Steel Making

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Module No. # 01
Lecture No. # 32
Solidification and Casting Processes

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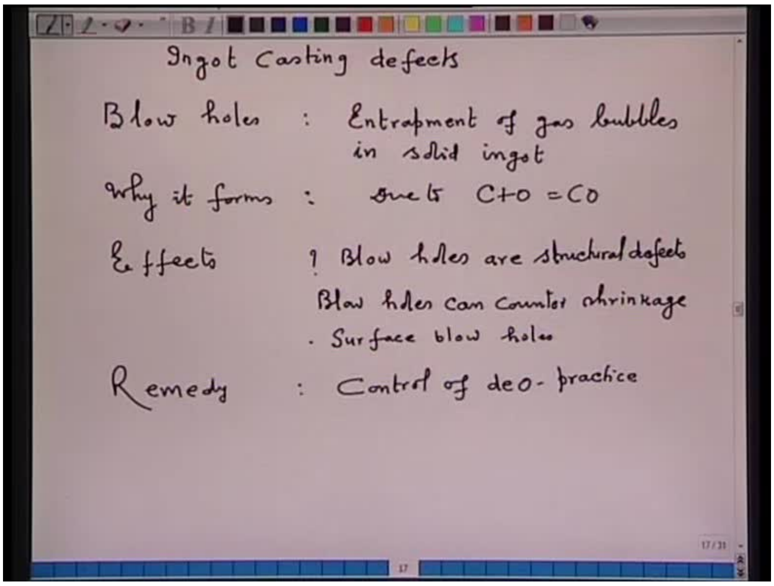

We continue our discussion from the last lecture, where we were discussing the casting defects, introduced during ingot casting. Now, another defect, which is very prominent, for example, blow holes. Blow holes are entrapment of gas bubbles in a solid ingot. They are entrapment of gas bubbles in solid ingot. Why it forms, or rather, how they form, or why it forms? In semi-killed and rimming steel, the deoxidation is not complete. In fact, in rimming steel, no deoxidation is done; in semi-killed steel, the steel is partially deoxidized. Therefore, during casting, the dissolved oxygen, it reacts with the carbon, and on account of this reaction, the CO gas evolves. And, this CO gas, escapes from the ingot to the atmosphere. And, when top portion of the ingot gets solidified, then, there are no chances of escaping of the CO gas bubble, outside the ingot, and therefore, these bubbles are entrapped. And, as a result of which, we get, so called, blow hole.

Now, what are the effects of these blow holes? What are the effects that it can produce? So, and, why it forms, I can write down, due to C plus O is equal to CO reaction during solidification. Now, what are the effects? In fact, blow holes are structural defects. Blow holes can counter the shrinkage, and, as a result, one can also eliminate the shrinkage cavity, because of the stirring provided by carbon monoxide bubble, during solidification. Blow holes, which are situated interior the ingots, they can be welded up during rolling. So, that is also one of the effect; then, in fact, surface blow holes, say, blow holes which are present at the surface, surface blow holes, are harmful. Why, because, during reheating, the steel will be oxidized, and as such, it will do the harmful during rolling. What is remedy? Remedy is only control of deoxidation practice; control of deoxidation practice, or, one should see that, the blow holes are not present in the ingot at the top surface, because, they are only the harmful.

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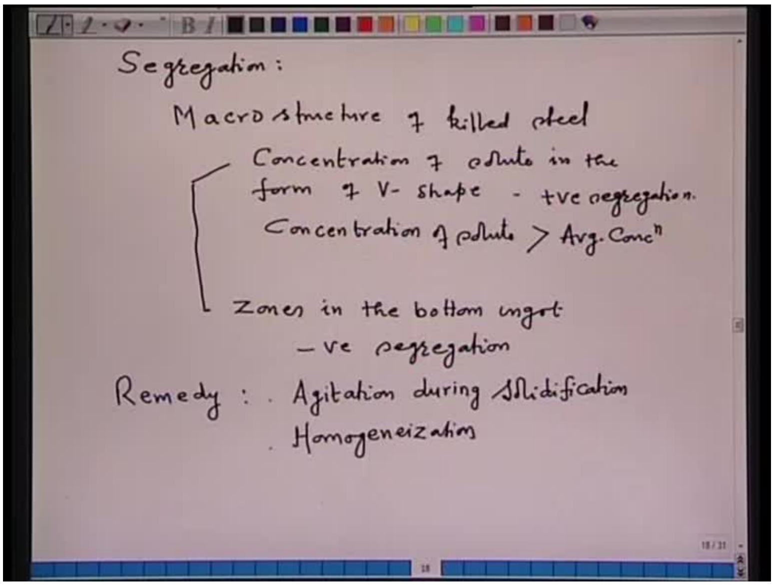

Now, another defect is, for example, segregation. As I have said in my first lecture on solidification, segregation is caused by the rejection of solute elements, during solidification. And, why there occurs rejection, because of the very low solubility of that impurity element, in the solid. So, the excess is rejected and on account of which, the segregation can occur. So, the mechanism, in fact, as the solidification proceeds, chilled layer forms in the vicinity of the mold, and the excess solute is rejected. And, as you seen, a machine zone forms; cells, they grow; dendrites are formed; and within the entered dendritic region, the liquid which is there, is enriched in the solute elements, because, it is accumulating throughout the solidification period, due to very low solubility of element, in the solid. So, as a result of which, inter-dendritic region will be enriched by the solid, and as we know that, the macro structure of killed steel, say, macro structure of the killed steel ingots, they show, for example, concentration of solute, in the form of V shape, which is found below the primary pipe; and, this is called positive segregation. That is, here, the concentration of solute is greater than average concentration, and that is below the pipe. Another region one can see, is a zones in the bottom ingot. There, concentration of solute is less than some average value, and this is called negative segregation.

