Fundamentals of Surface Engineering: Mechanisms, Processes and Characterizations

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Lecture-27
Surface Modification Techniques: Controlling Surface Metallurgy II

Hello, I welcome you all in this presentation related with the subjects fundamentals of surface engineering and we are talking about the surface modification techniques which are used for improving the surface properties. So, that the tribological resistance and the life of the component under the tribological conditions can be enhanced and we have also talked that there are 3 broad categories of surface modification.

One is where only the surface metrology is changed without any chemistry modification or chemical composition modification. Second method is related or second approach is related with the modifying the chemical composition of the surfaces. So, that the required set of the properties can be achieved and third approach uses the principle of putting in the required material at the surface in form of cladding or films or layers, coatings using variety of techniques.

So, that material or the layer which whatever has been deposited or applied at the surface can impart the properties which are desired, we are talking about the various methods which are falling in category 1 wherein only the surface metrology is changed without any chemistry or surface composition modification. And under this approach we have talked about like transformation hardening base methods under which we have talked about like flame hardening or laser hardening and induction hardening.

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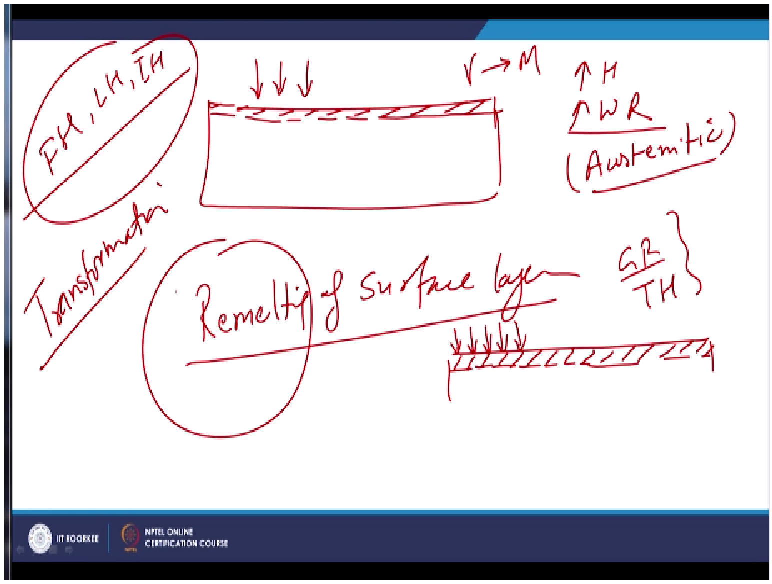

And in these harden in these processes basically the suitable heat source in form of like the laser or the flame or the current is induced. So, that the heating is done for the surface layers up to the required depth and there after rapid cooling results in the structural modification mostly it happens in form of austenite to the martensitic transformation. So, that the required increase in hardness is achieved which in turn improves the wear resistance.

So, this is how the first approach which means the one set of the processes wherein the transformation hardening is utilised. Now today we will talk about the another approach which is basically the re-melting of the surface layers. So, instead of heating up to a particular temperature which is basically austenitic temperature range in case of the transformation hardening, in this case the surface layers are brought to the molten state.

So, this is the surface of the component whose properties are to be enhanced then using the suitable high energy density heat source the heat is applied. So, that the near surface layers are brought to the molten state. And sequentially subsequently solidification will be leading to the development of the re-melted re-solidified layer which will have the improved properties primarily due to the grain refinement.

At the same time in some of the cases the transformation hardening also takes place, so the grain refinement and the transformation hardening these are the 2 mechanisms which can work with regard to the enhancement in surface properties using the re-melting of the surface layer technique.

