Fundamentals of Surface Engineering: Mechanisms, Processes and Characterizations

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Lecture-26
Surface Modification Techniques: Controlling Surface Metallurgy I

Hello, I welcome you all in this presentation related with the subject fundamentals of surface engineering and in the previous presentation we have talked about the principles behind the surface modification techniques where in surface properties are enhanced by changing the surface metrology only without changing any chemical composition and we have seen that the work hardening, transformation hardening and the grain refinement mechanisms work effectively using the various methods.

Like they are 2 category of the methods, in 1 of the categories where mechanical energy is used for controlled surface layer deformation and whenever the surface controlled surface layer deformation is applied, it causes the work hardening as well as improvement in properties is also caused by the grain refinement. And there is another category of the methods whether in thermal energy is used and this method primarily uses the principle of transformation hardening.

However, so in the in case of the transformation hardening basically the soft phases are transformed into the hard phases to improve the properties. The thermal methods also utilise the principle of the grain refinement for improving the mechanical properties. So, in this presentation basically I will be talking about the transformation hardening base methods which are used for improving the surface metrology. So, has to enhance the surface properties as well as they improve the wear resistance of the components.

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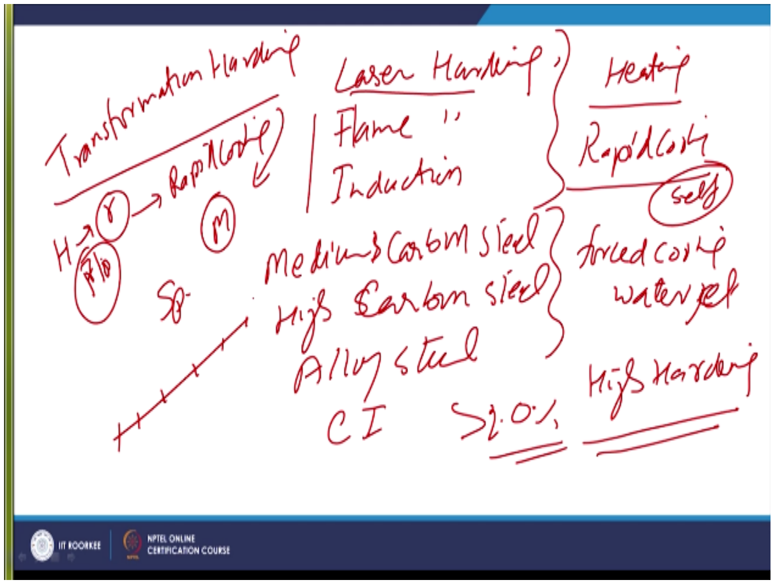

So, as I have said the transformation hardening methods there are 3 very commonly used transformation hardening methods. These are laser hardening, flame hardening and induction hardening. Both these methods follow the same principle which involves the controlled heating up to the required depth followed by rapid cooling. Sometimes rapid cooling happens just by the self cooling, no external cooling is required, but otherwise forced cooling is also used wherein water jet is applied onto the surface which has been heated.

So water jet is used for cooling the surfaces which has been heated by the flame and by the induction while in case of the laser normally self cooling if the dimensions are sufficient section thickness is having then even self cooling causes the required transformation hardening. And both these all these 3 methods are applicable for specific category of the metals which are having either like for medium which are having sufficient carbon content.

And the alloying elements especially in case of the ferrous metals, so medium carbon steels, high carbon steels and the alloy steel as well as cast irons which are having the carbon content greater than 2%, this is applicable. So, since these methods offer the high hardenability and that is why these can be strengthen or surface properties can be improved through the transformation hardening.

Transformation hardening primarily involves heating for austenitizing or austenitic transformation of soft phases into the austenite soft phases means ferrite and pearlite into the austenite followed by rapid cooling. So, rapid cooling facilitates the transformation of austenite into the martensitic which is being harder, then the austenite and other soft phases like pearlite and ferrite.

So, because of the formation of the harder phases it improves the surface hardness and thereby it improves the mechanical properties.

