Steel Making

Prof.DeepakMazumdar

Prof.S.C.Koria

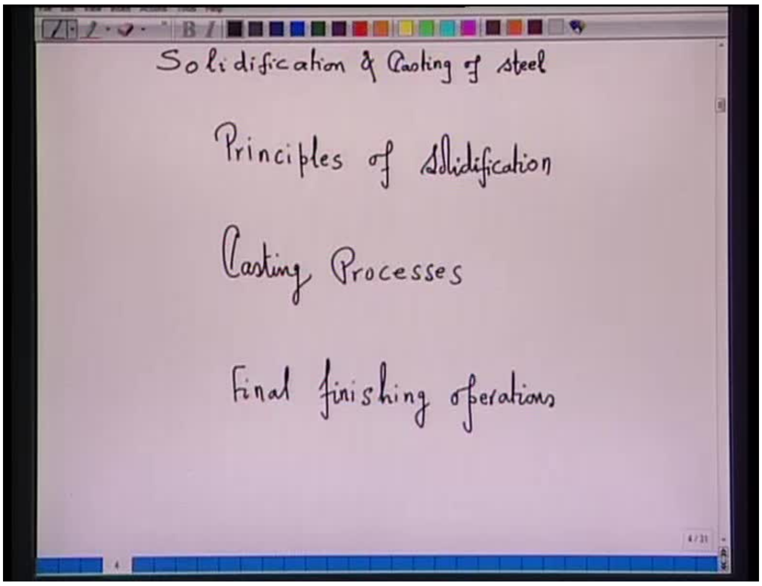
Department of Materials Science and Engineering

Module No.# 01

Lecture No.# 31

Solidification and Casting Processes

(Refer Slide Time: 00:31)



Solidification & Casting of steel

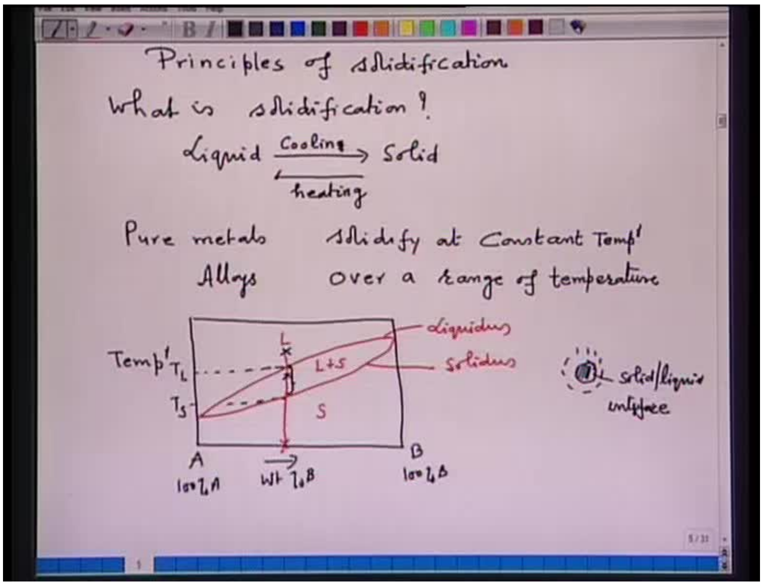
Principles of Solidification

Casting Processes

Final finishing operations

In the next few lectures, I will be discussing on solidification and casting of steel. Under this, we will be discussing principles of solidification, then, casting processes and then, final, finishing operations.

(Refer Slide Time: 00:41)



Principles of solidification

What is solidification?

Liquid $\underset{\text{heating}}{\overset{\text{Cooling}}{\rightleftarrows}}$ Solid

Pure metals solidify at Constant Temp'

Alloys over a range of temperature

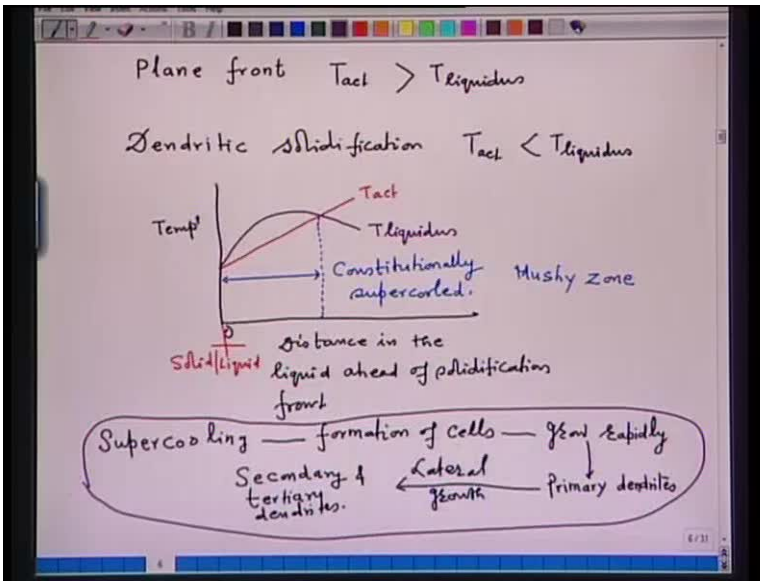
So, as such, first, we start with the principles of solidification. Liquid steel is tapped from primary steel making vessel. Then, various operations have been done in secondary processing; inclusion, modification, temperature control, whatever, has been done, that are the principles of solidification.First, what is solidification? In fact, solidification is, liquid to solid transformation; liquid to solid transformation, on cooling; the reverse, solid to liquid on heating.So, solidification is liquid to solid transformation, which occurs, when super heat and latent heat of solidification areremoved. Now, here, pure metals, they solidify at constant temperature; they solidify at constant temperature, as all of you know. What about alloys? They solidify over a range of temperature, over a range of temperature; what does it mean?