I think, because, in the bottom, the solidification is occurred earlier; so, there are no chance of further segregation, which is occurred already; but near the end of the pipe, or just below the pipe, solidification occurs towards the last stage. So, more solute will be rejecting during solidification and hence, concentration of the solute will be somewhat greater than the average concentration. In rimming steel, that is an advantage, that is, chances of segregation is very minimum. Why, because of the rimming action. The rimming action is provided by the reaction between carbon and oxygen, which forms carbon monoxide. And, due to the rimming reaction, there is a very good amount of agitation into the bath, and as a result of which, segregation can be very much minimized, when compared with killed steel; because in killed steel, there is no such agitation, during the solidification.

Remedy, how can we remove it? One way of removal - during solidification itself. Now, during solidification, how will we do? One, you provide agitation; agitation during solidification. Now, we have to see, how we are going to provide agitation during solidification. Because, if again agitate the liquid steel during solidification, then, it will homogenize the concentration, and hence, chances of segregation will be minimized. Another way of removal of this segregation is that, the macro-segregation, which results in the inter-dendritic region, can be eliminated, by a treatment called homogenization. Now, this homogenization treatment is given, after the solidification, to the ingot, during the reheating stage. Homogenization treatment does not part, or does not form a part of solidification process, but it forms a part, during rolling or heat treatment operation. So, at that stage, the macro segregation, which is there, in killed steel ingot, it can be eliminated by homogenization, that by heating over a long period of time.

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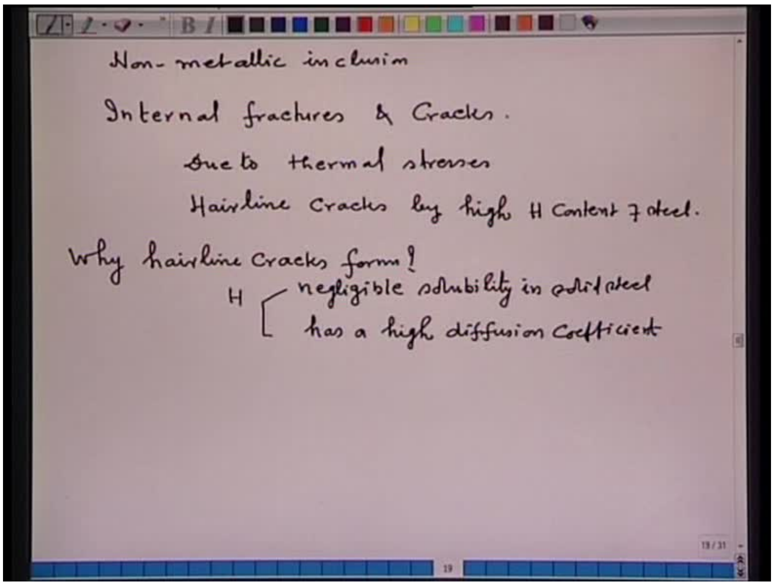

Now, another, say, defect, is non-metallic inclusions. As we all discuss, quite a lot about nonmetallic inclusions, there could be exogenous inclusions, or indigenous inclusions. Exogenous inclusions are the entrapment of refractory, wear of the refractory; and indigenous inclusion, they form during solidification, in the inter-dendritic region. Remedy is very simple; you have to modify them, because there is no other way. Then, another defect is internal fractures and cracks. Now, this is formed due to thermal stresses caused by, either rapid cooling of the ingot, or by rapid reheating, during rolling purposes. Now, here, hairline cracks are caused by high hydrogen content of steel. Now, question is, why hairline cracks form? Why they form? First, hydrogen has a negligible solubility in solid steel; and second, hydrogen has a high diffusion coefficient. What does it mean? Means that, which will result in desorption of hydrogen; that means, as heating is done, then hydrogen will continuously desorb from the steel, and because of the high pressure, sometimes, hairline cracks are developed on the surface.

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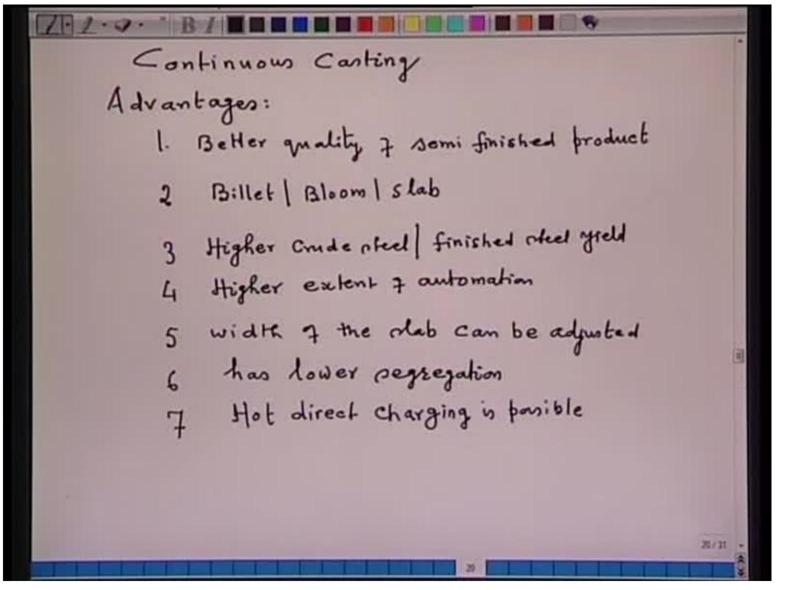