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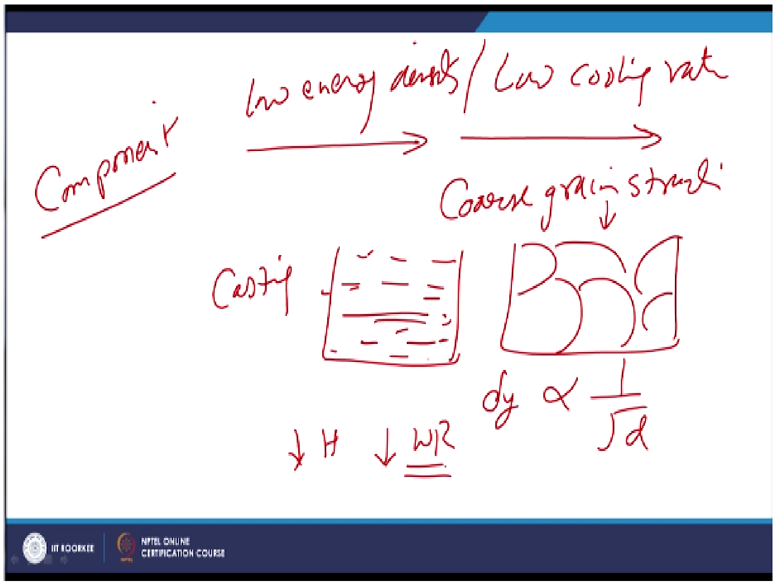

So, what is the logic behind this technique, for that we have to see that the components which are made using the processes of the low energy density or those processes wherein the metal experiences the low cooling rate during the solidification or during the manufacturing in different stages. So, low energy density processes as per as the thermal energy based processes, low energy density based processes will be leading to the application of the higher heat which in turn will be leading to the low cooling rate.

And when these conditions are present means when these during the manufacturing when such kind of conditions are present, these will be leading to the coarse grain structure of the metal. So, the processes like those which are like casting, casting the molten metal is allowed to solidify comparatively low at lower cooling rates. And this in turn results in very coarse grain structure in the casting and this kind of coarse grain structure.

As per Hall-Petch relationship offers the poor mechanical properties like yield strength is inversely proportional to the square root of the average diameter of the grains. So, since if the grain diameter is coarse then the yield strength will be lower and if the yield strength is lower than the material will have the lower hardness, so in general it is wear resistance will be poor.

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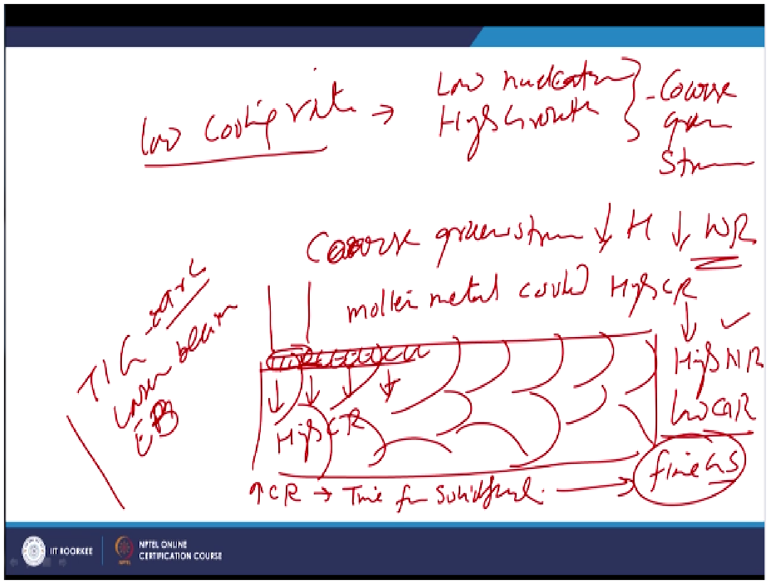

So in order to improve the properties of such kind of the materials which have been prepared using the processes which offered the low cooling rate during manufacturing stage. This results in the transformation through the low nucleation rate during the manufacturing a transformation and high growth rate. And this combination results in very coarse grain structure and as I have said coarse grain structure will be reducing the hardness, will be reducing the wear resistance in general.

So, idea is what if the metal is composed of coarse grain structure like this then melting of the surface layers using suitable heat source like it maybe TIG arc, it maybe TIG arc or it may be laser beam or it may be like electron beam. So, these are the high comparatively high energy heat sources as compare to what will be as compare to the others manufacturing process which we maybe leading to the lower cooling rate.