This I can illustrate. For example, I take an isomorphous system, say, I take an isomorphous phase diagram, consists of A and B; here it is, say,100 percent A; here it is 100 percent B, and I am adding here, weight percent B, then typically, an isomorphous system, it looks,for example, this one. This is an alloy of A and B. So, if I want to consider the cooling of this particular concentration of alloy, then, typically it cools, if this is the liquid; this is the liquid plus solid, and this is the solid. So, this particular alloy of this composition, this is somewhere here, temperature, then, it cools along this particular path. So, accordingly, this particular line is known as liquidus, and this particular line is known as solidus.

Here is the temperature. So, when I say, alloy solidify over a range of temperature, then, a super-heated liquid, which is just above the melting point, say,for example, here,we will remove its super heat; it will touch this particular point; it will not solidify immediately, on reaching the liquidus temperature; but, it will take some time, before it is completely solidified. So, this particular region you are seeing, this means, the solidification occurs over a range of temperature, and the range of temperature consists of, say, if this is the T L, which is the liquidus temperature;so, this one is the solidus temperature. So, that is what is meant by, solidification over a range of temperature.

Now, on touching the liquidus line, as we cool further, what will happen, a solid will form. For example, if I consider a point at this particular region, which is the liquid and solid, that means, I have cooled this alloy, from this temperature to this temperature,then, a solid will precipitate; a solid solution will precipitate. And so, if this is the solid and this is the liquid, then, this hasbecome a solid liquid interface. So, how the solidification will proceed? It will proceed through the advancement of solid liquid interface, and as a result of this, more and more solid will form.

(Refer Slide Time: 06:35)


Plane front $T_{act} > T_{liquidus}$

Dendritic solidification $T_{act} < T_{liquidus}$

So, it is the movement of solid liquid interface. Now, we can have either a plane front solidification, either a plane front solidification; this plane front solidification can occur, when temperature, the actual temperature is greater than liquidus temperature. Now, thissituation can occur, when no segregation is involved; due to segregation of solute, the liquid adjacent to the solid liquid interface is super cooled. How does it happen? As the liquid cools, solid is formed. Then, there is an solubility of the impurity, in the solid, as well as in the liquid So, depending upon the solubility of the impurity in the solid, the excess solute will be rejected into the liquid. So,therefore, the liquid which is adjacent to the solid liquid interface will get enriched with the solute element, and this is called the phenomenon of segregation.

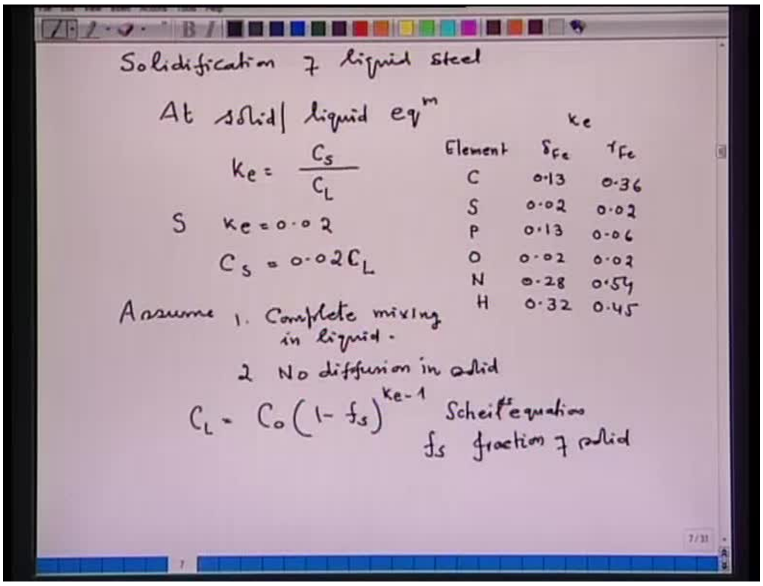
So, this type of, say, solidification, it occurs, which is called a dendritic solidification, called dendritic solidification. As a result of rejection of excess solute, which gets accumulated near the solid liquid interface, a condition arise, where T actual becomes less than Tliquidus. If I want to show over a diagram,for example, I take this one; this is, here is the temperature and this is here, distance in the liquid, distancein the liquid ahead of solidification front;ahead of solidification front; that means, if it is zero,so, this particular thing, is the location of solid liquid interface. So, as I move ahead of the solidification front in the liquid, then, I get this condition; that means, this is the T actual and this is Tliquidus. So, you are seeing, upto this region,upto this region, due to rejection of solute ahead, solid liquid interface,upto this region,T actual is less than Tliquidus; that is,Tliquidus is greater than T actual.

So, that means, the liquid within this region, which is a segregated one, is said to be constitutionally super cooled; constitutionally super cooled. And, this constitutionally super cooled phenomena occurs, because of segregation of the solute element; and this segregation occurs, because of the solubility difference betweenthe solid and the liquid. So, the excess solute will be rejected by the solid, and the impurity will concentrate near the solid liquid interface, in the liquid. So, on account of that, in that particular region,upto which the segregated portion is there, the liquid is said to be super cooled, and this particular zone is also called, mushy zone. So, the solidification occurs; that means, due to super cooling, due to super cooling, what has happened, formation of cells at the interface takes place; formation of cells at the interface and these cells grow rapidly; these cells grow rapidly, normal to the interface, in some preferred crystallographic direction, at high rates of solidification.

