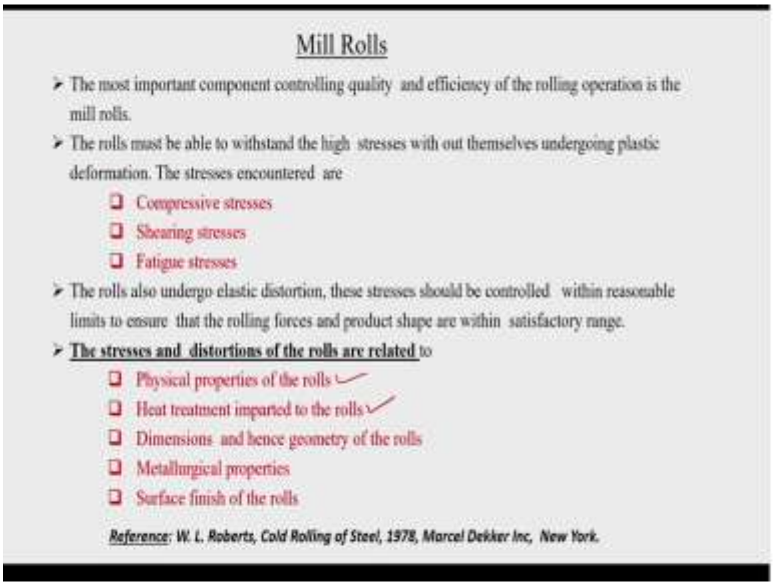
Plastic Working of Metallic Materials
Dr. P. S. Robi
Department of Mechanical Engineering
Indian Institute of Technology – Guwahati

Lecture - 22
Rolling Mills

So, this lecture though we have discussed most of the things in rolling, today we will discuss about the mill rolls. What are its facilities and what are the factors, which has to be considered about the mill? There are various other things okay, so far we discussed about the analysis of the rolling and then what are the load required and other things but when you are rolling mill, there are other problems which are coming to picture.

(Refer Slide Time: 00:54)



So, the most important component controlling the quality because what is say important is the quality of the product which comes out. So, the most important component controlling the quality and the efficiency of the rolling operation is this mill rolls because see finally when you want it to fix the sheet material, your surface finish should be very good but if it is a rough rolling where you have to reduce it, the surface feature may not be important.

But ultimately what happens is that people always look at, your customers always look at the quality of the product. So, if it is a sheet material, you need to have a very good surface finish, not only surface finish, the thickness across the length of the sheet should be uniform, so that is another important factor. So, the rolls must be, here many times if the rolls are not proper, you may find that surface finish is not good.

There is going to be large variation of thickness of the sheet and which will not be acceptable by the customers. These rolls is the, that is why the roll is the most important thing which decides quality and not only that, if the roll quality is not good, that is going to affect the rolling operation. We will come to that how it is going to affect okay, say something like roll flattening if it takes place or roll bending if it takes place due to a high pressure which is coming into high load which is going to come.

Then, also you have problems, so in that case your energy required for the rolling operation will increase. So, these rolls must be able to withstand the high stresses without themselves undergoing plastic deformation say because you are going to deform it and the pressure at the contact area is going to be very low and if at that time, the roll undergoes a plastic deformation, quality matters.

So, the stresses normally during rolling, the rolls encountered are compressive stresses as a result of your workpiece material as a result of the reaction between the workpiece material and the roll. There are shearing stresses which are going to come because material is going to plastically deform. There is going to be a change in the dimension or the material flow. So, shearing stresses are coming.

And it may that high stresses may also result in shear stresses of the roll. Similarly, at one instant, you are in contact at a point is in contact with the workpiece material, which is hard, it may be hot, all those things are coming into picture. The next time, it loses the contact and then there is a stress relief. So, there is going to be reversal of the stresses and this reversal of the stresses due to that there will be fatigue stresses generated inside which may result the life of the rod.