As regards the internal fracture, it is not much of the problem if you have the internal fractures, because, they get welded up during rolling. But, as regards hairline cracks, they can propagate onto the surface, and eventually, it may cause the so called, defect in the product. So, that is all about the ingot casting. Now, with this, let me proceed to the another casting method, which is continuous casting. As the name suggests, molten steel is solidified continuously, in the form of semi-finished product. That means, molten steel is cast in such a way, so that, it gets solidified constantly and continuously, in the form of semi-finished product. These semi-finished product can be ultimately, transferred to the rolling operation. So, if you compare this continuous casting, with just we have studied about the ingot casting, then, the following advantages emerge, over ingot casting; that means, I am now listing the advantages of continuous casting over ingot casting.

So, the advantages are, first, better quality of semi-finished product; second, the semi-finished product of a continuous casting plant, consists of billet, bloom and slab. As such, no slabbing mill or blooming mill or billet mill, in fact, is required, as you are requiring, when you have the ingot casting. So, the semi-finished product from continuous casting plant, can directly go into the rolling, for finished product, in contrast to ingot casting. Third advantage is, higher crude steel to finished steel yield. Fourth, higher extent of automation is possible. It will, better control can be exercised and quality of the product can be further improved. Fifth, as it is known that, the product is semi-finished; it has to be finished. In case of continuous casting, width of the slab, can be adjusted with the downstream strip mill requirement, for example, with respect to the width; that is slab is used to produce strip.

At the end of the hot rolling of slab, there is a, these strips are coiled. So, depending on the width of the coiler, the width of the slab can be adjusted, during continuous casting of steel. Another advantage is that, ingots of larger sizes have increasing transverse and longitudinal segregation. In comparison to that, continuously cast product, has lower segregation. Another very important benefit, for using continuous casting is, hot direct charging of the semi-finished product, into the rolling mill is possible. In fact, it is being done; because, the semi-finished product, after continuous casting, has a very high temperature of the order of 6,700 Celsius; then, that one can adjust, so, that much amount of energy you are going to save, while reheating the billet for rolling purposes. So, the last advantage, which is very important in terms of energy conservation issues, that is hot direct charging is possible; not only possible, it is being done; it is being practiced.

Now, having said so much and so much advantages of continuous casting vis-à-vis against ingot casting, how continuous casting is done? In continuous casting, the molten steel is poured from the ladle into the tundish, and from the tundish into the oscillating copper mold, which is cooled by the water. A partially solidified product is withdrawn constantly and continuously from the exit of the mold, which is then subjected to water spray, for complete solidification. That is how, the continuous casting is done. Now, this entire process is attained by combining ladle, tundish, mold, water spray below the mold, in such a way, so that, the speed of withdrawal of the partially solidified product, from the mold, is adjusted to the speed of pouring of liquid steel from ladle to tundish, and tundish to mold.

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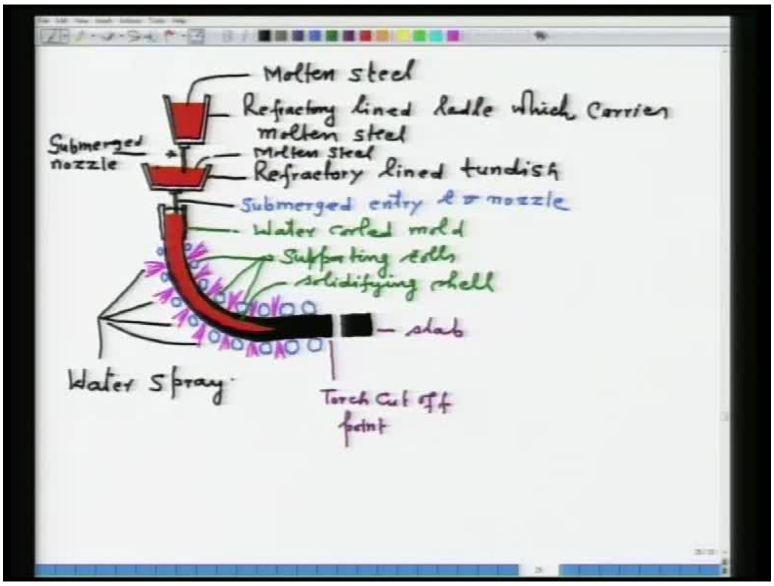

So, the figure shows the arrangement of different vessels in a continuous casting. So, this particular vessel, is a refractory lined ladle, which carry molten steel. So, the red one, that you are seeing, this is, in fact, molten steel. Below the ladle, a tundish is placed. So, this particular vessel, is refractory lined tundish. And, here is again, we have the molten steel. This particular, is a sort of a submerged nozzle, for entry of liquid steel, from ladle to tundish. So, this is, this one is the submerged entry nozzle. This one is, in fact, water cooled mold, and these are the supporting rolls. This one, this one, they are the supporting rolls, to support the solidified shell. This one is a solidifying shell, and somewhere here, we have a torch cut off point, where the slab of required length is cut, and sent to the rolling mill.