So, if very laser is applied over small area leading to the higher energy density. So, very thin layer of the component up to certain depth will be brought to the molten state, this depth will be influenced by the purpose for which surface modification is to be carried out. So, the required depth when is brought to the molten state because of the higher energy density very low heat will be required to bring it to the molten state.

And thereafter underlying metal which is still at lower temperature will be extracting the heat at much faster rate. So, very high cooling rate conditions will be experienced by the metal which was brought to the molten state. So, the molten metal being cooled at high rate, so high cooling rate is applied and this in turn leads to the situation of the high nucleation rate and low growth rate.

And this combination of high nucleation rate and low growth rate results in the fine grain structure this is one thing. Second thing since the cooling rate is high due to the high cooling rate the time for solidification is very less. So, very less solidification time is available means all the constituents which are being formed during the solidification will not much time to grow.

So, the time available for each phase to grow will be very less when he cooling rate is high and that is another reason behind the fine grain structure. So, this is one aspect where high nucleation rate and low growth rate and limited time availability for solidification limits the growth of individual phases and therefore we get the fine grain structure at the surface.

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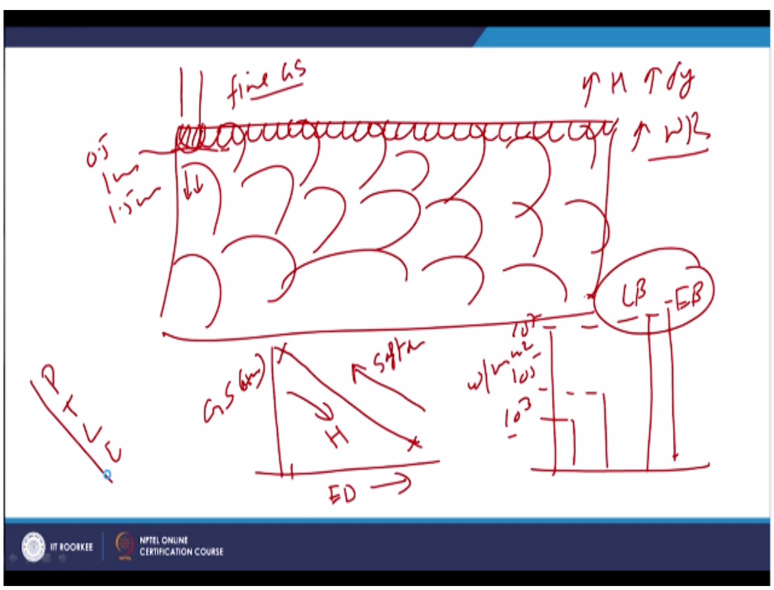

So, this is one simple concept which is used in case of the laser like re-melting using laser or re-melting using electron or re-melting using TIG arc or plasma arc. All these will be working in the same way except that difference will be there in terms of the energy density, energy density for electron beam for laser beam is too high as compare to the plasma and TIG arc like this.

So, like TIG arc may offer 10 to the power 3 or so 10 to the power 5 or so for plasma and then 10 to the power 7 or 8 watt/mm square for the laser and electron beam. So, high energy density processes will require to deliver less amount of heat to bring the surface layers up to the molten state. And which subsequently due to the high cooling rate it results in the fine grain structure.

So, if we compare here the higher is the energy density process lower will be the amount of heat that will be required to be supplied, higher will be the cooling rate which will be experienced by the molten metal and finer will be the grain structure. So, if we plot the energy density and the grain size relationship grain size relationship in terms of the micrometer. So, higher is the energy density lower will be the grain size.

So we can say when the energy density is low lot of heat is to be delivered to the surface. So, the cooling rate more heat means the lower cooling rate and so the coarser grain size, when the energy density is high we need to deliver very small amount of heat to bring the surface layers up to the molten state, this intern will be causing the higher cooling rate during the solidification and so the fine grain structure.

And so this intern so this is how we can say and this is the direction of increasing softness and this is direction for increasing hardness. So, this is how he can understand, so likewise we can use plasma or the TIG or laser or electron beam for re-melting of the surfaces. So, that required modification can be achieved where what are the conditions where this kind of the approach will be effective to improve the surface properties.