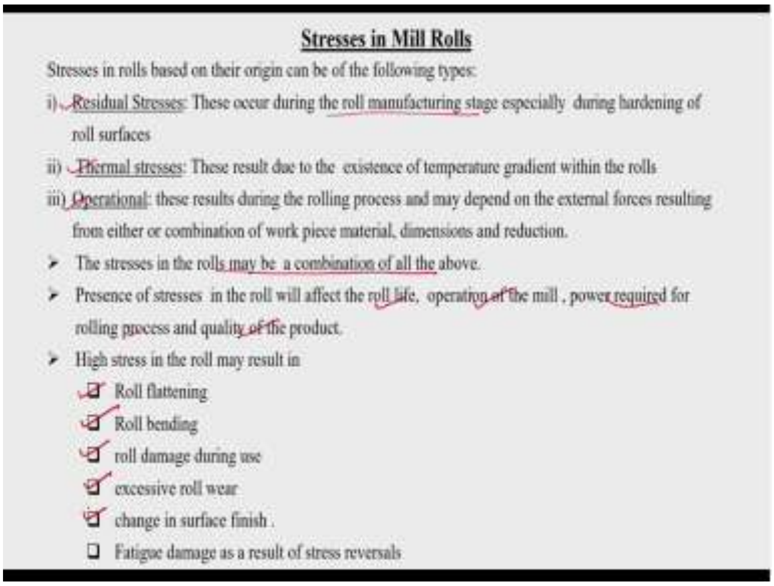
Now, because of the high stresses which it is encountering, the rolls also undergo elastic deformation. Normally, it will undergo elastic deformation and these stresses, elastic stresses should be controlled within reasonable limits to ensure that the rolling forces and product shape are within satisfactory range because if there is going to be elastic deformation of the roll at the point of contact then your shape will be affected.

Because along the length of the roll, this will be varying and so hence the thickness also may vary, you may encounter with very high energy required for because rod radius apparently it changes. The stresses and distortions of the rolls are related to one is the physical properties of the rolls, the heat treatment imparted to the rolls, whether it is very hard and whether it is really elastic whether it is hard so that it will not deform and the dimensions and hence geometry of the rolls.

If the roll diameter is very large, you may require very high forces but if the roll diameter is very less, you will require only very low forces through further deformation but then if the roll diameter is less, there is going to be roll deflection. So, you have to have backup rolls. There due to the reaction at the, your working roll and the backup roll, so there may be elastic deformation which is taking place.

So, all these things has to be taken into account. Then, the metallurgical properties of your workpiece material as well as the rolls and surface finish of the rolls.

(Refer Slide Time: 05:43)



So, these are the, so the stresses and distortion you will find that it depends upon all these things. So, in the stresses when you look at what are the stresses inside the mill rolls, say these stresses based on this origin, we can just categorize into residual stresses, thermal stresses and operational stresses. The residual stresses occur during the roll manufacturing stage and that too during the heat treatment process.

Because your surface hardness has to be very high, otherwise material may deform, so you may have to give a surface hardening heat treatment, sometimes instead of surface hardening you may go give a through and through hardening, through hardening process also you may give it, most of the case that is already being done so that you ensure the uniform hardness at their all surface, you may have to go through hardness heat treatment.

So, in that case, there is chance of a residual stresses at the surface at the roll may be near to a surface as well as at the inside it can happen. So, these are the residual stresses which will be there and that may result in the roll life. Another type of stresses are the thermal stresses, so these result due to existence of a temperature gradient within the rolls especially during heat treatment, the thermal stresses will be generated.

Because most of the time for all diameter is quite large, the volume of the roll is very large, so when you are doing the quench hardening, so at the surface it cools off very fast but in the center it is not cooling that fast, so naturally there will be thermal stresses. There is a temperature gradient which is going to take place along the radial direction of the rolls and that will result in thermal stresses.

Now, another type of stresses are, the stresses due to the operation. So, these results during the rolling process and it may depend on the external forces resulting from either the combination of the workpiece material, workpiece and the roll material, the dimensions and the reduction which are given into that okay. So, all these things matter, so when you are depending on a roll diameter also.

It will for a same reduction you may have, your contact link may be very large, so all those things will happen okay. So, the stresses in the rolls may be a combination of, may be a combination of all the above 3 types of stresses and the presence of the stresses in the roll will affect the roll life, it will affect the operation of the mill, the power required for the rolling process and the quality of the product.

So, it is not that it is just it will affect only one of these, so it will affect all these properties. So, if the stresses are high inside the roll, your roll life will get reduced. If the stresses in the roll is high, then it will affect the operation of the roll okay and because and then the power required for the rolling operation also and quality of the product also it will be affecting. So, high stresses in the roll may result how it is going to affect that is what I am telling.