So, on account of this, the formation of primary dendrites will occur; primary dendrites will form, and the lateral growth of primary dendrite, that is, the lateral growthof primary dendrite, will give us,so called secondary and tertiary dendrites, and tertiary dendrites.

And, that is how, the dendritic type of solidification, it proceeds in this particular fashion; this is contrary to the plane front. So, that means, a mushy zone consists of a mixture of solid dendrites, plus inter-dendritic liquid, because, when the dendrites have been formed, some amount of liquid which will be entrapped in the dendritic region, that is called inter-dendritic liquid; that is, liquid which is entrapped between the two dendrites.

(Refer Slide Time: 14:18)



Solidification of liquid steel

At solid| liquid eq^m

$$k_e = \frac{C_s}{C_L}$$

S $k_e = 0.02$

$C_s = 0.02 C_L$

	k_e	
Element	δ_{Fe}	γ_{Fe}
C	0.13	0.36
S	0.02	0.02
P	0.13	0.06
O	0.02	0.02
N	0.28	0.54
H	0.32	0.45

Assume 1. Complete mixing in liquid.

2 No diffusion in solid

$C_L = C_o (1 - f_s)^{k_e - 1}$ Scheil equation

f_s fraction of solid

Imagine, the dendritic structure is just like a tree-likestructure.Now, with this background, let us see the solidification of liquid steel. Let us see, solidification of liquid steel, of liquid steel. Now, steel, as all of you know, is an alloy of iron, carbon, silicon,sulphur, manganese, oxygen, hydrogen, nitrogen and inclusions. From a steel making, you have seen that, the liquid steel which you have, we have produced, it contains all theimpurities, which I have mentioned just now. So, that means, one thing is clear. It will solidify over a range oftemperature; it does not solidify at a constant temperature, but, it will solidify over a range of temperature.

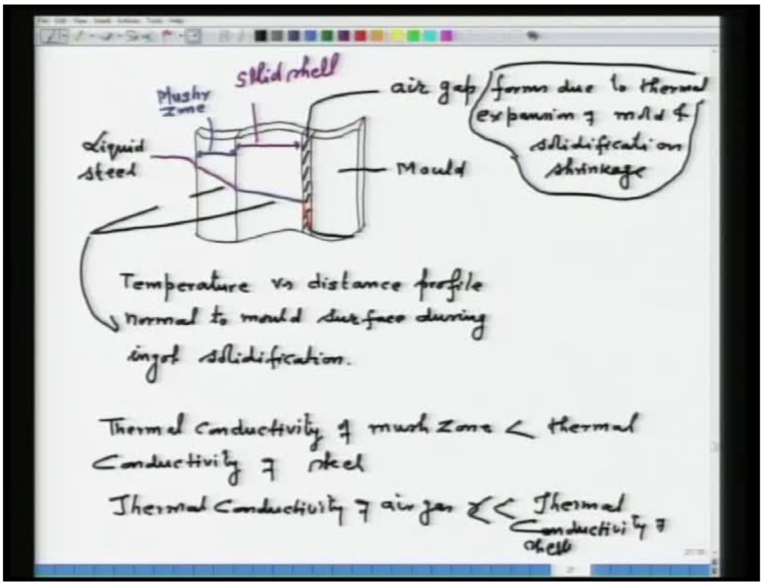
When this happens, what will happen to the impurity? On solidification, whatever solid will form, the impurity will partition between solid and liquid. So, at solid liquid equilibrium, at solid liquidequilibrium, it define a equilibrium partition coefficient which is K e, that is equal to, concentration of impurity in the solid, on concentration of impurity in the liquid So, thisequilibrium partition coefficient, and its value, will determine the extent of segregation. Now, let us see some of the values,for example. If I take, say, element and value of K e in delta iron and in gamma iron. So, I take here, carbon, sulphur, phosphorus, oxygen, nitrogen and hydrogen. Here it is 0.13, 0.02, 0.13, 0.02, 0.28 and 0.32.The K e value in gamma iron is 0.36, 0.02,0.06, 0.02, 0.54 and 0.45. So, particularly, you note the equilibrium partition ratio of sulphur and phosphorous.

So,it is very low, followed by oxygen also. But, so, what will happen, during solidification, because of a very low solubility of sulphur and phosphorous, the excess sulphur and phosphorous will be rejected into solidifying liquid. And, as a result, the last liquid which will solidify, it will have a higher concentration of sulphur and phosphorous, which will lead to formation of FeS. As I have said, in a steel making, when I was mentioning that, it is very important to control the impurity like sulphur and phosphorous. Now, you can correlate it, why it is so important. Now,for example, if I take, say, for sulphur, if we take,for example, the K e value is equal to 0.02. So,CS, that is equal to 0.02 L;so, you can,0.02CL. So, you can imagine, the concentration, or the solubility of sulphur in solid steel, is very low.

