves downwards. Hard burnt fire clay of low porosity is quite suitable for this region.

Cast iron blocks are also used in the upper part near the charging door. The area above the charging door serves only to protect the shell from the heat of stack gases. It is also lined with fire bricks.

2. Electric Arc Furnace:

The type of refractory used in this furnace depends on the type of operating practice, viz. acid or basic. If the lining is acid, the roof and side walls are built of silica bricks. The hearth has first a layer of fire bricks next to the shell, followed by two courses of silica bricks. The brickwork is rammed finally with a hearth mixture comprising silica sand mulled with about 4% ball clay. In the case of basic practice, the roof is constructed of silica bricks or silhmanite.

Sometimes, the outer circle is made of chrome-magnesite bricks and the side walls are lined with silica bricks. However, it is more advisable to use magnesite bricks. Chrome-magnesite bricks are also used for side walls. The hearth shell is lined with magnesite bricks. Stabilized dolomite bricks are also suitable for the hearth. The brickwork is thoroughly dried before the working hearth is rammed with magnesite or dolomite powder.

Maintenance A good refractory maintenance aimed at balanced wear is important to get optimum performance of an electric arc furnace. The slag line including the hot spots and the banks are the areas where most of the repair is necessary. Hot repairs to the furnace lining, in contrast to those made after shutdown, have potential advantages such as increasing the operating efficiency and preventing loss of heat. Eroded spots on the banks or hearth of the furnace are filled up immediately after tapping each heat by throwing furnace bottom sand or crushed ganister in the case of acid lining.

For basic lining the refractory maintenance materials are usually basic products but they differ substantially from the basic materials used for manufacturing of basic bricks. A maintenance material must have adequate refractoriness, but at the same time it must contain a percentage of low melting phases which promote sintering in the temperature of 925 to 1425 °C. In addition, a chemical binder must be included to impart sufficient strength after drying and prior to sintering.

However, this binder lowers the refractoriness of the maintenance material. Regarding grain size of the maintenance material, it may be noted that although a compact layer may give maximum wear resistance, the grade suitable for maximum compactness will not flow satisfactorily through the spray machine and will give rise to segregation. Moreover, if a wet maintenance material is used, excessively compact layer hinders escape of water vapour during drying. The large size grain fraction contributes to the rebound loss whereas the fine fractions lead to down flow.
For this reason, fairly even grain size distributions are generally selected. The maintenance materials are usually magnesia, doloma, doloma magnesia or magnesia chrome products. The range of minor constituents added as binding, sintering and plasticising agents include silicates, alkaline phosphates, sulphates, chromates and clays.

The machines used for application of the maintenance material include pressure chamber spray guns, rotary valve guns or centrifugal spinners.

3. Induction Furnace:

A high frequency current is carried by a water-cooled coil in the induction furnace. The inside of the coil is rammed with a thin layer of sillimanite refractory to form a melting chamber. The thin layer is rammed by hand around a core which is made in the form of a steel or asbestos cylinder. The core can be either withdrawn or melted with the first charge. When the lining is acid, rammed ganister bonded with clay or sodium silicate is used. For basic lining, sintered magnesite, fused alumina, and zircon give best results.

The refractories for lining must have the following characteristics:

- Compatibility with Alloys and Oxides: The life of the furnace lining depends upon its compatibility with the metals and alloys being melted and the oxides formed during melting.
- Retention of Strength at Steelmaking Temperature: This is a desirable characteristic, because at this temperature, the lining is subject to mechanical abuse when putting scrap into the furnace and when using crowbars to prevent scrap from bridging over.
- Low Thermal Conductivity: The refractory should have low thermal conductivity for prolonged life of the induction coils and less heat loss.
- Low Electrical Conductivity: Electrical conductivity of the refractory material should be low for efficient induction heating.
- Resistance to Slag Corrosion and Erosion: The refractory lining should be resistant to slag corrosion and erosion to minimize the chance of metal breakthrough and repair between relining's.
- Low Reheat Shrinkage: The lining should undergo small volume changes during heating up and cooling down of the furnace such that chances of development of cracks and subsequent metal breakthrough to the coil is minimum.

ELECTRIC ARC FURNACE (EAF)

Electric Arc Furnace (EAF) is a steel making furnace, in which steel scrap is heated and melted by heat of electric arcs striking between the furnace electrodes and the metal bath.

Two kinds of electric current may be used in Electric Arc Furnaces: direct (DC) and alternating (AC). Three-phase AC Electric Arc Furnaces with graphite electrodes are commonly used in steel making.