High stresses in the roll may affect the roll flattening because in the workpiece the resistance is very high, then the reaction of the roll will be very high so that there may be a small amount of roll flattening, which is going to take place. So, when the roll flattening take place, the radius of the roll increases, apparently it increases and when it increases the contact length keeps on increasing, so that will result in a higher energy.

Because if you wanted a roll with a larger radius, then your energy required will be very high because the contact length is going to, contact area is going to be very high okay. So, that will affect your operation of the mill, the power required for the mill. Now, if the stresses are high, the reaction when your stresses due to the work hardening behaviour of your workpiece and the roll length is very large and your billet is at a small area only.

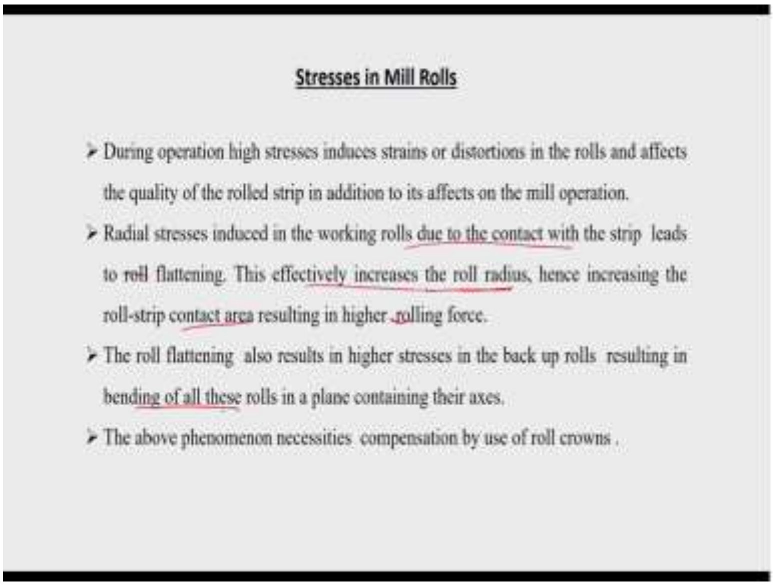
Then, what will happen is that there is chance of roll bending, so when the roll bends, you will find that non-uniform cross-sectional area is taking place of your product. So, the thickness of the product, there will be variation in the thickness of the products are all due to the roll bending. The roll damaged during use because if there was high residual stresses inside that, material becomes extremely brittle and then the chance of damage occurring like spalling and other things can take place.

So, in that case that also will affect the roll life. Now, if the stresses are high, if the workpiece is very high work hardening and other things, there is going to be a relative rubbing action or relative motion between the workpiece and though see you know that from entrance to the neutral axis, there is a relative motion which is taking place and from neutral access to the exit, there is going to be a relative motion between the workpiece and the dye.

So, only at the neutral axis only there is apparently there is no relative motion, all other places the velocity of the roll and the velocity of the workpiece material, it will be varying. So, that will result in excessive roll wear if your workpiece material is strain hardened that will result in excessive roll wear and the life of the roll will be getting affected. Then, change in the surface finish.

So, your high stresses may result in a non-uniform surface finish that also may come. Similarly, when the high stresses are there, the fatigue damage it may happen very fast because of the high stress reversals, which are taking place.

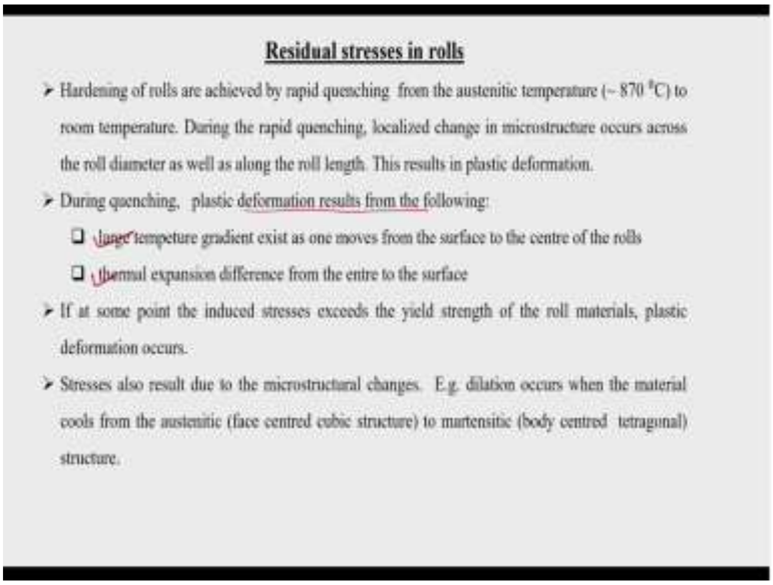
(Refer Slide Time: 11:56)