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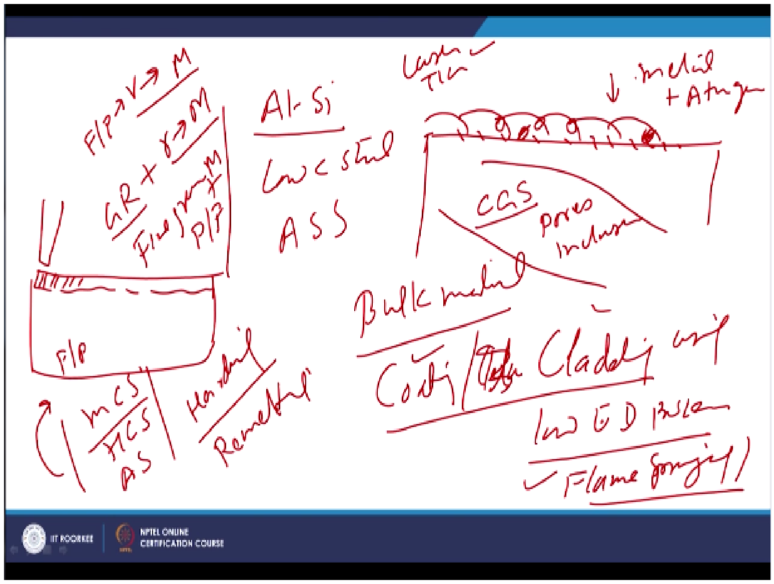

So, normally like aluminium, silicon alloys, low carbon steel, austenitic stainless steel for these kind of the metal systems when we apply these metal systems either in form of bulk material or these have been applied in form of coating or cladding using low energy density processes in that case also coatings or claddings are applied using the low energy density processes like flame spray.

So, this is like gas welding where oxi-acetylene flame is used to deposit the metal over the surface of substrate leading to the very low cooling rate during the development of the coating and which in turn causes the coarse grain structure. Apart from the coarse grain structure in flame spray coatings will see some of the force some of the inclusions.

So, force in form of the gas pockets and inclusions will also be there due to the interaction of the metal with the atmospheric gases. So, these kind of things will be leading to the presence of inclusions here and there. Sometimes even poor bonding is observed, so because of these issues like coarse grain structure, pores and presence of inclusions in flame spray coatings when they are subjected to re-melting by laser by TIG arc.

All these inclusions will start floating over the surface, porosity will be eliminated because of the re-melting of the metal, subsequent solidification will allow the escaping of such gases as well as if any kind of the poor bonding is there at the interface between the coating and the substrate then it will be leading to the increased metrological bonding. So, the issues related with the flame spread coatings to some extent are reduced by the plasma or electron beam or the TIG or the laser re-melting of the flam spray coatings.

So, that these issues are resolved like other cases if the TIG re-melting or the laser re-melting is applied, these certainly offer the higher energy density as compare to the flame spray heat source. So, the definitely the grain structure refinement takes place and if the metal is sensitive for the hardening and for that if we apply the re-melting approach then apart from the grain refinement like medium carbon steel or high carbon steel or alloy steels.

If these are their surfaces are brought to the molten state say these steels are ferritic and pearlite, so they are having the mixture ferrite and pearlite in the different propositions. So, if these are the main phases so when we apply in these kind of the steels the approach of the re-melting using the laser or TIG or electron beam then re-melting will definitely re-melting followed by the rapid cooling will be causing the transformation of the ferrite and pearlite.

First into the austenite after the solidification and then due to the rapid cooling it will be causing the martensitic transformation. So, the re-melting will be leading to the grain refinement as well as transformation of austenite into the martensite will be leading to the production of the fine grain martensite+soft phases like pearlite or ferrite as per the composition of the steel which is being subjected to the re-melting.