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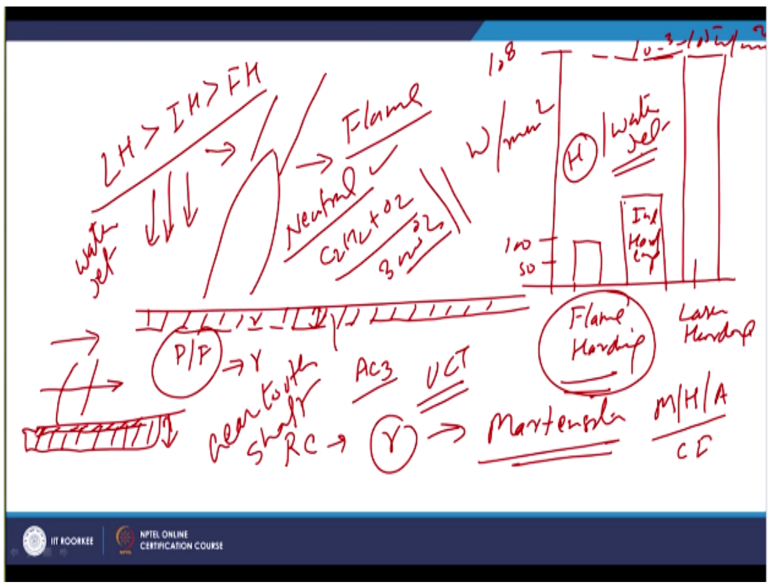

So, if we have to compare these methods then these methods can simply be compared with respect to the power density which is offered by these methods in terms of the watt/mm square. So, the first method like flame hardening which offers very low energy density or the power density, flame hardening like 50 to 100 watt/mm square. On the other hand if we talk of the induction hardening it will offers somewhat higher energy density for induction hardening.

And the laser hardening offers very high energy density which maybe to the tune of 10 to the power 8 or more for, so that is the kind of energy density which is offered by but for the induction hardening purpose normally 10 to the power 3 to 10 to the power 5 watt/mm square energy density is used. So, this is applicable for the laser hardening, so if we see this sequence laser hardening offers the highest energy power density.

Then induction hardening and then flame hardening, so based on this if we see the flame, so the surface which is to be harden in case of the flame hardening, the flame is used and the flame is produced. Basically this is the neutral flame which is achieved through the combustion of the acetylene and oxygen. So, the temperature generated is high enough of around 3000 degree centigrade.

But controlled application of the flame onto the substrate causes the transformation of the pearlite and ferrite into the austenite and once the flame has been applied onto the surface temperature will rise and rise in temperature is achieved in the range of although as per the composition of the material it is heated above the upper critical temperature limit which is called Ac3 line or upper critical temperature line.

So, that the soft phases are transformed into the austenite and once and this is achieved through the application of the flame. Since the flame offers the lower power density or lower energy density therefore the flame is to be applied for longer time to achieve the required rise in temperature. So, that the soft phases can be transformed into the austenite and once the heating up to the required depth is achieved the flame is moved.

And once the flame is moved will be applying the rapid cooling through the application of the water jet. So water jet will be causing water jet onto the surface which has been austenitized, so this rapid cooling will be leading to the transformation of austenite into the martensite. So, this is how the hardening is achieved in case of the flame hardening, since the power density or energy density associate with this process is low, that is why it process is slightly lower.

And this is effectively used for hardening the gear tooth surfaces shafts and other components wherever engine improvement in surface properties of the medium high carbon or alloy steels or cast irons is required. So, if we want to regulate the depth up to which the hardening is to be done then to adjust the depth of hardening what we have to do basically the speed of the flame is regulated.

So, that the amount of heat being delivered to the surface is adjusted and accordingly that the depth up to austenitization will be taking place that will be changed, like say if we are moving if the flame is moved at a faster rate. Then very thin layer will be heated to the austenitic state and that will be subjected to the martensitic transformation, if the flame is moved at a fast at lower speed.

Then the greater amount of the heat will be delivered to the substrate greater depth will be austenitized means the austenization will be taking place up to greater depth with subsequently on the rapid cooling will be subjected to the martensitic transformations. So, the depth up to which hardening will be taking place by this method that will be regulated through the speed of the flame movement and the flame is normally neutral.

So, that the maximum temperature is realised and efficient controlled austenitization is achieved. So, in this case in case of the flame hardening the heating using the oxides clean flame or fuel flame followed by rapid cooling using the water jet is used for hardening the surfaces. Of course there will always be kind of the variation in the cooling rates which will be experienced by the different zones.

