Steel Making

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Module No. # 01

Lecture No. # 33

Solidification and Casting Processes

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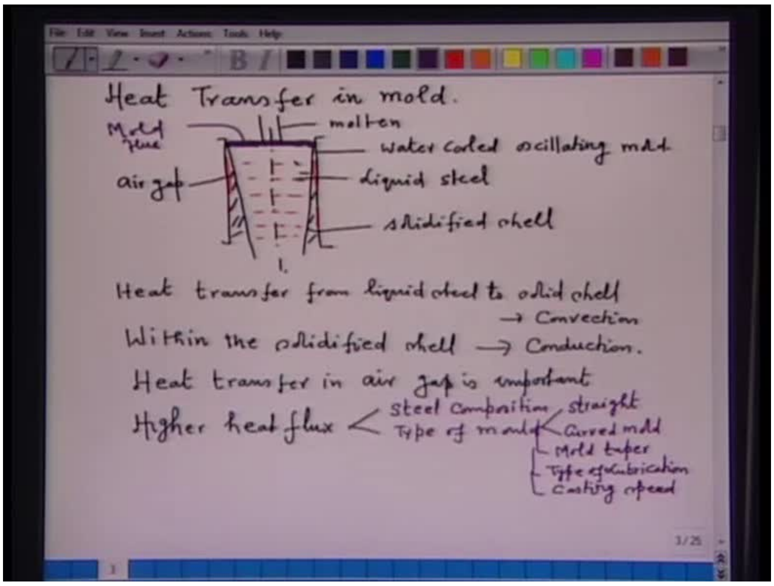

We continue our discussion on heat transfer in continuous casting. In that sequence, the first, is heat transfer in the mold, as I have shown in this particular figure. The molten steel enters from tundish into mold; that is, from here, the molten steel is entering. This one is the water cooled oscillating mold. Now, as the steel enters into the mold, a solid layer forms. As such, I have shown here, this is the solidified shell. As a result of heat transfer from liquid to the mold, a solidified shell forms. In the center, there is a liquid steel. As a result of solidification, and because of the shrinkage during solidification, and expansion of the mold, an air gap forms. This is the air gap. Now, this air gap maybe, continuous along the length of the strand or maybe discontinuous; it depends upon the oscillating characteristic of the mold and the expansion characteristics.

So, given this particular figure, the heat transfer steps in the mold, it consists of, that is, heat transfer from liquid steel to solid shell, and that is comprises of convection. What I mean is, here, the convective currents are here in the liquid. So, on account of that, heat will transfer to the solidifying shell; then, within the solidified shell and this heat transfer occurs by conduction. Now, as I have shown that, there is a formation of air gap between the mold and the solidified shell, as such, heat transfer in the air gap. Now, for all purposes, the heat transfer in the mold is very important. Now, why it is very important because, here, a solidified shell, or a partially solidified shell has to form. The shell must have sufficient strength, so that, it can sustain the liquid ferro-static pressure; because, as the, as the partially solidified strand is moving from the exit of the mold, the solidified shell should be able to sustain the ferro-static pressure of the liquid, which the shell contains.

So, it is therefore, the solidification in the mold, is a very important. In fact, the formation of solidified shell is a prerequisite for the successful casting of billet, bloom or slab. If we are able to extract heat at a faster rate, then, we can also increase the casting speed; that means, casting speed, strength of the partially solidified shell, they are all interrelated. And, they are interrelated with the, how fast, or how slow, heat transfer is occurring in the mold. Now, say, higher heat flux, it depends upon steel composition. Say, what is the composition of steel? Whether it is a peritectic, or eutectic, depending on that. Then, it also depend upon, type of mold; that is, whether we have a straight type of mold, and as I said to you in the last lecture, whether we have a curved type of mold; accordingly, heat flux will be affected. Then, it also depends upon, what is the mold taper. A very small mold taper is given, could be of the order of 1 percent, between the top and bottom of the mold, for the easy withdrawal of the strand.

So, mold taper is also important. Then, type of lubrication. In fact, the lubrication between the solidified shell and the mold, it makes the easy withdrawal of the strand, because, it reduces the friction. And, another factor that affects the heat flux, is the casting speed. You can understand yourself, higher is the casting speed, what will happen, and lower is the casting speed, what will happen. Again, they are all related with the heat transfer rate. So, heat transfer rate and casting speed, they are interdependent. Now, something about mold flux. You see, at the top of the liquid steel in the mold, this is a sort of a mold flux. This mold flux, the objective of putting mold flux is that, it melts and it drains down within the space, solidified shell and the mold. So, this mold flux has a very important role to play in continuous casting.