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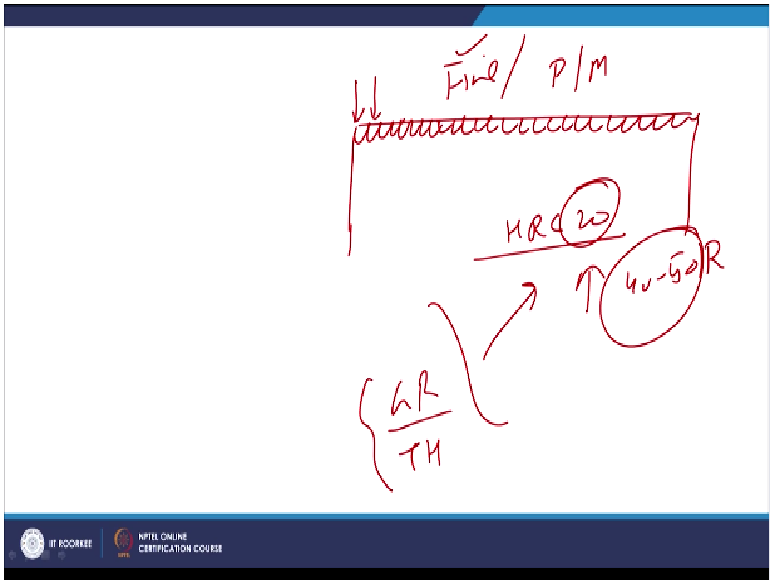

And if the steel which had the hardness of the HRC 20 subjected to the re-melting at the surface layers followed by the martensitic transformation during the solidification and after the solidification during the cooling to the room temperature. Then these kind of the presence of the grain structure, fine grain structure+presence of pearlite and martensitic mixture at the surface due to the re-melting will be leading to the significant increase in hardness from 20 HRC to maybe say 40 to 50 HRC.

So, means the re-melting using the laser or electron beam or TIG of the medium carbon steel, high carbon steel or alloy steel will lead to the formation of the fine grain, pearlite and martensitic structure. So, that it will be combining the effect of both grain refinement as well as transformation hardening and combination of both these will be leading to the significant increase in the hardness about 20 HRC to the 40 to 50 HRC and this certainly will improve the wear resistance.

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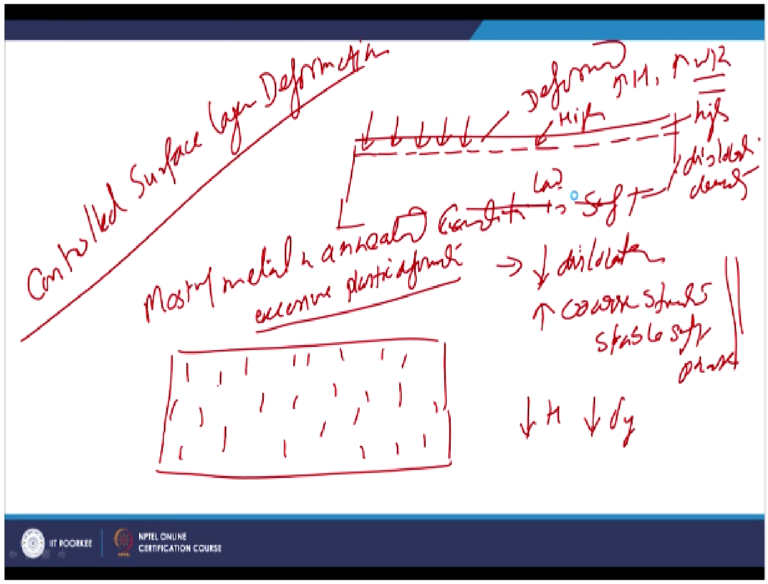

Now we will talk about the another approach or another method which is related with the surface metrology modification for improving the wear resistance that is about the controlled surface layer deformation. So, the basic in this approach the broader idea is that the surface whose properties are to be improved will deformed plastically up to the required depth using the controlled application of the stresses.

So, this surface layer is deformed plastically and plastic deformation will be leading to the increase in hardness for increasing the wear resistance. This is the idea but how this improvement in properties take place and what are the other effects related with this approach about that we will talk like most of metals in annealed condition is soft, it happens due to the very limited number of the dislocations.