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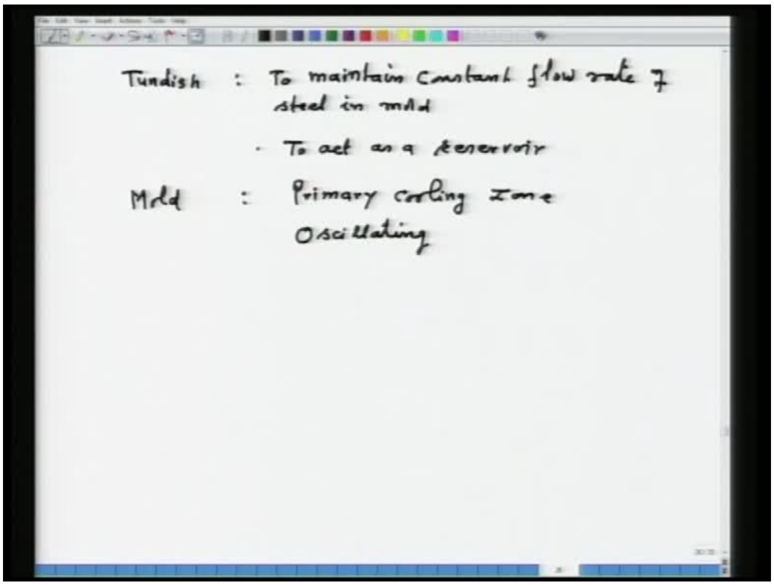

Now, below this water cooled mold, we have these all arrangement, which is shown over here. This is the water spray. So, in fact, the combination of refractory lined ladle, refractory lined tundish, mold and secondary cooling, they altogether, they are placed in such a way, so that, the molten steel can be cast continuously. Now, in short, I will define the functions of different vessel, in short. For example, the role of tundish, to maintain constant flow rate of steel in the mold; that is one of the important function. Another important function, it acts as a reservoir, during ladle change; because, when one ladle becomes empty, then, mold is to be supplied by molten steel, because it is a continuous process. At that point of time, the tundish supplies molten steel to the mold. Then, another important vessel is the mold, and whose, which is also called primary cooling zone.

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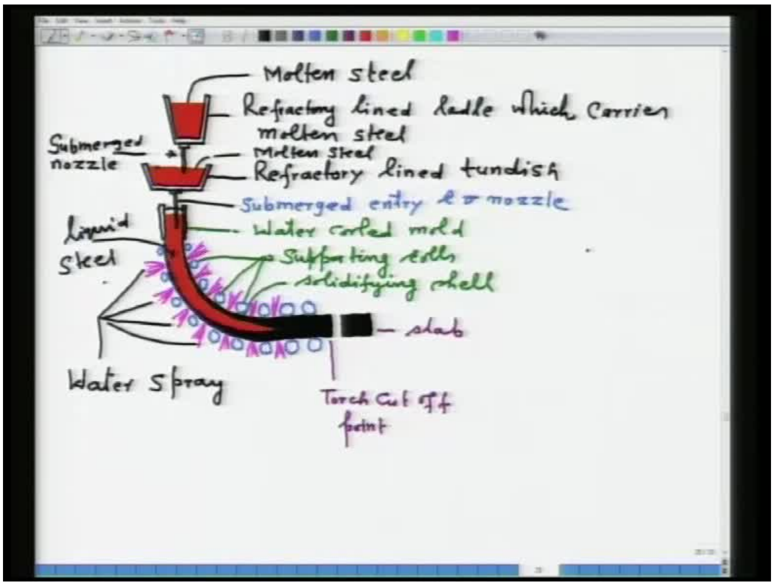

Its length, or height, whichever you want to call, is 0.7 to 0.8 meter, and the cross section depends upon, whether you want to cast billet, slab or bloom. Also, mold is oscillating and the oscillating function, it rather helps to strip the mold, so that, a solidified shell, along with the molten steel, it is, it can be withdrawn continuously, from the mold. So, as you see in the figure that, this particular red mark is the liquid steel.

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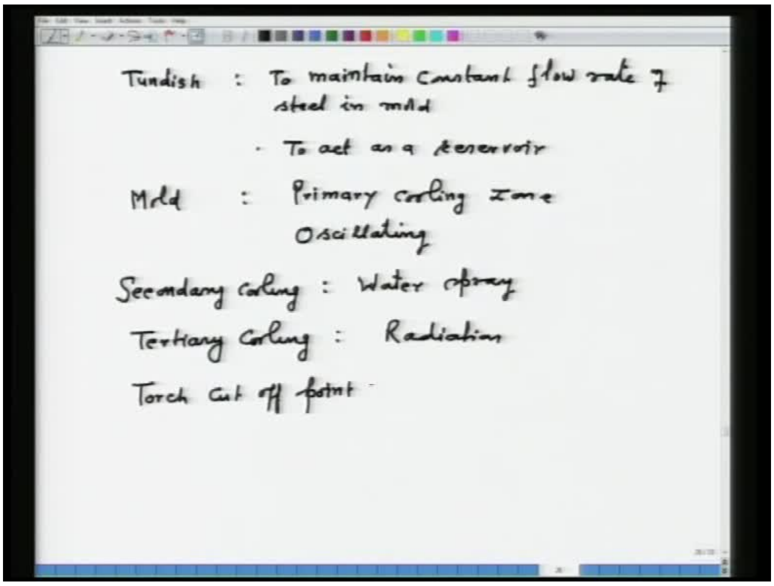