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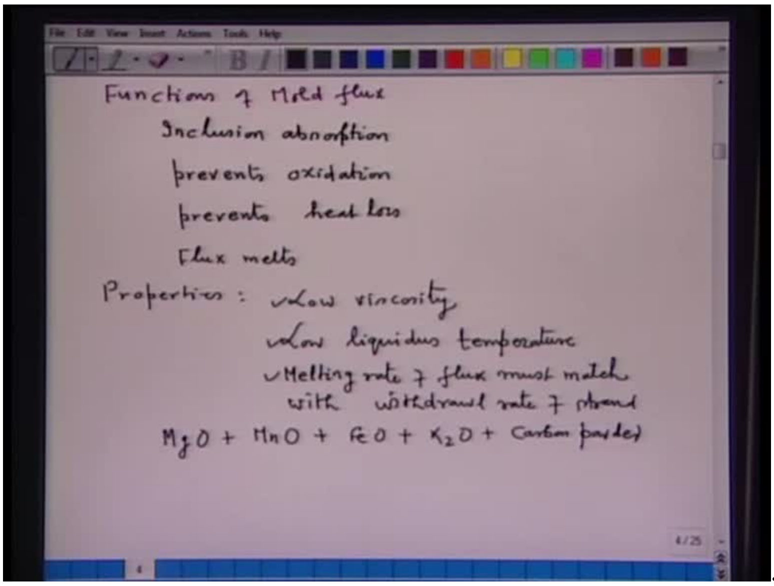

Let us see the function of mold flux. First, it helps in inclusion absorption; because, no sooner mold flux is added on the top of the liquid steel, it melts and due to stirring, or due to floating of the inclusion, it can be very well absorbed by the flux, which is molten, and which is kept on the top of the liquid steel. It also prevents oxidation. How it prevents, because, all the time, the top of the liquid steel in the mold, is covered by a slag. Therefore, the contact between atmosphere and the liquid steel is eliminated. Then, it also prevents heat loss, because of the slag, which has very low thermal conductivity. So, it does not allow much heat to be transferred into the surrounding. Then, now, this flux, it melts on the liquid, and the most important function that this liquid does, it is that, it enters into the air gap, and therefore, the air gap formation is, I do not say eliminated, but it is very minimized. Because, now, the air gap, which is created because of differential expansion of solidified shell and the mold, is filled by the lubricant. So, the chances of air gap formation is minimized. So, the, that means, the mold flux plays a very important role. In fact, for your information, I am tell you that, the provision of having mold flux, it helps during the continuous casting, because, at that continuous casting stage, some amount of inclusion can be made to float during continuous casting, because as long as liquid steel is available, as long as the agitation in the bath is there, the floatation of inclusion is possible.

In the mold, the central core is liquid; the agitation is provided by the tundish steel, which is submerged into the mold. So, the possibility of inclusion floatation is there in the mold. Now, what are the properties are required for mold flux? The properties which are required, it should have low viscosity, so that, it can flow (( )). Then, it should have low liquidus temperature. Why should it have low liquidus temperature? Because, then, it has to be molten at around 15, 1600 degree Celsius; that is important. Then, the melting rate of flux must match with withdrawal rate of strand. What does it mean? Flux is added all the time; it gets molten, and as the partially solidified strand is withdrawn through the bottom of the mold, the liquid flux, it enters into the air gap and to some extent, it may be entering along with the solid shell. So, continuous addition of flux is being done, so that, the top of the liquid is always protected by the slag. So, that is why, it must, the melting rate should be such, it should match with the withdrawal speed. Now, the flux, it may consist of M g O, M n O, F e O, K 2 O and sometimes, carbon powder is added; sometimes, carbon powder is added into the flux.

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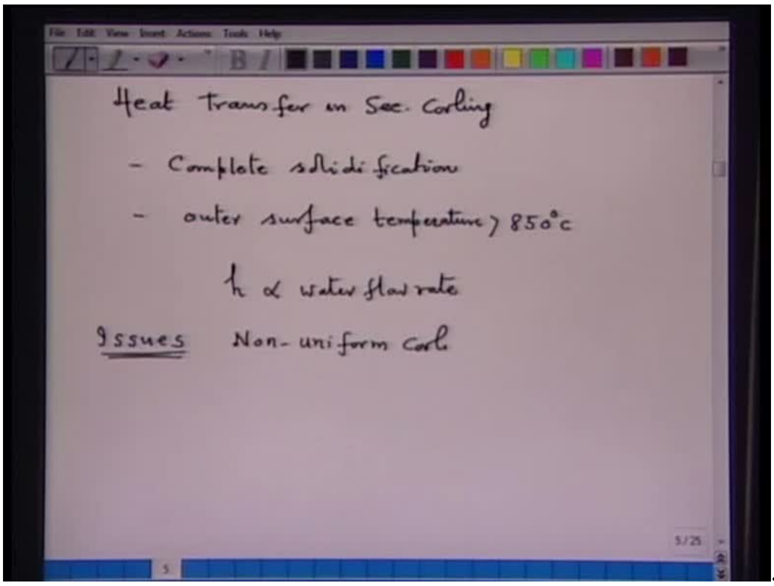