So, when you look at the stresses in the mill rolls, during operation how these comes, say high stressors induces strains of distortions in the roll and affect the quality of the rolled strip in addition to its effect on the mill operation. The radial stresses induced in the working roll due to the contact to the strip leads to roll flattening. This effectively increases the roll diameter. As I mentioned recently, it effectively increases the rolled radius and hence increasing the roll strip contact area resulting in higher rolling force.

So, this is going to affect okay. Then, the roll flattening also results in higher stresses in the backup rolls resulting because the contact area is high, so your reaction force is going to be very high, so that will result in the higher stresses in the backup rolls resulting in bending of these rolls in a plane containing their axes. Then, the above phenomena necessitate compensation by the use of roll crowns. So, all these things are coming.

(Refer Slide Time: 13:03)



Now, the residual stresses in the rolls. What is the source, how it happens? We mentioned that residual stresses are as a result of the heat treatment process. The hardening of rolls are achieved when you look at the through hardening of the rolls is normally a rolling mill that mill rods are not surface hardened, it is through hardened okay.

So, hardening of rolls are achieved by rapid quenching from an austenitic temperature something around 870 degree depending upon because these are alloy steels. So, your austenitizing temperature is going to be very high. So, from that high temperature to room temperature, you are suddenly quenching the material okay. So, during this rapid quenching, localized change in the microstructure also occurs.

Two things are happening; one is there is a localized change in the microstructure from a face-centered cubic structure that is austenite having a face-centered cubic structure at the surface because of the sudden water quenching or sudden quenching or sudden cooling. It transforms to a body-centered sorry face-centered tetragonal structure sorry base-centered tetragonal structure. So, this is what is going to happen.

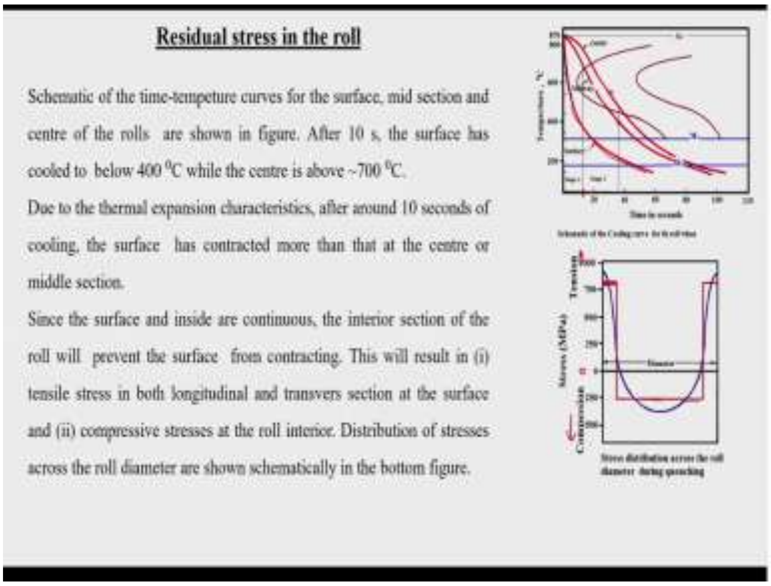
So, in that case, this phase transformation is accompanied by a change in the volume that is one. Second, at the surface, the temperatures has suddenly cooled but inside the temperature is still remaining high because it has to come out by conduction. So, that is also going to affect. So, microstructure changes across the roll diameter as well as along the roll length and when that is happening, if there is a change, it may result in the plastic deformation of the rolls.

So, during quenching, the plastic deformation results from the following; one a large temperature gradient if it is especially with larger diameter rolls, if there is a larger temperature gradient exists as one moves from the surface of the roll to the center of the roll during the quenching stage and when the larger temperature gradient exists, naturally there is going to be a change in volume and there is going to be a plastic, we will come to that how it is.