That means, the solidified shell in the core, contains liquid steel, and then, it gets solidified. So, then, we have secondary cooling, which consists of water spray. They are arranged over the entire length of the strand. Then, we also have a tertiary cooling, which is, in fact, due to radiation, when the strand passes after the secondary cooling zone. Then, the last, we have torch cut off point. And, the objective of the torch, is to cut the slab, bloom or billet, into the required length, so that, it can be fed in to rolling mill. How the operation starts? Before filling of the mold, a dummy bar is inserted at the bottom of the mold. Remember, to start the operation, a dummy bar is inserted at the bottom of the mold. Liquid steel gets poured into the mold, and this dummy bar is withdrawn, along with the partially solidified strand, from the mold, subjected to secondary cooling, and so on, so forth.

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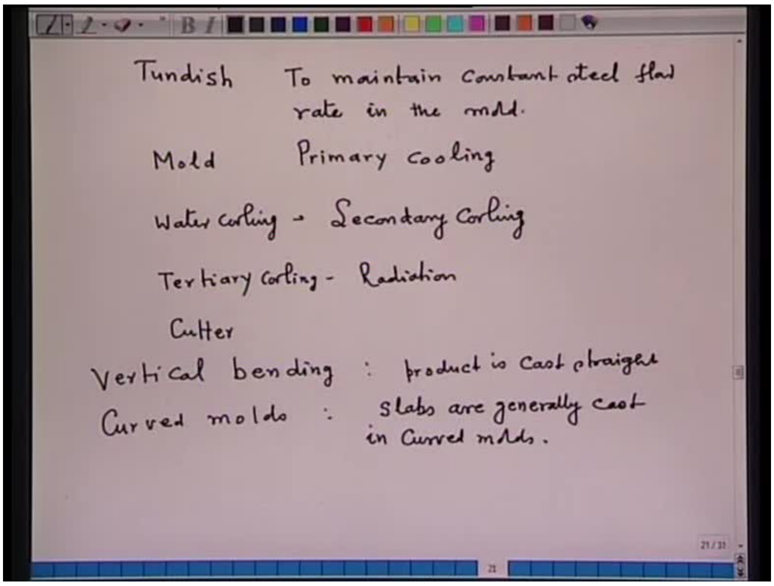

Now, some manifestations of this particular process, I will be putting now, as follows. For example, you have seen tundish. As I said, refractory lined rectangular vessel. Now, the objective of putting down an intermediate vessel, between ladle and the mold, is to maintain constant steel flow rate, into the mold; that means, for major portion of the casting period, the molten steel bath height in the tundish, is kept constant; except in the beginning, and towards the end period, when the ladle has emptied; otherwise, in major period, the height of the steel bath in the tundish, is kept constant.

As I said, mold is a copper mold, which has a very high thermal conductivity. Because, as the molten steel is poured into the mold, the solidification start, and it has to be very quick. So, it has to be of very high thermal conductivity. It is water-cooled and this particular, is called, in the terminology of continuous casting, this is the primary cooling. Length of the mold, maximum, it varies from 0.8 meter to 1.2, 1 or 1.2 meter; not more than that, length of the mold is. Then, below the mold, as the product is withdrawn, it is subjected with intense water cooling. So, this is called, then, the water cooling. Below, the mold, this cooling is called secondary cooling. And, the objective of secondary cooling, is to completely solidify the product. Because, at the exit of the mold, the product is partially solidified; the complete solidification occurs, in the secondary cooling zone.

Now, secondary cooling zone length, is of the order of 8 to 10 times that of primary cooling zone. Then, after the secondary cooling, we may have a tertiary cooling, and this tertiary cooling, is occurs, by way of radiation. So, location of complete solidification in the secondary cooling zone, is very important, because, after that, there is no sort of intense cooling; it just cools in the atmosphere. And then, we have a cutter, which finally, casts, or, which finally, cuts the product into the required length, which can be tolerated in the rolling mill. Now, just to give you an idea, a ladle, which is having, for example, 150 tons of steel, with the help of continuous casting, and at the speed of 3 tons per minute, a 150 ton ladle can be cast into a product, just in 50 minutes. So, the process is really very fast, and hence, the control at each stage, right from pouring of liquid steel from ladle to tundish, from tundish to mold, the partially solidified withdrawn strand, and the secondary cooling, all are very important thing.

Now, these machines, I mean, the arrangement of these three, it can be of few types. One of the type, for example, is a vertical bending. In the initial development of the continuous casting process, the entire process was vertical; ladle, from ladle to tundish, tundish to mold, then, withdrawal of the strand, was also vertical. So, hence, the length of the plant, or height of the plant, was very high. Now, then, came the vertical bending; that means, the partially solidified product from the mold, goes to the secondary cooling, and from there, it is bend. So, in the vertical bending, product or semi, semi-finished product, is cast straight; then, it is curved, with the liquid core is still present. So, that is an important; that means, the solid shell, which is formed must have sufficient strength, so that, the bending can be allowed; and the whole idea of bending, is to decrease the height. Now, another important development to decrease the height, is that of curved molds. Now, here, the slabs, they are generally cast in curved molds.