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So, this is about the heat transfer in the mold. Now, heat transfer in secondary cooling. As the partially solidified strand is withdrawn from the mold, it is subjected to the intense cooling, which is provided by the water spray. It is the water pressure, it is the location of the nozzles, which are producing water spray, distance between the two nozzle, because, it is not one; there could be several nozzle, which are placed one after the other; so, the distance between the two nozzles; so, all these affect the secondary cooling of the partially solidified strand, which is withdrawn from the mold. So, all these parameters, pressure of water, distance between the two nozzles, or distance between the two spray, or the location of the nozzles, all are very important; so that, one is, or one gets the complete solidification of the strand. So, the, in the secondary cooling zone, in fact, complete solidification occurs, in this particular range. Then also, air is taken, so that, outer surface temperature, so that, outer surface temperature of the strand, it remains somewhat greater than 850 degree Celsius in order to avoid volumetric expansion caused by transformation from austenite to ferrite,

If the temperature has dropped, then, austenite to ferrite transformation may occur, and that will result in the formation of cracks. So, the arrangement of water sprays produced by the nozzle is a very important step, for having a better quality of the cast product. Because here, if you are looking for hot direct charging of the strand, which is billet, bloom, or slab, then also, the temperature at the exit of the continuous caster, again, plays a very important role. The heat transfer rate is decided by the heat transfer coefficient; then, simply heat transfer coefficient is proportional to water flow rate. So, accordingly, higher is the water flow rate, higher will be the heat transfer coefficient; more heat will be transferred. But then, one is to see that, the heat is transferring from center to the outward. So, the chances of rapid cooling may also cause the thermal stresses in the strand, and as a result of which, the cracks may develop.

So, these things have to be optimized. So, issues in secondary cooling: one issue is that, non-uniform cooling. Non-uniform cooling means, width is very large, for example, of a slab; thickness is relatively very low. For example, 2000 millimeter is the slab width, around 150 or 200 millimeter is the thickness. So, placement of the water spray is important, so that, you should have a uniform cooling; and, a uniform cooling will not result in thermal stresses, but a non-uniform cooling will result in thermal stresses on the surface and tendency for surface cracking is there. So, this is about the heat transfer in the secondary cooling zone.

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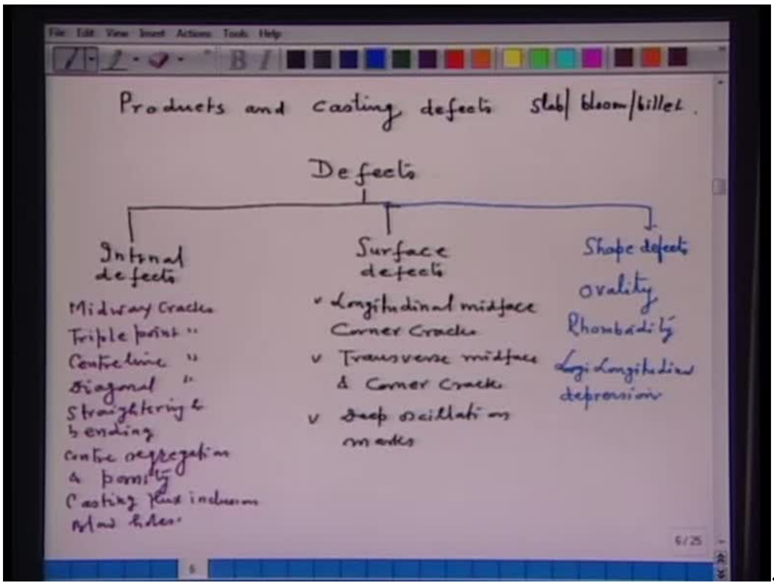

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Now, since you have seen, the continuous casting is very fast; a 150 tons of steel can be transferred in 50 minutes in the form of slab, bloom, or billet. The entire strand is in the state of motion. So, you pour the liquid steel into the mold; the mold oscillates. The moment the solidified shell forms in the mold, it is withdrawn, subjected by several forces. Right from the top of the mold, to the cutter of the continuous caster, the strand is continuously in motion. There could be frictional forces; there could be non-uniform cooling; there could be lack of lubrication; several things could be there. So, it becomes very important to understand the product, and casting defects well. The products are very clear; it is slab, bloom, or billet. The defects, they can be classified, say, first, is the internal defects. Now, internal defects, they consists of cracks. Because of the continuous motion of the solidified strand, and the liquid core is getting solidified during the motion, there is every chances of formation of cracks during solidification of molten steel, to continuously cast slab, billet, or bloom.