Then, another is the thermal expansion difference because the surface is cool to very fast from that high temperature it contracts but the inside it is not cooled that fast, so the amount by which it has contracted at the center is very less okay. So, there is going to be a differential thermal expansion behavior from the surface center, this also will in the plastic deformation inside the material okay.

If at some point, the induced stresses due to these two phenomena, if it exceeds the yield strength of the roll material, naturally the residual stresses if it exceeds the yield strength of the roll material, then plastic deformation at that point will take place. It is going to deform plastically. Then, the stresses also result due to microstructural changes. That is dilation occurs when the material cools from the austenitic to martensitic temperature.

(Refer Slide Time: 16:28)



And you will find that there is something around a 4.5% approximately variation in the volume change. So, how this comes? We have to explain it with respect to the cooling curve okay. So, I have just for the simplicity CCT diagram and the cooling curve everything has just schematically represented. So, do not take these values which have been shown here, it is a schematic representation to have an idea only it has been put up.

The schematic of the time temperature curve for the surface at the surface at the mid-section and at the centre of the rolls are shown. When it is suddenly quenched and you look at what is the temperature variation at the surface, you will find that temperature variation of the surface is along this curve because it is in direct to contact with your quenching medium, which is water or oil or air.

The cooling is very fast at the surface because it is directly in contact with the quenching medium whereas at the center it is not in direct contact with the quenching medium or maybe at the mid-section also it is not in contact with that. So, from the mid-section or from the center of the roll, the heat has to be transfer only by conduction okay. So, that conduction is a slow process compared to the convection.

So, surface will be cooled very fast whereas the mid-section, this is a mid-section curve and this is a center, the temperature drop will not be that fast, so but if you look at this temperature at this time there is a big difference which is there. So, maybe let us say after 10 seconds if you look at that the surface is cooled to say below 400 degree centigrade. Of course, this depends upon the thickness of your piece.

And whereas at the mid-section, it is something maybe around 700 or approximately whereas at the center, it is still higher just reaching to 800 only. So, these are 727 is for a plain carbon steel, the authentic to your pearlitic transformation to my eutectic temperature is 723 okay. So, that means this is much higher. So, that thing the surface has contracted more due to this coefficient of expansion, also shrinkage which is taking place the surface because it is cooled fast, it has contracted much faster.

And whereas the center, it is still at the higher temperature, so it has not contracted. So, the result is that outside it is trying to contract but inside is trying to opposite. So, there is going to be a tensile stress at the surface. So, since and let that is also there, the metal is a single piece, it is in directive, it is a continuous piece. So, surface there is an interior of the section will prevent the surface from contracting.

So, this will result in the tensile stress at the surface whereas at inside it is compressive stress at the roll interior. So, there is going to be a variation in the stress and that is what is going to happen. At the surface, you are having this is a tensile and this is a compressive direction okay, this is the zero. So, here up to some distance, see you will find that the stresses are much higher, so maybe 750 megapascal and other things which are coming here, these are just schematic only.

So, do not take that value as a true value whereas after that it is compressive stresses, which are taking place. So, this is the distribution of the stresses, which are there.

(Refer Slide Time: 20:15)

The surface layer will be plastically deformed if the stresses exceeds the yield stress of the roll material. This will lead to generation of compressive residual stresses at the surface an tensile stress at the interior of the rolls.

If the stress exceeds the ultimate tensile stress of the material, cracking will occur. However, this phenomenon is not very common.

Effect of martensitic transformation

Volume change during martensitic transformation is around 4.6 %. During the fist stage, The stresses present are due to the radial temperature gradient. The surface tries to contract. However, the centre tries to prevent the contraction. Hence surface region in tension and inside under compressive stress.

During the second stage, from time t1 to t2, the surface having reached the Ms temperature transform to martensite and expands. The centre contracts due to normal cooling and restricts the surface from expanding. Hence surface is in compression and centre in tension.

Now, the surface layer because of that tensile stresses are there, it will plastically deform if the stress exceeds the yield strength of the roll. So, maybe if you look at that, mostly if it is up to this high level, there is going to be a plastic deformation. So, you may need to have a material having a higher yield strength for this purpose, otherwise it will plastically deform at the surface and then okay your roll quality will become poor.