Now,so, that means, excess sulphur will be rejected adjacent to the solid. Now, say, one can obtain the equilibrium solidification condition; if equilibrium is reached, then, the extent of segregation will be minimized. In order to reach equilibrium condition, one has to give very long time, because the diffusion processes in the solid, is very extremely low, as compared to in the liquid. So, considering the equilibrium, say, equilibrium solidification, it requires mixing and homogenization of composition, in both liquid and solid state. Now, say, if we assume that, there is a complete mixing in the solid state; that is, we make, if we assume that, complete mixing, complete mixing in liquid stage, and no diffusion in solid,that is a very ideal condition, no diffusion in solid, because, when solid will form, the diffusion processes will take place in the solid, to equalize the concentration, and that requires a very long time.

So, based on this assumption, complete mixing, no diffusion in the solid, one can arrive at an equation, the concentration of C L that is equal to C 0, 1 minus f s, raised to the power K e minus 1, and this equation is known as Scheil's equation. So, very famous equation, Scheil's equation, where f s is the fraction of solid, f s is fraction of solid; C L and C 0, I have already defined. So, with this equation, one can analyze, what is the concentration of an impurity in liquid. We know f s, and f s value can be determined from the phase diagram, by applying lever rule. And, accordingly, the value of K e can be obtained, from what I have given over here, or from any standard book. So, one can analyze, what will be theextent of segregation and so on.

(Refer Slide Time: 21:30)



Temperature vs distance profile normal to mould surface during ingot solidification.

Thermal conductivity of mush zone < thermal Conductivity of steel

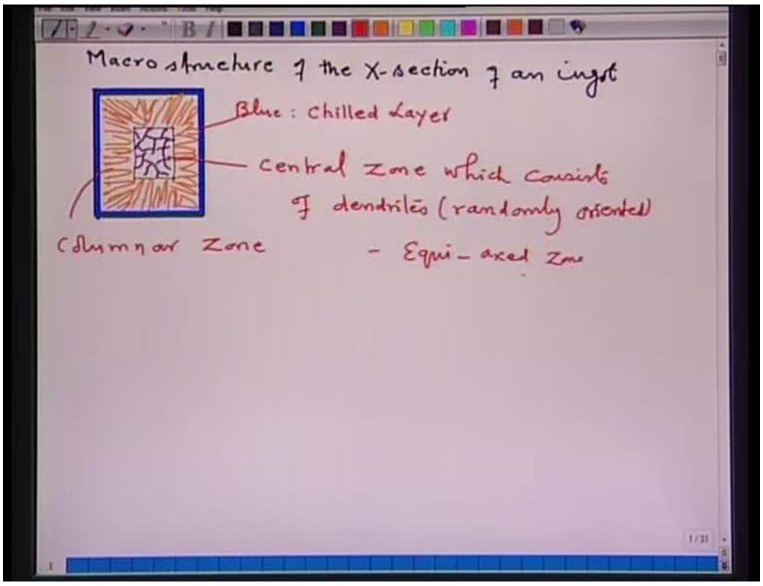
Thermal Conductivity of air gap << Thermal Conductivity of shell

During solidification, we have solid steel shell near the mold, followed by liquid, rich in solute element, which is called mushy zoneand liquid steel, when we observe solidification, normal to mold surface. Now, this is what, in this particular diagram, I am going to show, temperature versus distance profile, normal to mold surfaceduring ingot solidification. Now, let me, first of all, write down, this particular is the mold, and this particular region, this is the air gap, and this is the air gap; and the air gap forms, due to thermal expansion of mold and solidification shrinkage. That means, air gap forms, due to thermal expansion of mold, thermal expansion of moldand solidification shrinkage.

So, this is the reason for formation of air gap, which is a very important phenomena in solidification, because of the differential rates of thermal expansion and solidification shrinkage, the air gap forms. Then, next to air gap, we have, this is the solid shell; this is the solid shell, that is, from here to here is the solid shell. Then, from here to here, we have the, so called mushy zone. We have,so called mushy zone, andhere, we have liquid steel, we have liquid steel. Now, knowing that, the thermal conductivityof mushy zone is smaller than thermal conductivity of steel, whereas, thermal conductivity of air gap, as all of us know, thermal conductivity of air gap, is much smaller than thermal conductivityof shell, solid shell,than thermal conductivity of shell. Now, as a result, if we want to show the thermal gradient, or the temperature versus distance profile in mushy zone, solid shell and mold and air gap, it can be shown, something this particular way.

So, first of all, we have the liquid steel. It comes over here. This is the profile. Now, because the thermal conductivity of mushy zone is smaller than thermal conductivity of steel,so, temperature gradient will be steeper in this mushy zone. Now, solid shell has a higher thermal conductivity. So, the gradient will not be that steep, but it will be somewhat flattener. This is the thermal gradient in steel shell. Now, the most important, is the thermal gradient or the steep temperature drop in the air gap, because of the very small thermal conductivity of air gap. So, the temperature drops suddenly in the air gap and then, again, the temperature decreases. So, that is how, this particular…This is the temperature versusdistance profile, shown normal to mold surface, during ingot solidification, and it strongly depends upon the thermal conductivity, as shown in the figure.