Internal defects, major will be, in the form of cracks. Now, the cracks, you can have midway cracks, triple point cracks, center line cracks, diagonal cracks, then, straightening and bending, crack resulting due to straightening and bending; because, you have to bend it; first, you bend it; then, you straighten. So, all, everywhere you put a load on the solidifying strand; then, center segregation; center segregation and porosity; then, casting flux inclusions. Because you have put flux at the top of the mold, when it becomes liquid, from the inclusions may be drawn, because of the motion of the liquid.

Then, you may have blow holes; then, cluster type of inclusions, because, the molten steel is poured from the led, from the tundish, into the mold by submerged entry nozzles, and the alumina inclusions, they may clog on the walls of the submerged entry nozzle, and they may fall as a clog. So, this may also appear in the casting strand.

Now, say, another is a surface defects. They appear on the surface. Surface defects, say for example, longitudinal mid-face cracks, corner cracks, then, transverse mid-face and corner cracks; then, deep oscillation marks. From where they are coming, because, the mold is oscillating at a certain frequency. Sometimes that, these oscillation marks are deep on the surface, and if the strand is reheated for rolling operation, that area will be oxidized. So, many times, you have to scrap, so that, you can remove the deep oscillation marks. Next could be, shape defects. Here, ovality; because of the several pressure, thermostatic pressure, rolling pressure, straightening, bending, all, it may not have the shape, which you thought; a billet, or bloom, or slab; or rhomboidity, or you have longitudinal depression.

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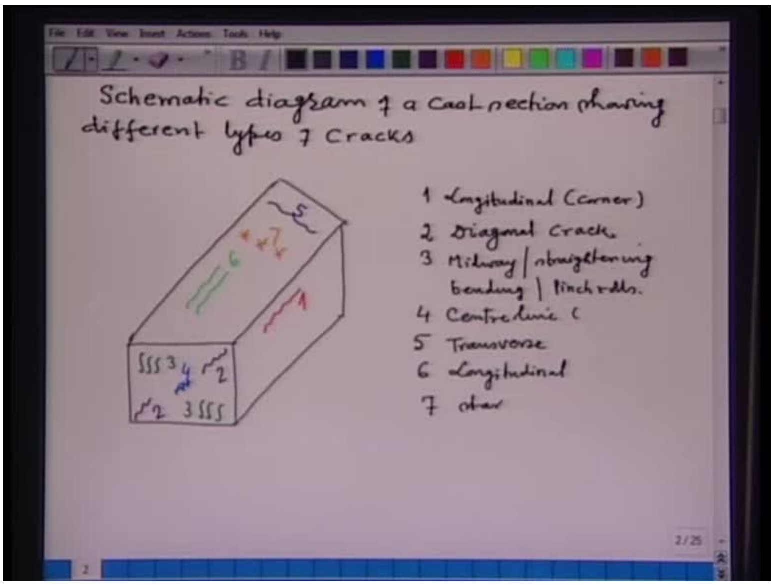

So, what is the origin of cracks? Now, before you go, I would like to show you the schematic diagram of a cross section is showing different types of crack. Now, one is the longitudinal crack, longitudinal corner, which is shown by the red mark. Second is a diagonal crack; third is the midway, or straightening, bending to pinch rolls; then, fourth is a center line crack, which is shown by the blue color; then, fifth is the transverse, and sixth, again, the longitudinal, and seventh, a star crack. So, these are the, say, different types of crack. I thought, I will just show you where they are present, and so that, you can appreciate. Now, say, let us see, how the cracks are originated. So, origin of cracks. Of course, anything has to crack, one should have stresses; without a stress, material will not crack. Now, as you understand, or as you observe continuous casting, everywhere, the solidified strand is subjected to the stresses. And, if that, one is to manage the stress, such that, the cracks are minimized, and you get a better quality strand.

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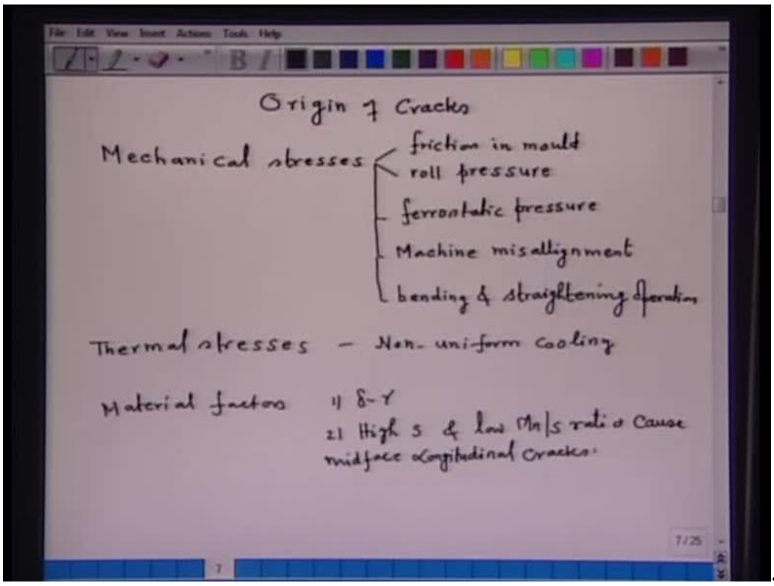