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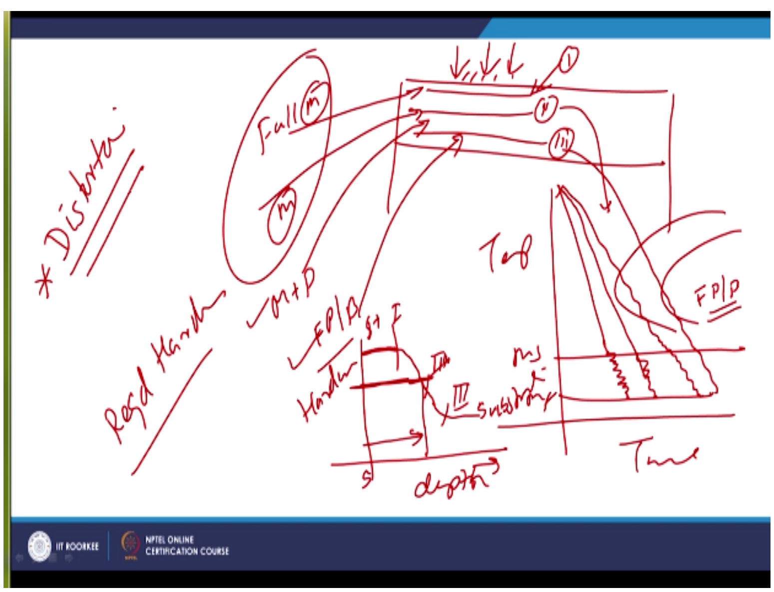

Like if we say this is the depth up to which austenitization has taken place then by the water jet cooling maximum cooling rate will be experienced by the surface. Then somewhat lower cooling rate will by the sub surface region and the metal systems which are existing for at further lower depths up to further deeper as portion from the surface that those will be experiencing further lower cooling rate.

So, if we compare this with the CCT diagram if the cooling rates are supreme post using the CCT diagram. So, the highest cooling rate will be like say at this level, the second level and third level. The surface will be cooled at the maximum rate there is somewhat lower cooling rate further lower cooling rate. So, if say surface is and this is the slide like say MS start and MS finish and this is the temperature this type diagram.

So, the surface will be experiencing the highest cooling rate like this in any case entire austenite will transform into the martensite below this there will cooling rate will be somewhat lower. So, maybe like this again whole of the austenite will be transform into the martensite but if we talk of the third zone where cooling rate is further lower will see that part of the austenite is transforming into the pearlite.

And remaining austenite is transforming into the martensite and if the cooling rate is further lower then we will see that most of the austenite transforming into the fine pearlite or bainite. So, this kind of structural variation will be leading to the like full martensitic transformation at the surface, here also full martensitic transformation in this case will be taking place then it will be having the martensite+pearlitic transformation.

And then fine pearlite or benedict transformation in the regions which are too deep below the surface. Since the highest hardness will be offered by these phases somewhat lower hardness in the subsurface region and further lower hardness in further subsurface regions. So, if we try to plot the variation in hardness from the surface is surface and going deep, so depth increasing depth from the surface.

If we plot x-axis and hardness in the y-axis then the distance up to which full martensitic transformation has taken place their hardness will be maximum and then we will see that the combination of the martensite means mixture of a martensitic and pearlite is being from then according to the fraction of the martensite and pearlite hardness will be gradually reducing.

So, as we go deeper and deeper martensite fraction will keep on decreasing while the fraction of the pearlite will keep on increasing and then we will see that fine pearlite is being formed and the subsurface zones. So this is corresponding to the zone surface as well as the zone 1, then zone 2, then zone 3 and then this is the substrate where no change in the structure is there, so, there will always be variation in hardness.

Now there is another point the depth up to which case hardening has taken place or the depth up to which required hardness is being achieved for that what we have to do, we have to set the required hardness level. And then required hardness level is this much then this is the depth up to which required increase in the hardness has been achieved through the laser hardening or flame hardening or the induction hardening.

So, this is how we try to find out that the depth up to which required hardness has been achieved and there will be very limited depth up to which the maximum hardness will be there and below that the hardness will be somewhat lower as per the kind of phases which are being formed. So, this method, flame hardening method is somewhat slower and it takes longer and since the amount of heat which is to be applied onto the components that will be more. So, there will be possibility for the distortion of the components which is being subjected to the flame hardening.