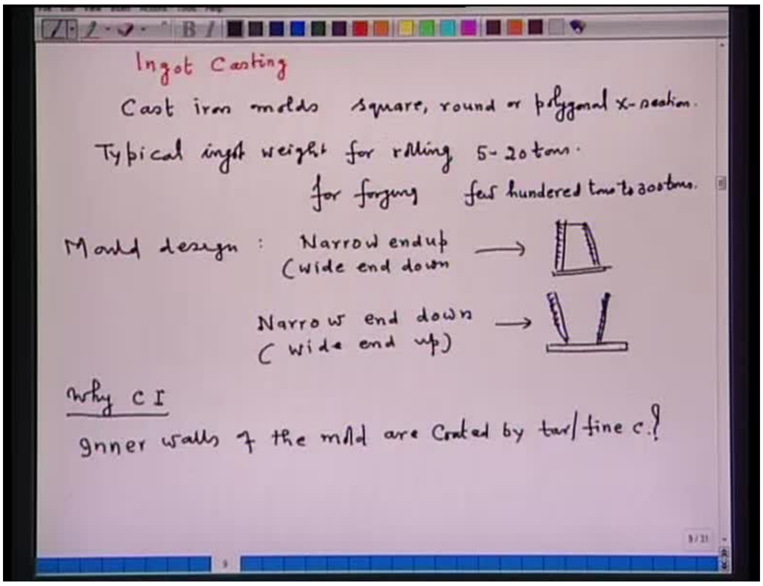
(Refer Slide Time: 26:44)



Macro structure of the X-section of an ingot

Now, suppose, if we pour a killed steel into the mold. And, you would like to see, how the macro structure is developed in the ingot. So, for that, let us see the macro structure of the cross section of an ingot. So, this is, the blue one, blue color, that is, this one is a chilled layer; mold is water cooled; as you pour the liquid, the liquid which is in contact with the surface of the mold, it gets immediately chilled. So, as such, we have the chilled layer; then, I have said that because of the segregation, a mushy zone will form. In the mushy zone, which consists of dendrites and inter-dendritic liquid,so, this,so, this will be so-called columnar zones, or which also consist of dendrites. In the central portion, the central portion, we have a central zone, we have a central zone, which consists of, which consist of dendrites, but they are randomly oriented and we call dendrites which are randomly oriented and we call it Equi-axed zone.

(Refer Slide Time: 28:39)



Ingot Casting

Cast iron molds square, round or polygonal x-section.

Typical ingot weight for rolling 5-20 tons.

for forging few hundered tons to 300 tons.

Mould design : Narrow end up (wide end down →

Narrow end down (wide end up) →

why CI

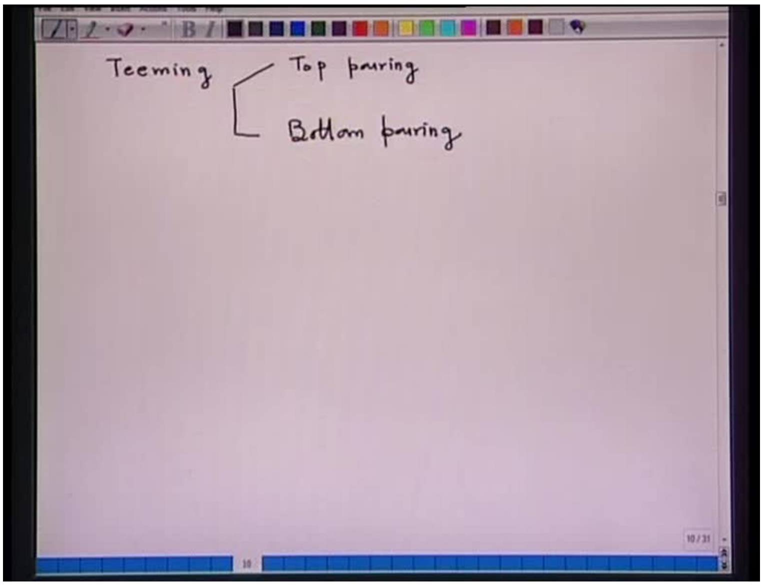
Inner walls of the mold are coated by tar/fine c.?

So, now, with this background on principle of solidification, let us see now, the ingot casting; let us see now, ingot casting, the first in the casting process. Now, ingot casting, is done in cast iron mold, is done in cast ironmolds. The molds can have square, round, or polygonal cross section, orpolygonal cross section. Typical ingot weight, typical ingot weight, it varies, for rolling,5 to 20 tons; whereas, for forging, huge size, that is, from few 100, few 100 tons to as high as 300 tons. Mold design,mold design, two design,one, narrow end up, narrow end up, which automatically means, wide end down; that means, if I can show it over here, this is the bottom plate; this is the narrow end up, or wide end down. Second design is, narrow end down; narrow end down, automatically means, wide end up. If I can show over here,so, this is the narrow end down; this is the narrow end up.

Now, the question comes, why cast iron molds; why cast iron mold and a conical shape, because, thermal coefficient of cast iron, is different from that of steel. Steel contracts more than cast iron;therefore, detachment becomes easier. Now, that is what, the importance in the design. Conical shape, it facilitates ingot, while pulling ingotfrom the mold through a crane. Now, here, narrow end up molds, they are most convenient for stripping the ingot, after solidification. So, that is what the answer, for why cast iron molds and why there is a conical shape, because of the easier stripping of the ingot, from the mold, after solidification.