So, the origin of crack. The first is, say, you have the mechanical stresses. Now, this mechanical stresses, that is due to motion; that is where, we are very clear. Now, we have to analyze our continuous casting, wherever mechanical stresses are producing, those point has to be taken care of, so that, the mechanically stressed induced cracks are not present. So, first, they will be at the friction in the mold; because, the solidified shell, or partially solidified shell in the mold, is constantly in touch of the mold; mold is oscillating; strand is also moving. So, a friction can cause crack. Then, roll pressure; because, for the withdrawal of the strand, you have to put some roll and pressures to put over there. Then, ferro-static pressure, and for that purpose, the strand of the solidified shell, particularly in the mold, should have sufficient strength, so that, the ferro-static pressure, which is exerted by the liquid, that shell can sustain. Later on, in the secondary cooling zone, the shell of sufficient thickness has developed.

So, probably, the effect of ferro-static pressure may not be that high, as compared to, in the mold. Fourth, crack can often machine misalignment, because, continuous casting is a resultant of arranging ladle, tundish, mold, water spray, that is, secondary cooling zone, cutter and so on, and anywhere, if some sort of misalignment is occurred, it can result in the problem. Then, bending and straightening operation. Now, you can imagine, you have to bend, apply the force; again, you have to straight, you have to apply the force again. So, these are the certain, which I thought, could be the mechanical stresses. The more, after observing the continuous casting machine, if you find, you may add it, so that, you understand. Now, another stresses that can be induced, thermal stresses. Now, thermal stresses will be induced, because of non-uniform cooling of the strand. Once the strand is withdrawn from the mold, it is subjected to the intense cooling of the water spray. The location of the water spray, the distance between the water spray, and after you spraying the water, the water will roll out; there could be a difference in the water temperature, at the time when it impinges and at the time when it leaves.

If the distance between the two sprays is large, then, after getting cooled by the first water spray, then, the strand can be reheated, before it enters into the second spray. So, these are all, though are the small things, but that all result in the, so called, non-uniform cooling; that is, this non uniform cooling, as obtained by the location of the water spray, by the draining of the water of the top of the strand, water pressure, and so on. And, this non-uniform cooling, will result in the stresses and hence the cracks also. Third could be, material factor. What material factors means, if the material itself, shows some transformation from liquid to solid, and the expansion is associated, then, it may result in cracking. For example, in iron carbon system, the delta to gamma transformation is one such thing. Second, high sulphur and low manganese-sulphur ratio, cause mid-face longitudinal cracks. So, one has to adjust these particular things. Now, here, the surface cracks are more critical, than internal cracks. You know, the internal cracks can be welded up during rolling operation; whereas, surface cracks, on heating the slab, will, the material under the surface crack, or wherever the surface cracks are there, the material will be oxidized, during heating. So, surface cracks are more critical, than internal stress.

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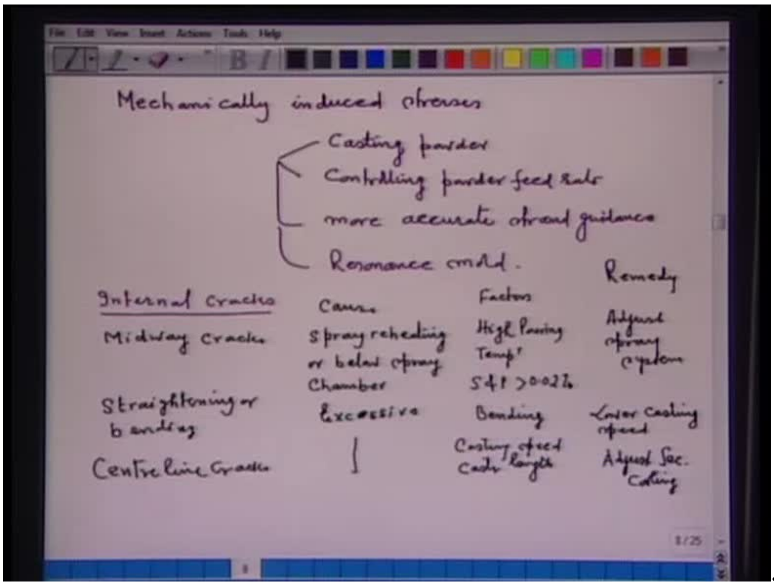