The main advantage of the Electric Arc Furnaces over the Basic Oxygen Furnaces (BOF) is their capability to treat charges containing up to 100% of scrap. About 33% of the crude steel in the world is made in the Electric Arc Furnaces (EAF).
Structure of an Electric Arc Furnace

- The furnace consists of a spherical hearth (bottom), cylindrical shell and a swinging water-cooled dome-shaped roof.
- The roof has three holes for consumable graphite electrodes held by a clamping mechanism. The mechanism provides independent lifting and lowering of each electrode.
- The water-cooled electrode holders serve also as contacts for transmitting electric current supplied by water-cooled cables (tubes). The electrode and the scrap form the star connection of three-phase current, in which the scrap is common junction.
- The furnace is mounted on a tilting mechanism for tapping the molten steel through a tap hole with a pour spout located on the back side of the shell.
- The charge door, through which the slag components and alloying additives are charged, is located on the front side of the furnace shell. The charge door is also used for removing the slag (de-slagging).
- The scrap is charged commonly from the furnace top. The roof with the electrodes is swung aside before the scrap charging.
- The scrap arranged in the charge basket is transferred to the furnace by a crane and then dropped into the shell.

SOLIDIFICATION OF METALS

Solidification is a comprehensive process of transformation of the melt of an alloy into a solid piece of the alloy, involving crystallization of the liquid phase, segregation of impurities and alloying elements, liberation of the gases dissolved in the melt, shrinkage cavities and porosity formation.

- Structure of ingots and castings
- Segregation
- Gas pores
- Shrinkage
Fine and homogeneous grain structure is the most desirable for the common castings and ingots. It is achieved when the crystallization proceeds under the following conditions:

- Formation of a large number of stable nuclei;
- Fast extraction of latent crystallization heat and the superheat of the liquid.

These conditions are realized when a melt comes to a contact with a wall of a cold metallic mould. Small equiaxed grains (chill crystals) form at this stage. Latent crystallization heat, liberating from the crystallizing metal, decreases the undercooling of the melt and depresses the fast grains growth. At this stage some of small grains, having favorable growth axis, start to grow in the direction opposite to the direction of heat flow. As a result columnar crystals (columnar grains) form. Length of the columnar grains zone is determined by the constitutional undercooling. When the temperature of the melt, adjacent to the solidification front, increases due to the liberation of the latent heat, constitutional undercooling will end and the columnar grains growth will stop. Further cooling of the molten alloy in the central zone of the ingot will cause formation of large equiaxed grains. Formation of the grain zones of an ingot is presented in the figure.

The crystals, growing as a result of solidification of ordinary alloys, are in dendrite form.

**Segregation**

Composition of solidified alloy is not uniform. Concentrations of impurities and alloying elements are different in different parts of the casting. This difference is a result of different solubility of impurities in liquid and solid phases at the equilibrium temperature.

*Segregation* is a result of separation of impurities and alloying elements in different casting regions. *Micro segregation* is a segregation of impurities between the dendrite arms. This kind of segregation may be considerably diminished by diffusion of the impurities atom into the dendrite arms during homogenizing annealing.
**Macro segregation**

Advancing the solidification front towards the ingot center causes enrichment of the liquid in the central zone by impurities and alloying additives, rejected by the solidifying metal and pushed by the solidification front. Segregated impurities are arranged as V-shape marks on the vertical section of the ingot. This effect is called normal macro segregation.

Gravity segregation is a segregation caused by precipitation of primary crystals, which are heavier than the melt.

**Gas pores**

Gas pores, entrapped in the solid structure of a casting, arise from different origins:

- Gas (Hydrogen) dissolved in the liquid during melting (from damp materials, atmosphere, oils, etc.). When the melt cools down and solidifies hydrogen solubility decreases and it is forced out from the melt. The gas bubbles are trapped by the dendrites, forming gas porosity.
- Gas pores, called blowholes, may be a result of chemical reaction occurring in the solidifying alloy. If a liquid steel was not deoxidized by deoxidizers (aluminum, silicon), Oxygen and carbon, which are solved in the steel, form carbon monoxide by the reaction: \( C + O = CO. \) The bubbles of CO, trapped by the dendrites, form blowholes.
- Surface blowholes may form as a result of the decomposition of some constituents of mould dressing.

**Shrinkage**

Shrinkage is a contraction of alloy volume caused by:

- Contraction of the melt when it cools down to the liquidus temperature
- Contraction of the alloy owing its solidification (cooling from liquidus temperature to solidus temperature). All metals except bismuth have higher density in solid state, than in liquid.
- Contraction of the solid alloy cooling from the solidus temperature to the ambient temperature.

**Shrinkage cavity**

When a large isolated region of liquid phase remains within solid, surrounding it, shrinkage cavity will form in this region. The common mould structure includes a riser a “head”, in which the melt solidifies last and “feeds” the main casting with liquid alloy, compensating the casting shrinkage.
Shrinkage porosity

This shrinkage defect is a characteristic for the central regions of castings (ingots) of the alloys with a wide temperature range of solidification. In these castings “feeding” melt is not able to infiltrate through the interlacing dendrites. The local micro-spaces between the dendrites arm remain isolated from the melt in riser forming micro-cavities or shrinkage porosity.