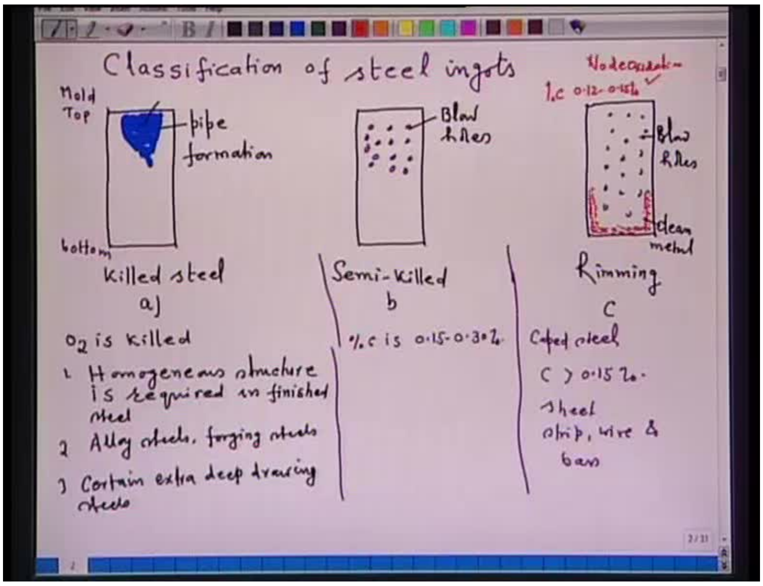
Another important thing, that, inner walls of the mold, inner walls of the mold are coated. They are coated by tar, oblique, fine carbon. Again, the question is why. If you do not coat it, what will happen? The solidified shell, which is in contact with the mold, it may get stick. So, during the stripping, it becomes very difficult. The coated material, it decomposes, which prevents sticking of solidified ingot on the mold surface.

(Refer Slide Time: 33:33)



So, that is what, why inner walls of the mold are coated by some coating material. Next thing, teeming; how the liquid steel is teemed in the ingot. One can have top pouring; bring a ladle, put it on top of the ingot, slide gate is opened; the liquid steel is teemed into the ingot and that is the toppouring. Another is, say, bottom pouring. Another is the bottom pouring. In the bottom pouring, the liquid steel is poured into a channel, and this channel, now, subdivides into two ingots, or two ingot mold, and the liquid steel, which is coming from the ladle, is bifurcated into the two streams, and the liquid steel begins to fill in the mold, from bottom to the top; that is what the bottom pouring consist of. Now, another important thing, is the classification of steel ingots. We can produce different types of steel, which are, which are classified, based on the oxygen contentof the steel, or based on the oxygen killing. So, as such, we have three different types of ingot that are being produced.

(Refer Slide Time: 35:18)



Classification of steel ingots

Killed steel
a)

O_2 is killed

1. Homogeneous structure is required in finished steel
2. Alloy steels, forging steels
3. Certain extra deep drawing steels

Semi-killed
b

% C is 0.15-0.30%

Rimming
C

Capped steel

C > 0.15%

Sheet strip, wire & bars

Major three types of…One, is the killed steel; second is the semi-killed steel and third is the rimming steel. For orientation, I will put, killed steel is a; semi killed steel is b, and c is the rimming steel. Between semi killed and rimming steel, that is b, between b and c, some different type of ingot can also be produced, which will depend upon the rimming action; that, I will tell you, what does it mean. So, first of all, let us concentrate on the killed steel. The structure, or the macro structure, I have shown. This is the ingot, which is the top of the mold; this is the bottom of the mold; and because of the contraction of the steel, in case of killed steel, a pipe formation occurs. Now, this pipe formation is, because of the contraction of steel. The steel, which will be last to solidify, the amount of steel, is not sufficient to meet the contraction, which is occurred during solidification. Hence, the top most part of the ingot has a pipe, or a shrinkage cavity, which has to be scarved during processing. So, this is about the macro structure of killed steel.

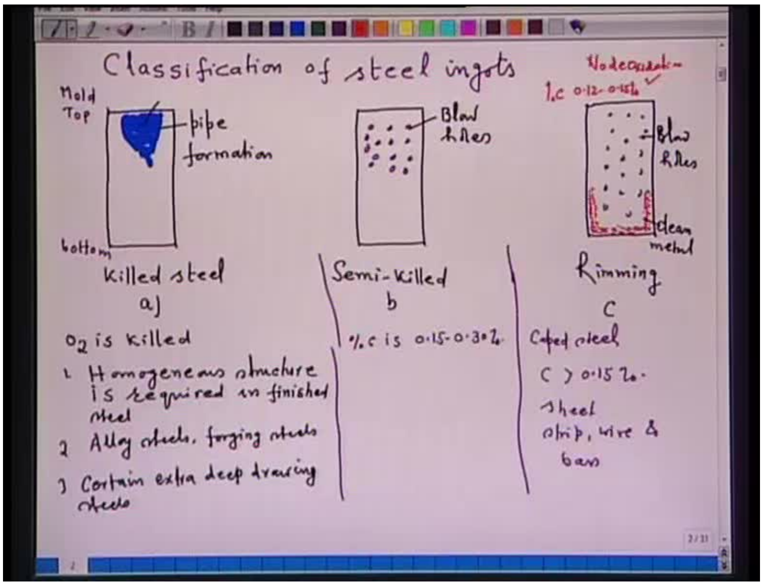
Now, in semi-killed steel, the steel is not killed completely; part of the oxygen is left over. So, on solidification, whenever the solubility between the carbon and oxygen arrives, the carbon monoxide bubble forms. And hence, the macrostructure of the semi-killed steel is characterized by, theseare the,so called blow holes; and these blow hole forms when? Say,60, 70 percent of the steel is solidified; because, oxygen content is still not sufficient,so that, it can form right from the beginning; steel is also not fully killed.

c is the rimming steel. Now, in the rimming steel, no deoxidation is done. Because of thereaction between carbon and oxygen, that occur during solidification, large amount of carbon monoxide bubbles are generated during solidification. These bubbles may eject the droplets and the droplets fall back into the liquid steel. They bring oxygen. So, on account of that, there is large amount of CO, that can be entrapped. So, these are the blowholes. Now, because of the formation of CO, and this is called rimming action. Now I can use the term rimming, because of the rimming action, the gradients will be minimized, and the steel which is solidifying, in contact with the mold, it is a very clean steel, which is free from segregation. And, this sort of a layer, which is just close to the wall of the mold; this is the clean metal, the clean metal.