Now, the mechanical stresses can be eliminated, or can be reduced, by improving mold practices. So, what are the, say, mold practices? Say, mechanically induced stresses can be partially eliminated by improved mold practice, and the improved mold practice consist of using casting powder, then, controlling powder rate, controlling powder feed rate, then, more accurate strand guidance and by having resonance mold; whereas, the (( )) induced cracks are, can be minimized by having more uniform cooling; that means, by having the so called, air water spray, that is, by having the mist spray cooling and some of the continuous casters, they do have the mist spray cooling in order to have the uniform cooling of the strand in the secondary cooling zone. Now, some of the reasons for, say, internal cracks, I will give you few. The rest, you can see from the literature and make yourself update; for example, you say, internal cracks. Among the internal cracks, I will take few types, give you the factors that influence and then, some remedies, which we think it is possible.

So, first, I will consider, for example, midway crack. The cause of its formation is the spray reheating, or below spray chamber. What does it mean? It is the distance between the two spray is important, where the strand is moving out of contact of water. So, the strand gets reheated up, because the heat from inside of the strand is coming out and when it does not find any water, then, the top of the strand can be heated up. So, that is called the reheating of the strand. The factors that influence this particular thing, is a high pouring temperature, or when sulphur and phosphorous is greater than 0.02 percent.

What is the remedy? Adjust spray system to minimize reheating or lower pouring temperature. If you see, for example, straightening or bending crack, this may be caused due to excessive deformation; excessive deformation near solidification front, due to straightening or bending. The influencing factor is the bending on liquid center and the remedy could be lower casting speed.

For example, if you take center line cracks; the cause of center line cracks, for example, in slabs, bulging of white face at the liquid crater tip; in billets rapid cooling of center region below the liquid pool, that could be the causes, as I have said. Now, about the factors that affect, the casting speed could be one of the factor; casting speed, caster length, spray water intensity, secondary cooling, all these factors, they may affect the center line cracks. So, the remedy could be, we have to adjust secondary cooling; we have to reject the roll. So, these are some causes, and factors, and the remedy for some crack; however, they are so many type of internal cracks, that one can see in the literature, and one can update those things; these are the few examples, that I have given.

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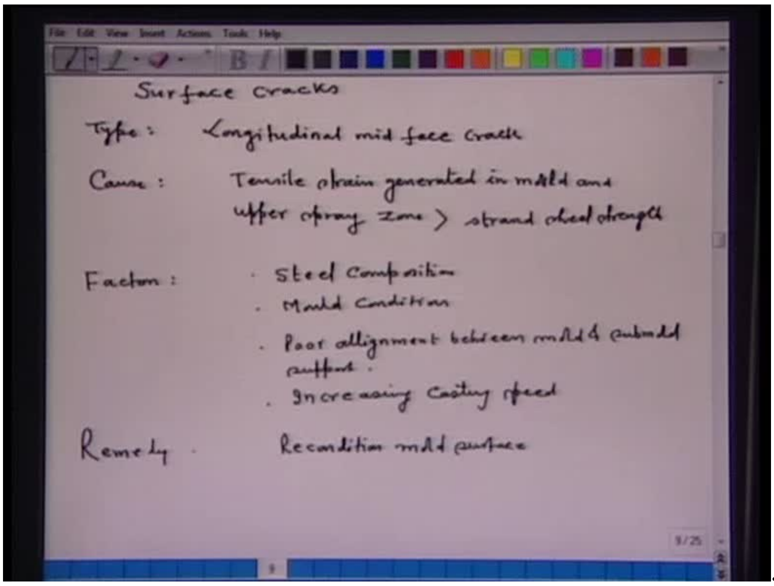

Now, similarly I give a few examples for surface cracks. Surface cracks, the types and remedies. Say, type, take for example, longitudinal mid-face cracks; cause, it can be tensile strain, generated in the mold, and upper spray zone is greater than strand shell strength; that means, when the tensile strain generated in the mold and upper spray zone, when it is greater than the strand shell strength, naturally a surface crack will form. Now, the factors that influence, they cannot…There could be multiple factors, for example, steel composition could be one factor; mold condition, improper cooling, loss of taper, irregular mold oscillation, they all could be the factors, that can influence the mold condition, and hence, the longitudinal mid-face crack; or, poor alignment, poor alignment between mold and sub-mold support, and increasing casting speed, these are the some of the reasons, or some of the factors, that can influence the formation of the longitudinal mid-face cracks; or, there could be other, which one has to analyze. Now, the remedy. Remedy could be, a recondition mold surface and adjust mold condition to ensure uniform cooling, reduce cooling in the upper spray zone, because, just after the mold, secondary cooling is done. So, if you adjust the cooling over there, change mold powder, also, if possible, or the check shrouding system also.