This will lead to generation of compressive residual stresses at the surface. When the plastic deformation takes place, there will compressive residual stress at the surface okay and that inside it will be tensile stress because the roll is getting cooled. So, at that sudden quenching time at the surface is the plastic deformation has taken place, there will be a residual stress but with the time inside also will shrink, so there will be tensile stress which is taking place.

So, these things within such a time period it is going to happen but if the stress during that quenching stage, if it was so high that it exceeds the ultimate and self-strength of the material, then definitely a cracking will occur there but this cracking is very rarely found okay unless it is such a very in such a very harsh environment, otherwise it will not crack. Most of this roll material if people are not subjecting to water quenching okay.

It is either air quenching or oil quenching. Now, this is what we were discussing about due to the thermal expansion behavior or contraction due to a thermal expansion here from the high temperature to the room temperature. Now, there is another effect which is going to come, there is going to be a phase transformation. For most of the steel, above around 723 degree centigrade or something of course that depends upon the alloying element.

With manganese and nickel, it will decrease the austenitic temperature range but for in an alloy steel, any other element is added it will always increase the austenitic temperature region, the temperature will go high. So, that also depends upon the composition of your roll material. So, when you are quenching from the austenitic temperature to room temperature whether you are going to have a martensitic temperature or a martensitic structure or a ferritic structure or a bainitic structure that depends upon your cooling rate.

It has to escape the nose of your TTT curve, the continuous cooling transformation diagram if you look at it, you will find that most of the case, the surface it escapes there and also the TTT diagram and when the temperature say in this case also if you look at, at the surface if it is coming, it just reaches here, this is your Ms temperature and suppose this is your Mf temperature.

Maybe within say 20 minutes, it has reached to the martensitic temperature, a martensitic sharp temperature, so it is going to transform to martensite and maybe after 40 seconds, it is completely at the surface is fully martensitic, 100% martensite okay. Whereas even at that time also know, you may find that the center is still at a higher temperature and surely it is passing through your bainitic transformation range or sometimes it may depending upon the section thickness, it may go to pearlitic also.

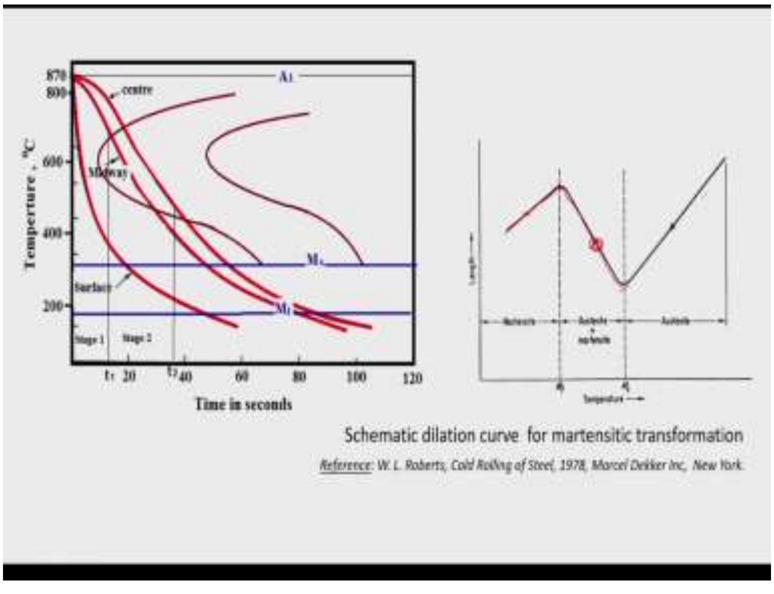
So, this variation is going to be there. So, at the surface you have a martensitic structure where the change in the volume is going to be something around 4.6% or 4.5%. Volume change during martensitic is around 4.6%. So, during the first stage, initial state, the stresses present up due to the radial temperature gradient and the surface tries to contract okay because there is going to be the volume change is going to take place.

However, the center when the surface is trying to contract, the center tries to prevent the contraction because that is not happening. The transformation is not taking place, hence the surface region is in tension and inside is under compressive stress. So, this is the first stage, stage 1 this region. Now, you look at the stage 2, this is also just schematic only. So, during the second stage from time t1 to t2, when you are moving from here to here during that time, the surface having reached Ms temperature transforms to martensite.