Now, let me write down the characteristics of all these ingots. Now, first is the killed steel. Now, here, oxygen is killed. How it is killed? By aluminium. So, killed steel, as you recall, from deoxidation is done by aluminium. And, killed steel is used, or killed steel ingots are used, when, first, homogeneous structure is required in finished steel; homogeneous structure is required, in finished steel; that is the number 1. Number 2, typically, alloy steels, alloy steels, forging grade steels, forging steelsand steels for carburized type, they are produced as a killed steel ingots. Certain extra, certain extra deep-drawing, deep-drawing steels, certain extra deep drawing steels, a very low carbon,for example, less than 0.12 percent maximum; these steels are also killed.

But, the killed steel solidification, has two problems. One, the pipe formation, as we are seeing, this is the pipe formation for killed steel; and second problem for killed steel is, the alumina content of the steel, which is being obtained by use ofaluminium. So, these are the important issues for killed steel ingot. Now, about the semi-killed, we have, say, percentage carbon for semi-killed steel, the percentage carbon is in between 0.15 to 0.3 percent. Now, here, you must be wondering, why there is no solidification shrinkage, or pipe formation is occurring, though steel is semi killed. It is not killed with aluminium; maybe by silicon and manganese.

(Refer Slide Time: 35:18)



Classification of steel ingots

No deoxidation ✓
%C 0·12-0·15%

Killed steel
a)

O_2 is killed

1. Homogeneous structure is required in finished steel
2. Alloy steels, forging steels
3. Contain extra deep drawing steels

Semi-killed
b

%C is 0·15-0·3%

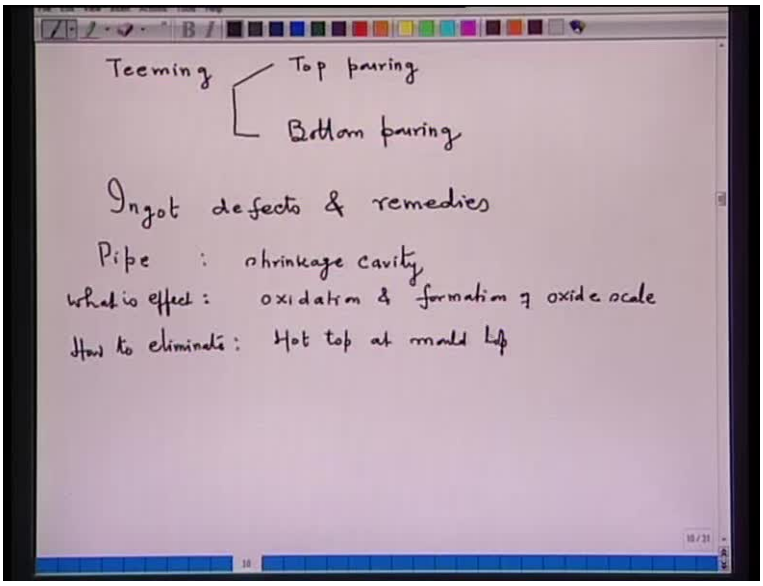
Rimming
C

Caped steel
C > 0·15%
sheet strip, wire & bars

Because of the evolution of carbon monoxide during the solidification, it counter-balances the solidification shrinkage. So, in killed steel, there is no CO evolution, because, there is no oxygen over there. In semi-killed steel, partly there is oxygen; it is not killed completely; but it is semi-killed. In between semi-killed and rimming one, or in the rimming steel, this another grade, is produced, which is called caped steel. In the caped steel, it is the variation of rimming steel practice. The rimming action is allowed to begin in the beginning, and is then terminated, after a minute or two, by closing the top of the mold, by a cast iron cap. In fact, this caped steel is also a modified form of rimming steel practice, which is done, as I have said earlier. A little amount of CO is allowed to occur. But soon after, the top of the mold is closed by a cap, and more, is that, the close by the cap and this steel, this caped steel ingot, they are produced for carbon to be greater than 0.15 percent. Now, this practice of killed, caped steelingot production, is used for, say, sheet, strip, wire and bars.

About, say, rimming steel, in the rimming steel, no deoxidation is done. No deoxidation is done. The percentage carbon, is in between 0.1 to 2.15 percent. Because of the large evolution of carbon monoxide, the steel, or the solidified layer in contact with the mold is very clean; and it will also be low in the solute, because of continuous stirring, that is provided by the CO bubbles. And, this rimmed quality ingot, they are suited for steel sheets. So, that is what the different type of ingots, that is being produced and they are useful and so on.