And very coarse grain structure as well as presence of more stable soft phases. So, these are the reasons behind and metal in anneal condition will have the minimum number of the dislocations like this, from the dislocation theory we know that presence of very few dislocations reduces the hardness, reduces the yield strength and therefore by the mechanical deformation or plastic deformation using mechanical force.

If we increase the number of dislocations in the metal which is being considered then it will simply increase the yield strength of the material because according to the dislocation theory deformation is facilitated through the movement of this dislocations. And when we have large number of dislocations then resistance to the movement increases to this dislocations and therefore resistance to the plastic deformation is also enhanced.

So, presence of few dislocations is good from the deformation point of view but when this number of dislocations are increased significantly. Then we find increased resistance to the movement of this dislocations and which in turn increases the yield strength of the metal. So, in this approach basically the excessive plastic deformation of the surface layer is facilitated or achieved.

So, that near surface layers have large number of high dislocation density or increased number of the dislocations near the surface layer,s while the underlying surface may have very limited number of the dislocations. So, here the large number of dislocations while limited number of dislocations are available in the substrate or in the base metal, metal which is in annealed condition.

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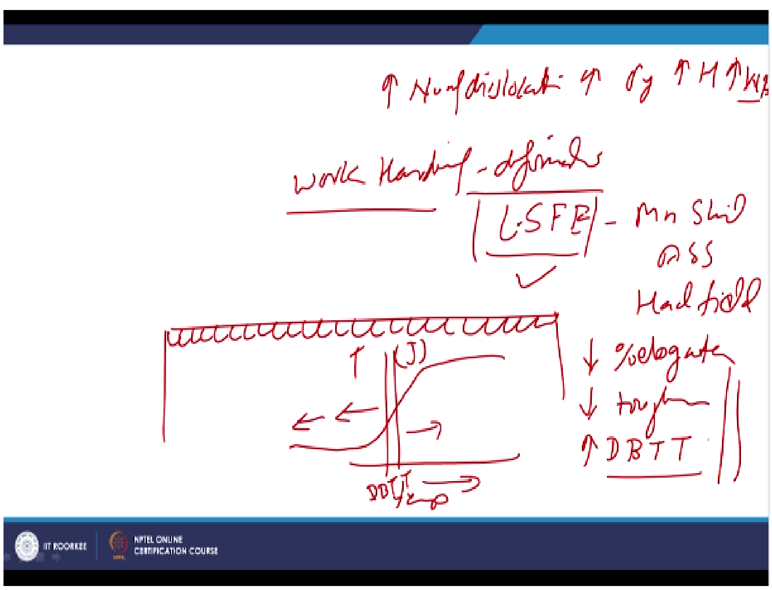

And here so increasing number of dislocations increases the yield strength which in turn increases the hardness and which in turn is expected to increase the wear resistance. But at the same time so these are the effects of work hardening, work hardening means due to the deformation of the metal increase in hardness and increase in strength is taking place.

As you know that different metals respond to the work hardening in different ways low stacking fault energy materials like high manganese steel, austenitic stainless steel had field steel all these respond very rapidly. So, means the presence of means little bit increase in the dislocation increases the hardness and strength significantly and will see that so the work hardening through the controlled deformation increases the hardness of the low stacking fault energy methods materials significantly.

So, these materials when the surface layers are deformed in very controlled way using various approaches then it leads to the significant improvement in the yield strength and hardness. But at the same time some undesirable effects are also offered and those undesirable effects are like reduction in the percentage elongation, reduction in toughness of the material at the as well as increase in ductile to brittle transition temperature.

This is the temperature where will see that the temperature at which sharp drop in the toughness takes place, toughness in terms of the energy observed and here we have temperature. So, higher is the temperature, higher is the toughness and this is temperature where this kind of transition is observed. So, this will be the ductile to brittle transition temperature, it is always desired that this temperature is on the lower side.

So, the drop in toughness during the service temperature conditions does not takes place and if the DBTT that is ductile to brittle transition temperature is happening at a higher temperature. Then there will be very large tendency or very much possibility then the material will come across the temperatures which are below the ductile to brittle transition temperature.