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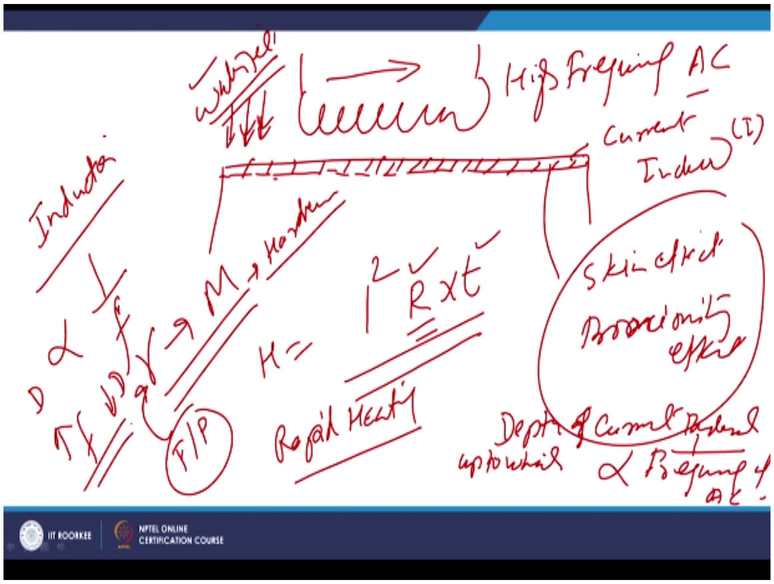

Now the another method which is used is the induction hardening, induction hardening uses somewhat higher energy density. So, here the coils are used through which high frequency AC current is supplied and this coil is brought close to the surface which is to be hardened. So, that at the near surface layers the current is induced and this said whatever current is induced this is localised over a very thin layer.

And this localisation happens due to the skin effect and proximity effects and once the induced current is localised over a very thin layer. So, current flowing over thin layer causes the high resistance means the current is localised over thin layer. So, whatever is the resistance of the material, whatever is the current and the time for which it is flowing this will be determining the heat which is being generated.

So, the heat generated is determined by the I square Rt, I is the current induced R is the resistance of the material and t is the time for which this current is induced and which will be causing the heating. So, since the current induced is localised over a very small area, so this causes the very rapid heating of the near surface layers. And the heating up to required depth is realised it will be subjected to the rapid cooling using the water jet.

So, basically the coil is moved past the surface means over the surface there is no physical contact and once the heating up to the required depth is realised the surface will be subjected to the cooling through the water jets. And once it is achieved means the rapid cooling is done. So, the austenite will be transforming into the martensite, so just like a flame hardening.

In this case the high carbon or medium carbon steel or alloy steel which is being subjected to the heating through the induction effect surface layer heating will be causing the transformation of the ferrite and pearlite into the austenite and once the austenite is formed up to the required depth the rapid cooling using the water jet will be transforming the austenite into the martensite.

And which in turn will be causing the required improvement in the hardness, now they are certain things like the depth up to which current induced the depth of depth up to which current is induced up to which current induced, this is found inversely proportional to the frequency of current or frequency of basic current which is been supplied to the coil, this is found inversely proportional to the frequency of current.

So, if which means that d is the depth, this is found inversely proportional to the frequency of the current which means greater is the frequency higher is the frequency, lower will be the depth up to which current will be induced.

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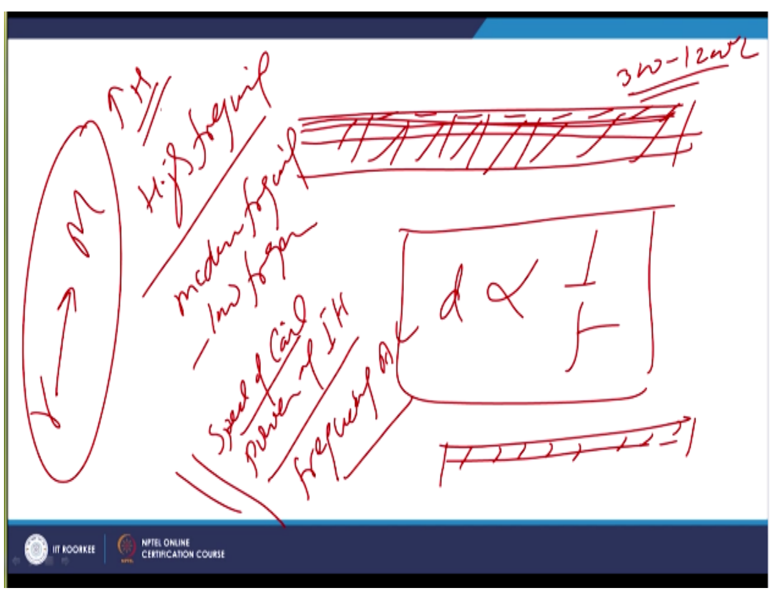

So, which means if we want that very thin layer is hardened then high frequency AC current is used then somewhat medium frequency current is used if we want somewhat greater depth of the hardening and low frequency will be used for greater depth of hardening. So, because the depth up to which current will be induced is found the function of the frequency and it is inversely related.