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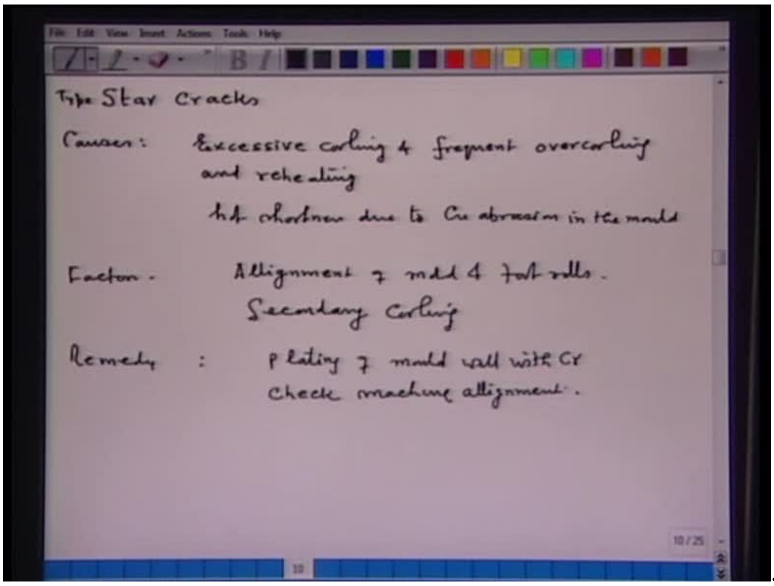

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Now, if we take another example, say star cracks. This is the type, star cracks. The causes, excessive cooling, and frequent over-cooling and reheating; this can also be due to hot shortness, due to copper abrasion in the mold. The copper has a melting point of 1078 degree Celsius. Factors that influence - alignment of mold and foot rolls, and secondary cooling. Remedy, one can do, for example, check mold walls with, now plate, say plating of mold wall with chromium could be one of the remedy; another, check machine alignment.

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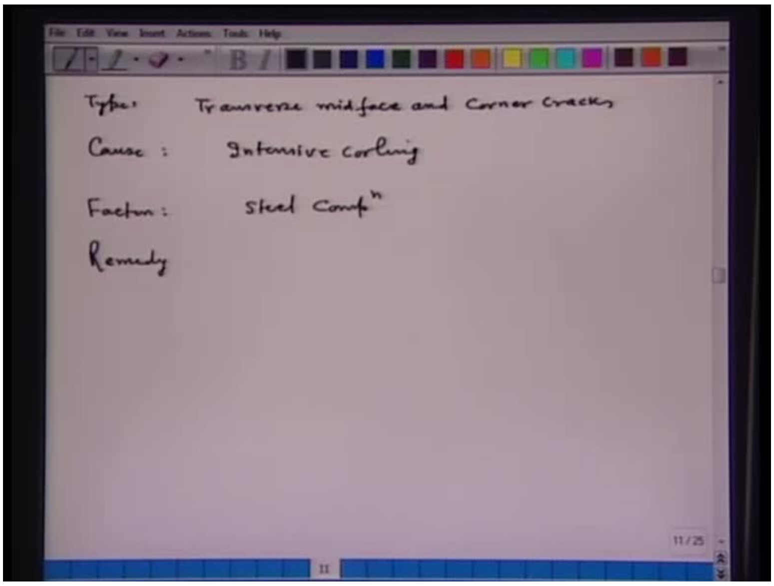

Now, if you see, still one more type of crack, for example, type, if I take, say, transverse mid-face and corner cracks, the cause or causes, intensive cooling, frequent local over cooling, straightening of the strand within unfavorable temperature range between 700 to 900 degree Celsius, can all cause the formation of the above type of crack. Now, the factors which can influence steel composition, one has to check the steel composition with reference to Aluminium, Vanadium, Niobium and Manganese greater than 1 percent, they are highly susceptible to these cracks. Remedy, you have to check by spray water flux, to ensure minimum cooling or reheating cycle, and you have to maintain the surface temperature at least above 900 degree Celsius. So, what I have shown, these are the some types of surface cracks or internal cracks and their remedies. There are more type of surface cracks, or internal cracks. You can consult the references which I will be giving you at the end of these lectures, and you can update yourself. Now, we have seen the defects in the modern continuous casting plant. So, many developments have taken place for improving the quality of the continuously cast product.