Now, here, in the curved molds, the strand leaves the mold at an arched section. At the time, it is necessary that, strong shell has already been formed, because, the mold is slightly in the curved fashion. Straightening is done progressively, by passing through circular arcs, with increasing radii. So, what is important, in case of curved mold continuous casting is that, there, the product, or the strand, which leaves the mold, it is also curved in nature, and gradually, it is being withdrawn and subjected to secondary cooling.

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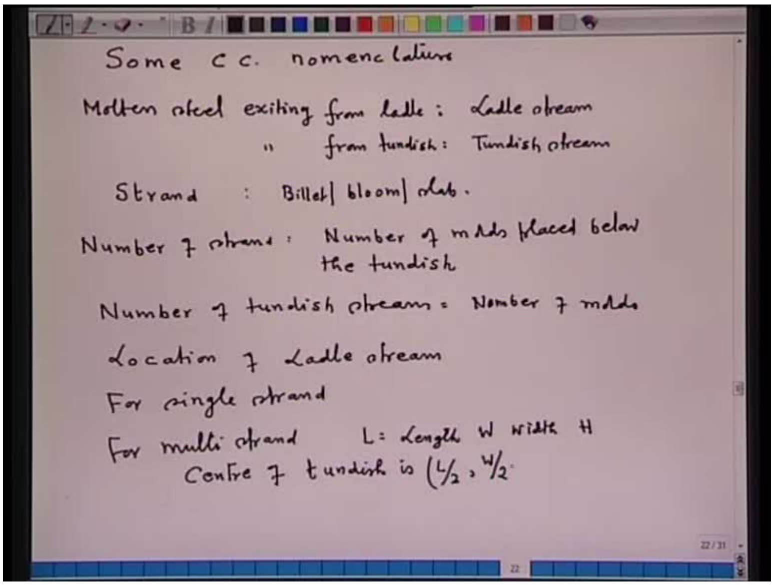

Now, say, some continuous casting nomenclature; say, molten steel exiting from ladle, that is normally called ladle stream. Then, molten steel exiting from tundish is called tundish stream. Now, also, you will hear, or you must have heard, while I was delivering the lecture about the strand; the strand is, in fact, the name given to semi-finished product. And, these names, these strand means, is a billet or bloom or slab. In fact, the strand means, they are the solidified products. So, you can have a slab casting machine, or a bloom casting machine, or a billet casting machine. Number of strand, that means, number of molds placed below the tundish. Say, we have a single strand continuous casting machine, where one mold is kept; or, we have a multi strand casting machine, as you must have heard, the names, or you will be reading in the books, there are more than one, the molds are kept below the tundish.

For example, say, also, we can say, number of tundish streams, that is equal to number of molds. Say, if you say, one tundish stream, say it is a single strand continuous casting machine; two strand, two tundish stream, we say it is a twin strand casting machine. A 4, 6, or 8, then, we say, 4, 6, or 8 strand continuous casting machine. Now, this 4, 6, and 8 strand, are normally used to cast molten steel, in the form of bloom, or billet. Twin strand casting machine is used for slab. A slab, the dimensions, or the cross section of the slab, is 1500 to 2800 millimeter width, into 150 to 270 millimeter thickness. Billet, it is a square section, 100 into 100, or 150 into 150, and bloom is slightly rectangular in cross section. Now, for single strand, tundish stream is obtained through tundish nozzles, which are placed at the bottom of the tundish, and the flow rate is controlled by slide gate, or by walls.

Now, here, the location of tundish stream, location of ladle stream, is important. In fact, the ladle stream is submerged into the tundish. So, the location of ladle stream, with reference to tundish nozzle, is important. For single strand, now, by now, you are familiar, for single strand, molten steel enters from one end of the tundish, and exits from the other end of the tundish. For multi strand, if L is the length of tundish, W is width of the tundish, and H is the bath height of the tundish, then, center of the tundish is located at L by 2, and W by 2; at L by 2 and W by 2, Z is equal to 0.

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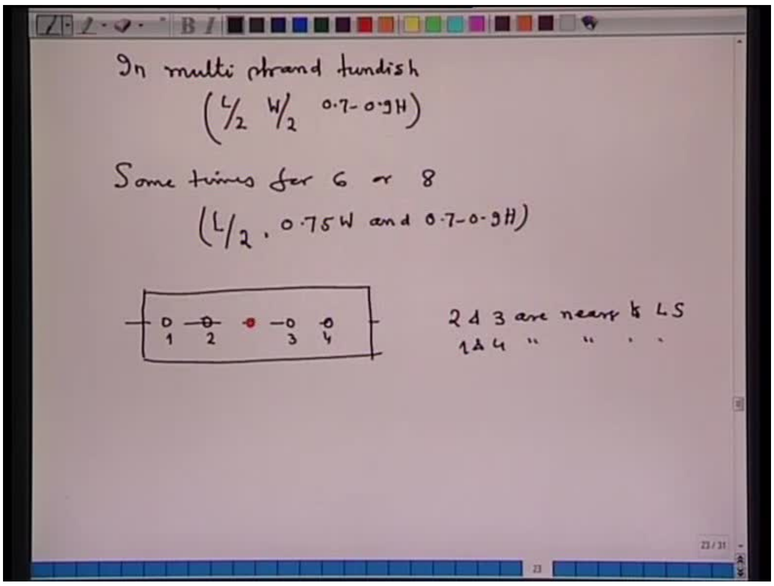