So, the depth up to which current will be induced will be inversely proportional to the frequency, higher the frequency lower will be the depth. And since the current is localised near the surface layer as per the frequency, so if the frequency is low, the current will be induced up to the greater depth and accordingly the austenization will be taking place up to the greater depth with subsequently on rapid cooling will be causing the austenite to martensitic transformation to achieve the required improvement in surface properties.

So, this the temperature range due to the induction heating can vary like say 300 to 1200 degree centigrade. So, the speed of the induction coil and the current frequency the power of the induction coil all those has things hard to be optimised to achieve the required depth of the hardening. So, that required improvement in properties can be achieved, so basically the speed of the coil power of the induction heating.

And the speed will be governing the time and power of the induction heating as well as the frequency of the AC current. These are to be optimised, so that the required depth of the hardening can be achieved through the austenitization followed by rapid cooling, again this method primarily uses the principle of austenite to martensitic transformation for improving the hardness and improving the mechanical properties.

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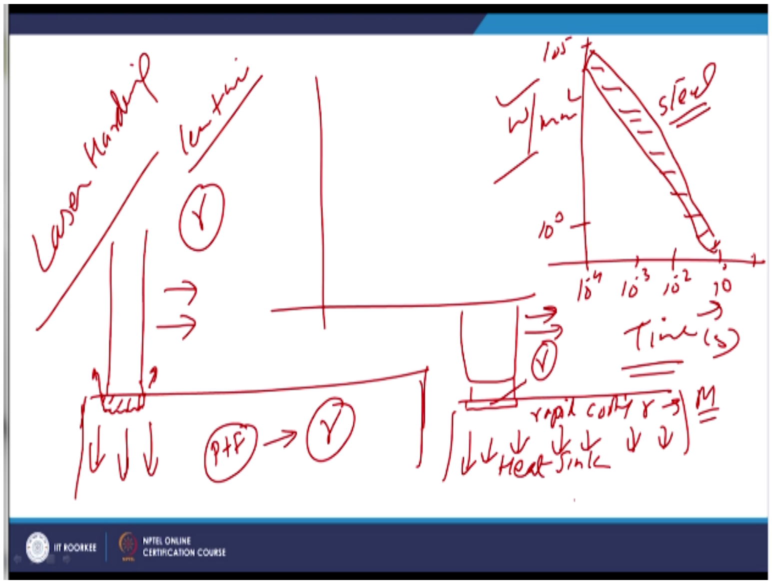

Now another method is the laser hardening, as I have said the laser uses the very high energy density like 10 to the power 3 to 10 to the power 5 watt/mm square and here we have the time, in the x-axis we have time 10 to the power -4, 10 to the power -3, 10 to the power -2, 10 to the power 0 and then like this. So, there is a particular band which is used for induction heating purpose.

And this goes in like this for steels, this is the kind of the combination of the exposure time, time in seconds and the power density as per as the laser is concern. So, higher is the power, lesser will be the laser interaction with the surface which is required for the hardening purpose, this is applicable for the steels. Now we will see the kind of the variation which is observed when the laser is applied onto the surface.

So, very small area will be subjected to the application of the heat, so because part of the heat, part of the laser is reflected back, part of the laser is absorbed which is converted into the heat and this intern causes the very rapid rise in temperature. Because the energy density associated with the laser is very high, so it requires very less time for heating or and for raising the temperature of the material up to the required austentization.

So, in this case also the pearlite and ferrite when they are heated with the help of laser it gets transformed these gets transform into the austenite and once these have been austenite through the proper control of the power or the energy density and the laser scanning speed will try this will be austentized and once it is austentized and if the section thickness is sufficient as soon as the laser beam is removed from a particular location.

The heat is extracted immediately by the underlying low temperature base metal, so basically the base metal here acts as a heat sink**.** So, the heat is extracted by the base metal itself quickly from the region where laser has been applied. So, if the laser has been applied over this area this there will be rise in temperature up to the austenitization condition and then this austentized layer will be subjected to the rapid cooling as the heat is extracted by the underlying base metal as soon as the heat the laser beam is removed from a particular location.