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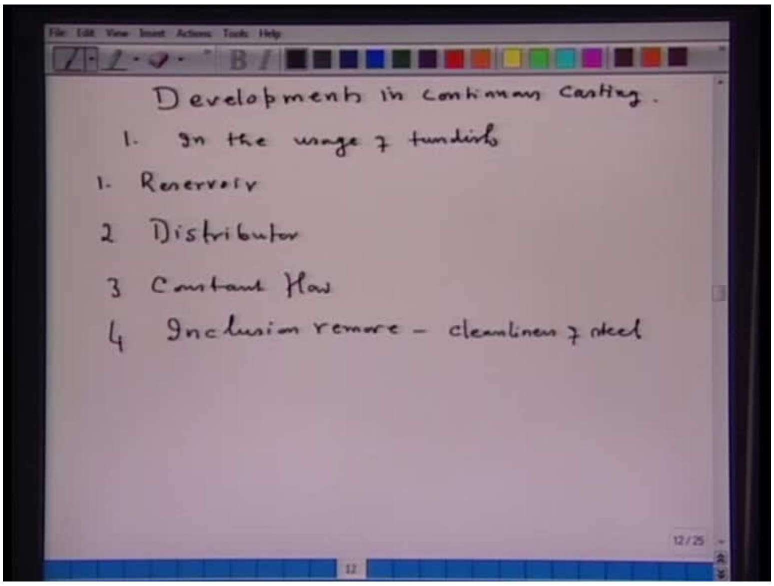

Let us take it now, say development in the continuous casting. Now, the first development that took place is, in the usage of tundish; because, in the original installation of continuous casting machine, tundish was considered to be a source of supply of molten steel to the mold; that means, it was considered to be a transferring vessel between ladle and tundish. But, with the modern, or in the modern continuous casting machine tundish is no longer a transfer vessel, but it can perform several functions. So, I am listing the functions, which a tundish plays in a modern continuous caster. The first function is, it acts as a reservoir, and in order that this function is being fulfilled during the continuous casting, an optimum capacity of the tundish is desirable. Now, why this optimum capacity is desirable, because, nowadays, there is a concept of sequence casting; that is, once ladle is emptied, continuous casting is not stopped; the next ladle is brought above the tundish.

So, the time that is taken place between replacing one ladle and bringing another ladle, in that period, tundish supplies the molten steel to the mold. So, that is called sequence casting and three sequences or four sequences, depending on that, during the idle period, when there is no ladle on the top of the tundish, then, the mold gets molten steel from the tundish. So, in that connection, the tundish capacity is very important, and tundish capacity should be designed such that, between the idle period, the sufficient amount of steel is in the tundish, so that, the continuous casting process goes on. So, the sequence casting and ladle scheduling is important in developing the tundish capacity. Second, it also acts as a distributor; because, in a multiple strand casting machine, you have 4 nozzle, tundish nozzle, 6 tundish nozzle. So, a tundish, it distributes the molten steel in all the strands. Important is that, super heat in each strand should be same; chemical composition should be same. So, in its distribution role, strand similarity is important, and when we have a strand similarity, then, all the strands will be similar and quality problems will be less. Also, in this distribution, particularly for multi strand continuous casting machine, the strand breakout chances should be minimized, and that can be done when, the tundish supplies steel of the same temperature, and of the same chemical composition to all the molds. So, that is the function of the distributor.

Third, it feeds steel at a constant flow rate. For that purpose, constant head of molten steel is needed in the tundish. Fourth, which has been explained in recent years, that is the inclusion removal. And, this acts to cleanliness of steel, and as a result, you have reduced clogging of the submerged entry nozzle for feeding molten steel from tundish to mold. So, you see now, the tundish, in the original installation of continuous casting machine, was simply considered to be a transfer vessel. In the modern continuous casting machine, in addition to its function of transfer vessel, it performs several functions. Now, the idea of performing of several function is, has come from very simple reasoning, which is as follows. Now, you imagine a tundish capacity of 30 tons, and if the casting rate is, let us say 4 tons per minute, then, very simple, if I divide 30 tons by 4 tons per minute, then 7.5 minutes, that come, it is the residence time available to me in the tundish, of the liquid steel; that means, on average, the steel spends 7.5 minutes in the tundish before steel exits the tundish. So, the availability of 7 and half minute is the key concept in exploring the various functions of the tundish, and to extend the tundish, to contribute for better quality of the steel. So, that is what the objective behind this.

Now, in order to fulfill this objective, it is utmost required that, during the continuous casting process, the flow pattern, or the flow of liquid steel in the tundish should be modified such that, all these functions can be fulfilled to our expectations. For example, the inclusion removal, it requires the flow pattern in the tundish to be very slow. So, you require time to give time to float out the inclusions. If you want to carry out some mixing, then, you require a tundish flow pattern, or the liquid steel in which it flows from the entry to the exit, should have high velocity. So, these differential requirements, they led to the modification of existing tundishes, and this aspect, we will discuss in the next lecture.