And in that case material will lose it is toughness and that may fail in brittle manner under the impact conditions. So, this is one of the undesirable affect of increasing the hardness to the plastic deformation or work hardening based approach.

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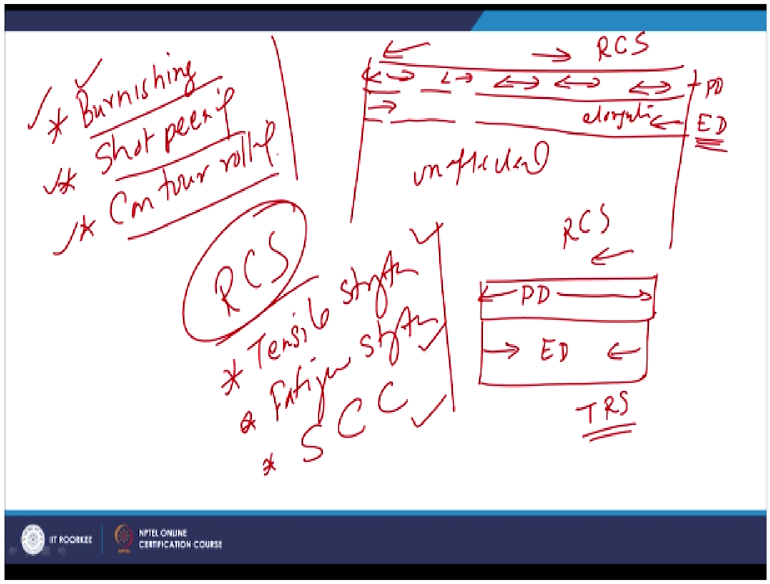

So, how the controlled surface layer deformation is achieved near the surface layers there are various methods these methods include like burnishing and shot peening, these are the methods which use the controlled surface layer deformation and then there is contour rolling. In these methods apart from because near surface layers are subjected to the plastic deformation while the sub surface layers remain under the elastic deformation conditions.

So, surface layers which are subjected to the plastic deformation below that there will be a zone which will be under the elastic deformation and below that there will be unaffected portion. So, because of this what we find elastic deformation which is means surface layers which have been elongated while the sub surface layers which are under the elastic deformation elongated under the elastic deformation condition.

So, this sub surface layers will tend to come back when the once the processing of the surface layer is over. So, these sub surface layers tend to attain the same size or the same dimensions again. So, means the elastic deformation tries to regain the same conditions what were there earlier and because of this what we experience that surface layers experience the residual compressive stresses.

Actually the surface layers will subjected to the tension under the plastic strain conditions while the sub surface zones were under the elastic deformation conditions. So, sub surface zone tends to come back while the surface layers will remain or will remain there only. So, because of these 2 kind of dissimilar conditions being experienced by the 2 different layers surfaces experience the residual compressive stresses.

So, this is what we can see the sub surface zone is trying to come back which is under the elastic deformation condition while the surface layers which are under the plastic deformation conditions will be experiencing the tensile strain. So, because of these 2 opposite effects what we find that surfaces experience the residual compressive stresses while the sub surface zone which are not allowed to return they will be experiencing the tensile residual stresses.

So, tensile residual stresses if they are in the sub surface zone that will not be that harmful as compare to the surface layers. So, if the surface layers are having the residual compressive stresses it is favourable from the tensile strength point of view which is also favourable from the fatigue strength point of view and stress corrosion cracking point view.

So, resistance of the material subjected to the controlled surface layer deformation using either of these methods will be leading to the improvement in tensile strength, fatigue strength and stress corrosion cracking, what is the mechanism of the improvement in these behaviours of the material due to the development of the residual compressive stresses about that I will talk in the next presentation as well as I will also talk about the details of the 3 methods which are based on the controlled surface layer and deformation for improving this surface properties.

Now I will summarise this presentation, in this presentation basically I have talked about the 2 approaches 1 was the re-melting of the surface layers for grain refinement as well as transformation hardening. In some of the cases for improving the surface properties as well as the underlying principle of improving the surface properties in the approach which uses the controlled surface layer deformation for improving the surface properties, thank you for your attention.