So, this rapid extraction of the heat from the heated zone causes the cooling rapid enough. So, rapid cooling of the austenite causes the martensitic transformation, so if the section thickness is sufficient then application of the laser will develop the heat as soon as the austentization is complete and removal of the laser from that particular location will cause the rapid cooling due to the absorption of heat rapidly from that particular location.

And that rapid cooling will cause the austenite to the martensitic transformation. So, now if we see in this case again our austenite to martensitic transformation is being facilitated. Now we will see 1 typical diagram which is used for determining the energy densities to be used for variety of application whenever the laser is used.

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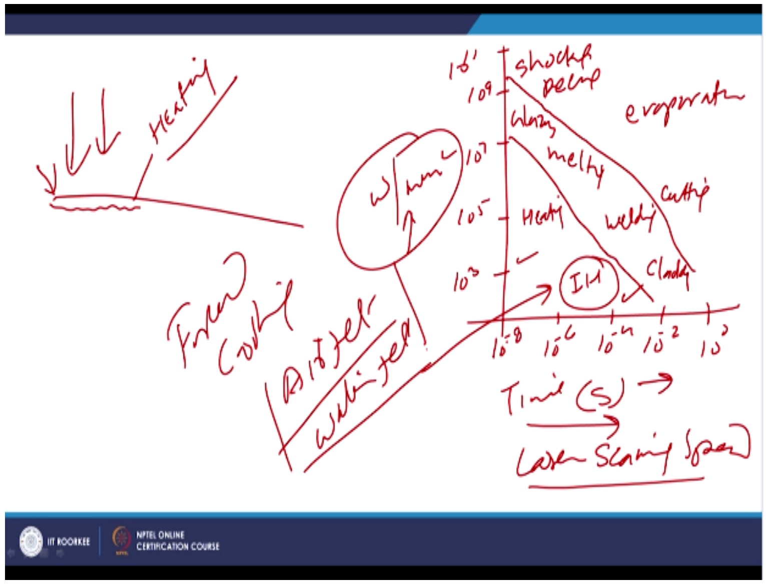

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So, if we see this diagram here 10 to the power -8, 10 to the power -6, 10 to the power -4, 10 to the power -2, 10 to the power 0, this is laser interaction with the base metal time in seconds. And this is -8 then the power density on the other side we have to do the power 3, 10 to the power 5, 10 to the power 7, 10 to the power 9 and 10 to the power 11, that is watt/mm square.

So, in one side we have the power density of the laser and another side we have the interaction of the laser with the base metal. So, if we want to use the laser just for the heating purpose then this is the kind of combination which is used, this is the zone for the heating purpose and especially for induction hardening, this is the band which is used means the lower energy density and longer laser interaction with the base metal.

And if you want to perform melting then energy density and the interaction time goes in like this. So, this is the portion where in melting is used and our cladding uses the lower energy densities somewhat higher for welding and then glazing for further higher energy densities. And here we use the cutting range where ablation or the controlled evaporation is achieved, this is the band for evaporation and the laser shot peening uses further higher energy density.

So, laser in the case of laser shot peening the laser is applied onto the surface for a while, so that expansion heating causes the expansion and then laser is immediately withdrawn. So, that leads to the development of the compressive residual stress onto the surface. So, this is the zone where the energy density of the laser and the laser interaction which is influenced by the laser scanning speed.

So, higher is the laser scanning speed lower will be the time for which laser will be interacting with the substrate. So, basically the longer times and lower energy densities are used for the heating purpose, because what we want just the laser is applied onto the substrate, so that it gets austentized**.** So, we want to use the laser for heating purpose only and as soon as the laser is removed rapid cooling by the substrate itself normally causes the sufficient provides sufficient cooling rate for austenite to martensitic transformation.

In order to inform the hardness and the wear resistance, but if the section thickness is the limited that we may have to use the forced cooling methods which may involve like air jet or it may be water jet. So, as per the section thickness which is to be subjected to the hardening with the help of laser will be using either self cooling or the air jet or the water jet, now here I will summarise.

In this presentation basically I have talked about the 3 methods related with the transformation hardening primarily in these methods we have seen that how the difference sources of the heat can be utilised for achieving the fully austenitic state in the near surface layers. So, that subsequent rapid cooling can facilitate austenite to the martensitic transformation.

And for the cooling purpose we may use water jet, we may use air jet or we may use the self cooling as per the section thickness. So, basically self cooling is applicable only case of the laser hardening, water jet is invariably used for the rapid cooling purpose in case of the flame hardening and the induction hardening, thank you for your attention.