In multi strand tundish, ladle stream is located in the tundish at L by 2, W by 2 and 0.7 to 0.9 H location; that means, the stream is submerged into the bath; and also, the tundish nozzles are symmetrical on both sides of ladle stream; that means, if I have a 2 strand casting machine, then, one nozzle is on the left side of the stream, and another nozzle is on the right side of the stream, at equal distance from the ladle stream. Sometimes, for 6 or 8 strands, say, sometimes, for 6 or 8 strands machine, the ladle stream in the tundish is asymmetrical to the tundish nozzle, and this asymmetricity can be defined as, or the ladle stream can be located at L by 2, 0.75 W and at 0.7 to 0.9 H. Now, in multi strand casting, 4, 6, or 8 strand casting machine, the location of ladle stream is very important, because, if you look from the top of the tundish, then, it looks something this way. I show top of the tundish; this is the center line, and this is where, here, the ladle stream is hitting, with just at the center. And, one tundish nozzle is here; another is here; one is here and one is here.

If it is a 4 strand continuous casting machine, then, you can imagine that, the molten steel, which is entering into the nearby tundish, and molten steel stream that is entering in the farther most tundish, they may have a dissimilar temperature, as well as composition; and accordingly, the strand which is coming out, from all the four molds, will be dissimilar. So, in order to avoid dissimilarity of the strand, it is essential that, the temperature and chemical composition of molten steel, entering into the nearest nozzle and farthest nozzle, they are approximately same. So, in that, if I put 2, 1, 2, 3 and 4, so, I will call 2 and 3 are nearer to ladle stream, whereas, 1 and 4 are farther to ladle stream. All the four strands are placed below 1, 2, 3 and 4. So, if there is a variation in temperature and chemical composition, then, the strand will be dissimilar, and hence, that precaution is to be taken. The ladle stream is arranged such that, these thing does not happen.

Now, with this, another important issue is, now, how the heat flow in continuous casting occurs? Now, you know, you can simply think that, mold is the heart of continuous casting; the mold provides first solidification. It is the mold, where solidification begins, and on account of solidification, a partially solidified, with partially solidified strand, now, I can use the word strand, is withdrawn. What are the requirements? The strength of the solid shell, which is formed in the mold, should be very strong; otherwise, there will be, break up will occur.

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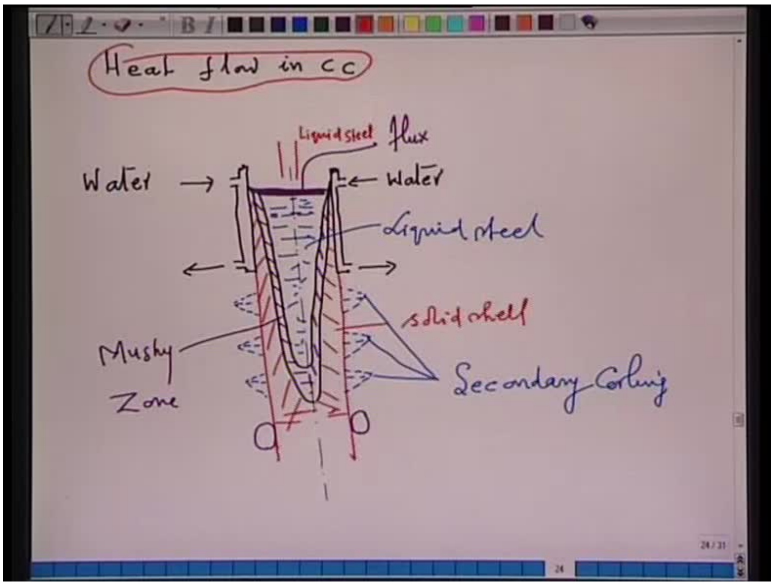

The solid shell, which forms in the primary cooling zone, or in the mold, is of very thin. So, the heat flow in continuous casting, heat flow in continuous casting, is important. I have shown here, the heat flow, which is occurring during continuous casting of steel; that is, when the steel is poured from tundish to mold, it is from there, the solidification begins. So, you see, here, this is the liquid stream, which is entering; this is the mold; this one, this unit, which is shown by the black, is the mold, and here, it is a water cooled mold. During cooling, a partially solidified strand is formed, and this red portion is shown the partially solidified strand. In the center of the mold, (refer time: 49:00) still, there is a liquid steel is there; that means, this partially solidified strand, is holding liquid steel; that means, this partially solidified strand, must have a very high strength.

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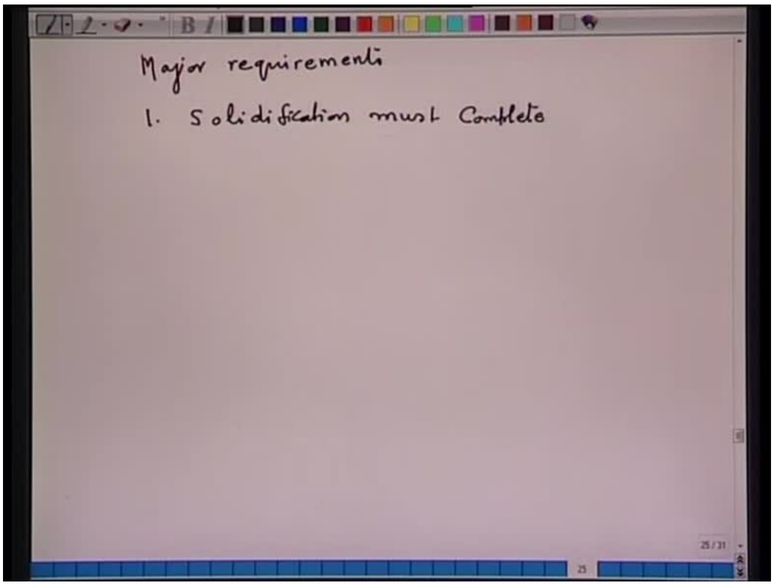