(Refer Slide Time: 44:50)



Teeming
- Top pouring
- Bottom pouring

Ingot defects & remedies

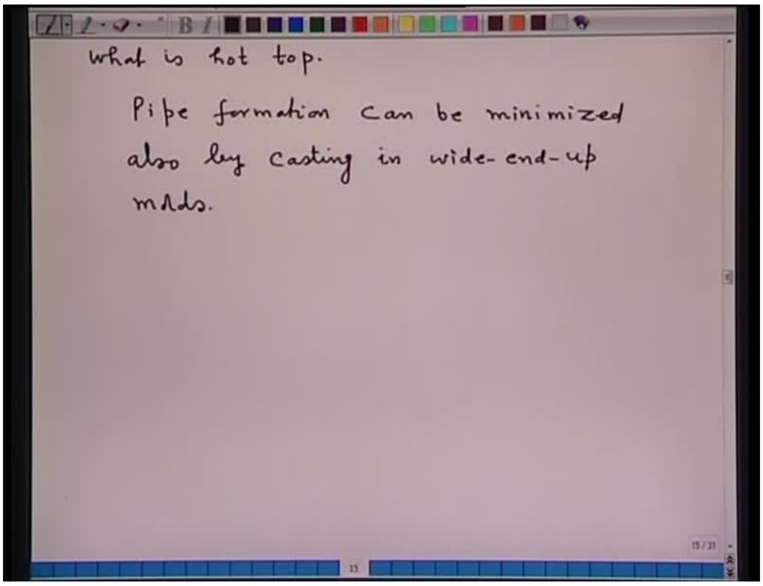
Pipe : shrinkage cavity

What is effect : oxidation & formation of oxide scale

How to eliminate : Hot top at mould top

So, now with this, let us see, ingot defects and their remedies. Ingot defectsand remedies, and remedies.Now, the first ingot defect is pipe; why it forms? It forms because of shrinkage; because, liquid steel shrinks on solidification; pipe is a shrinkage cavity, which is formed at the top of the killed steel ingot. Mind you, it forms only in the killed steel. What is its effect? During reheating, oxidation, and formation of oxide, oxidation and formation of oxide scale. What will it do? It will prevent welding, during, hot rolling; because, when you hot roll it, oxide scale is very brittle, so, the welding will not occur. Hence, pipe portion of the killed steel ingot has to be rejected. How, to eliminate? Now, pipe formation is eliminated, by putting hot top at the, by putting hot top at mold top. So, what is hot top?

(Refer Slide Time: 47:03)

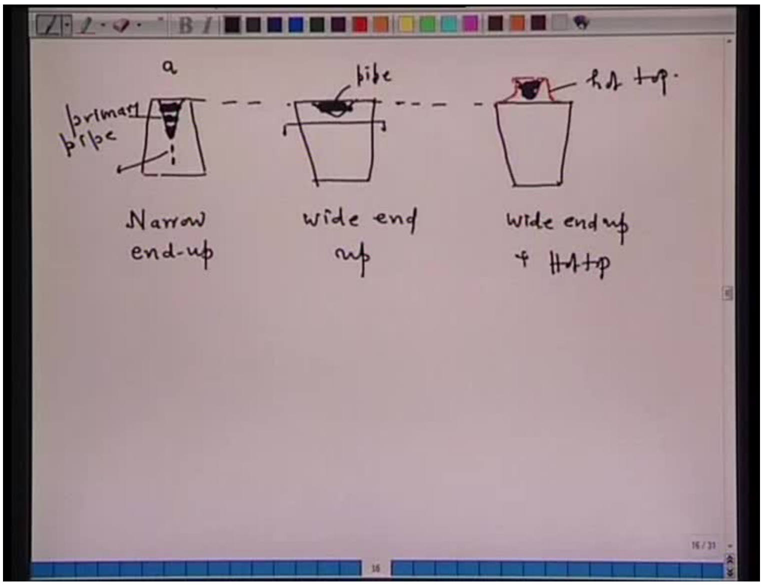


what is hot top.

Pipe formation can be minimized also by casting in wide-end-up molds.

The hot top keeps the ingot top, hot and molten, for a longer period. As a result, liquid steel from top compensates the shrinkage, which has occurred during solidification. So, that is what, in fact, hot top is; that means, top of the ingot is kept hot, so that, the liquid steel remains molten for a longer period. Sometimes, use of insulating and exothermic materials on the top of ingot, further ensures, availability of hot metal at the ingot top. Pipe formation, in fact, pipe formation, which occurs due to shrinkage of liquid steel on solidification, it can be minimizedalso, by casting in wide end up molds. That means, there are two ways, in which it can be done; one way, by hot top; another way, is to casting in wide end up molds. By casting in wide end up molds, what happens,the pipe, though it will form, or the shrinkage cavity will form, but it will form at the top, it is shallow and wider in nature.

(Refer Slide Time: 49:06)



So, I show you, by way of this sketch. In the figure a, anarrow end up mold is used for casting. So, you see, this is the ingot top; and the, because of the solidification shrinkage, the pipe formation extended deep into the ingot. And, this is, in fact, the primary pipe, and to some extent, secondary pipe has also been formed. Now, if I take wide end up mold, in the wide end up mold, you can see, this is, now, the pipe formation; and, pipe formation is now occurring at the top of the ingot, and you see also, it is shallow in nature and little wider in nature. So, you can use more amount of ingot, as compared to, when casting is done in narrow end up. Now, if I provide a hot top;so, this is the hot top; may have exothermic mixture, or whatever way; this is the hot top. Now, the level of steel is ingot is same here, as well as here. Now, you see, if I provide hot top with the wide end up mold, and if I cast it, what will happen? The pipe formation, it goes in the hot top, and the entire ingot remains free from solidification shrinkage. That is how the solidification shrinkage is eliminated. Next defects, we will discuss in the next lecture.