So, when the martensite transformation takes place, it expands okay from face-centered cubic to body-centered tetragonal it expands and the center contracts due to normal cooling because center is cooling at a normal right. It may not even reach Ms temperature before that it may enter into the nose of the TTT curve also. So, due to a normal cooling and restricts the surface from expanding okay.

So, when the surface is trying to expand the center is not trying to expand, so it will just pull back, so there will be compressive stresses at the center and surface is in compression and center is in tension.

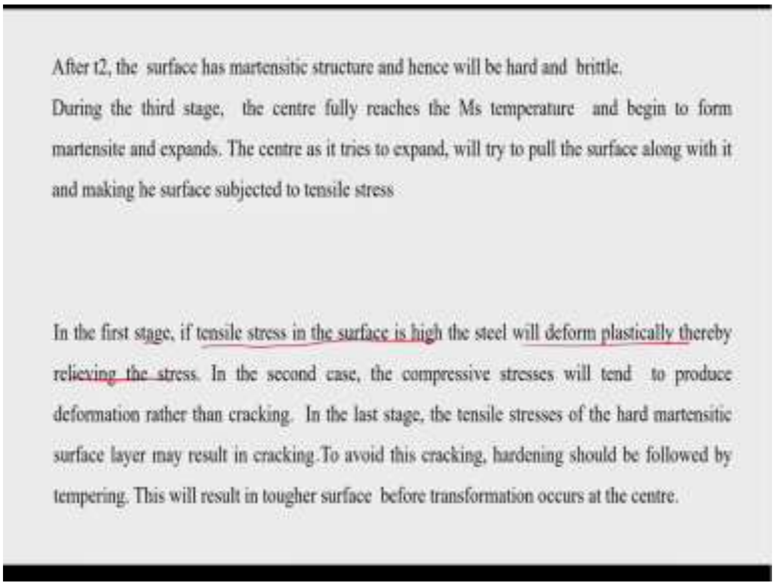
(Refer Slide Time: 25:37)



So, there is going to be a variation there. You see that when the variation in this one from austenite at higher temperature when the temperature comes from there is going to be a cooling and when once it crosses the Ms temperature because of the martensitic transformation if there is an expansion which is taking place and at this time, it is completely martensitic.

But since the material is still cooling, there is again going to be from this temperature, this is going to be the coefficient of thermal expansion whereas this is going to be due to the martensitic transformation temperature. So, that is what is shown here.

(Refer Slide Time: 26:16)



Now, after t2 see after this with the time after that, the surface has martensitic structure and hence will be hard and brittle but during the third stage that is after stage 2, this is the third stage when you take it, the center fully reaches the Ms temperature and begin to form martensite and expands provided it escapes the TTT curve okay. If it is very slow and the roll diameter is very large and depending if you have something like hot work die steel another thing, then it may go to several hours I think.

So, it may move towards the right, the TTT curve may move towards the right. So, that also it depends upon your the particular TTT curve for this, but in normal case here what we have, it begins to form martensite and expands. The center as it tries to expand, will try to pull the surface along with it and making the surface subjected to tensile stresses.

So, in the first stage if tensile stress in the surface is high and the steel will deform plastically thereby relieving the stress. The moment if the tensile stress s is high in the first stage, it will just deform plastically. Once it deforms plastically, there will be relieving of the stresses but surface may look bad. In the second case, the compressive stresses will tend to produce deformation rather than cracking.

Because that is also a plastic deformation is going to take place okay. So, when the plastic deformation is taking place, it will not crack but whereas in the last stage, the tensile stress of the hard martensitic surface layer, it may result in cracking because surface is going to be very hard with a very fast cooling, the hardness or hard means it becomes brittle and it may result in cracking.

So, to avoid this cracking before the centre itself reaches the room temperature, better to take it and do your tempering heat treatment because that is also elevated to a higher temperature above the Ms temperature is going and you are going to a bainitic temperature range. Bainite structure is the best heat treatment for these type things after hardening, so that now the toughness is very high by bainite heat treatment okay.

You call just tempering heat treatment not bainite heat treatment by tempering heat treatment. So, this will result in tougher surface before transformation occurs at the centre without a much compromising on the hardness of the material okay. So, these are the major things which will come. Next, we will discuss about the diffractions of the roll, roll flattening and bending of the rolls, that part we will discuss in the next section.