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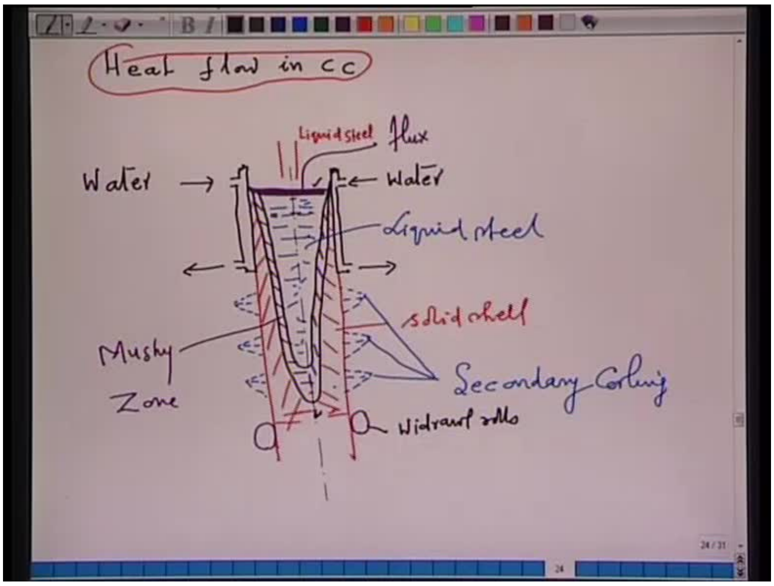

Near to the liquid steel, there is a mushy zone, that is being shown, and this mushy zone, it extends also, in the secondary cooling zone. So, first of all, the major requirements for heat flow, first of all, solidification must complete before the strand enters into the withdrawal roll; that means, the solidification, it begins from here, and it ends over here. So, these are the, say, withdrawal rolls.

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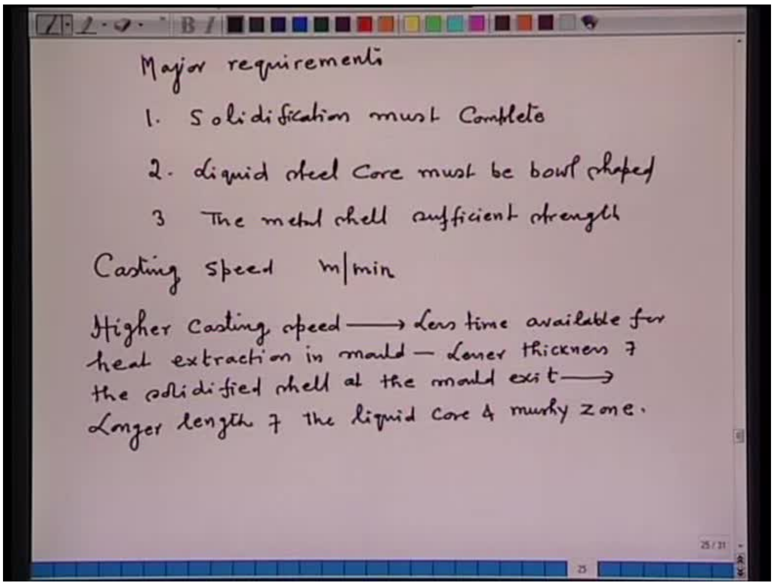

That means, the entire strand must be solidified, before it enters into the withdrawal roll. Second important thing is that, liquid steel core must be bowl shaped. With that, what I mean, this is the liquid steel shell, and this shape is a, sort of a bowl shaped, and this shape is necessary for solidification. Third important requirement is, metal shell in the mold, the metal shell which is produced in the mold, should have sufficient strength. If not, then, what will happen, the breakout will occur. So, therefore, the casting speed must be matched, with the rate of pouring of liquid steel from tundish to mold, such that, the solidification occurs completely, before the strand enters into the withdrawal roll.

Now, what is the casting speed? The casting speed is the rate of linear movement of the strand and it is given in terms of meter per minute. So, higher casting speed, which, one may be tempted to increase the productivity, what it leads to, you will be having less time available, for heat extraction in mold. Because, extraction of heat in the mold is the primary, important; that form the solid shell, which has to withdrawn. So, the primary cooling, that is in the mold, is of very important. So, less time available for heat extraction in the mold. So, what will happen, lesser thickness of the solidified shell will be there, at the mold exit.

As a result, what will happen, longer length of the liquid core, and what will be longer again, that of mushy zone. Therefore, the casting speed must be optimized. Now, what is important here, from consideration of the heat transfer in continuous casting, what has emerged as a most important issue, is that of adjusting the heat transfer condition. I repeat once again, unless, or the primary cooling in the mold does not form a metal shell of sufficient thickness, it will create problems during the further heat extraction mechanisms. So, the most important thing, is the casting, is the mold part. Now, the further things we will discuss in the next lecture.