Surface Engineering for Corrosion and Wear Resistance Application
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Lecture - 55
Laser Surface Engineering: Hardening and Melting

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Welcome to the 55th lecture of Surface Engineering. We have been in the last couple of lectures we discussed the various fundamental aspects of laser material processing and if you recall we actually discussed that the overall scope can address four different possibilities namely the forming, machining, joining and surface engineering.

So, these are the four major scopes of application engineering applications of using laser as a pure source of heating, non contact source of heating we are not talking about spectroscopy or metrology or any other applications those also could be engineering applications, but essentially manufacturing related application.

So, where laser is purely a source of heating and a laser is useful because it can deliver a certain quantum of a very very precise quantum of energy at the desired spot and we have extreme high level of many variability in terms of delivering the right quantum of energy at the desired spot and so on. Now, today onwards we are going to discuss pure surface engineering, we are not talking about additive manufacturing or various other processes not mentioning or joining and so on.

Now, while we discuss surface engineering using laser as a source of heating I would like to divide the whole approach into two possible modes of strategies. Number one like here we are going to talk about only on the micro structural changes, so we are not changing the composition. So, the phase aggregate that we have on to the surface, we can subject the component surface to rapid cycle of heating and cooling.

So, essentially if you consider a component and subjected to in terms of either temperature as a function of time or temperature as a function of depth. In either case you actually will see a rapid heating maybe a little bit of residue time of the surface during which the heat can propagate further and then we cool and this cooling is essentially a process of self quenching.

So, this is in terms of the temporal distribution the time distribution similarly as a function of depth we expect the temperature. So, at the surface the temperature will be the maximum and as a function of time or as a function of depth we will expect the temperature to gradually decrease as we go below the surface.

So, using this kind of a heating cooling cycle and a distribution of temperature as a function of depth which will gradually decrease and of course, this as a function of time this will increase with time this will gradually increase. So, using this kind of a cycle we essentially would like to change the microstructure and please remember by micro structural change we mean the identity, the shape size distribution morphology of the phase aggregate that we are dealing with.

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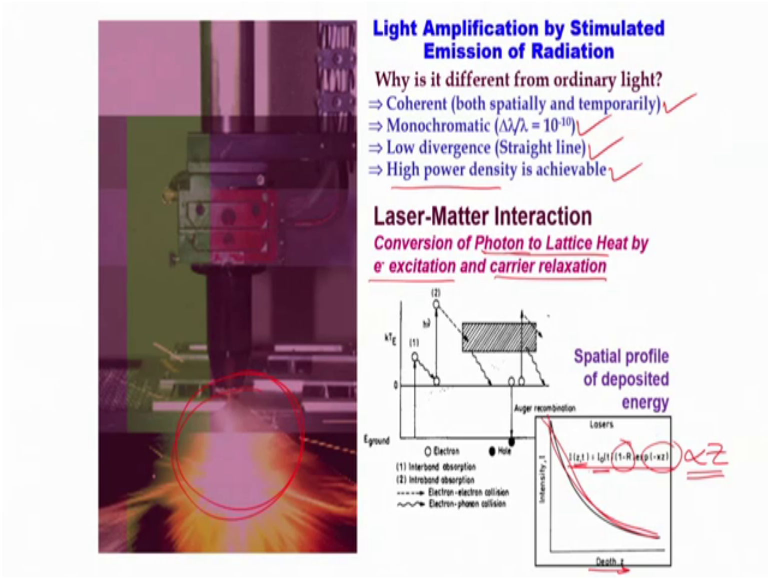

So, when we do that we also would like to just make you recall that there are four specific reasons why we use laser because of coherency, because of monochomatic, because of very low divergence or very precise path of movement and then finally, very high power density at the desired spot. So, this is how laser is different than ordinary light and using this directed source of heating, we actually allow the solid to get heated up and undergo certain amount of micro structural changes.

So, the conversion of incident photon the packet of energy light energy to lattice heat, so photon to light heat lattice heat is an instantaneous process less than nanosecond through electronic excitation and carrier relaxation. So, a very fast excitation of electrons to higher engine state followed by rapid falling back onto the ground state and in the energy is converted the incident energy is converted into lattice heat.

The also please remember that we are talking about an energy deposition profile let us say the intensity of heating or the lattice heat that we generate as a function of depth from the surface will decay exponentially. So, this exponential decay this factor which involves a absorption coefficient times depth. So, as a function of depth is dependent on the initial quantum of energy that is incident, but in course of depth or time it decreases because of this absorption coefficient and also because of the fact that much of the incident energy is reflected back.

So, yesterday we discuss as to how we can reduce this reflectivity or improve the absorptivity of laser light, going to lower wavelength or creating certain absorbent coating on to the surface or certain texturing onto the surface and so on.

So, this huge source of heat is localized, confined to the surface which can go all the way which can vary over a wide range and because of which we can actually go to a situation where we can rapidly melt vaporize or simply on the other extreme we can say only heat and not even melt.

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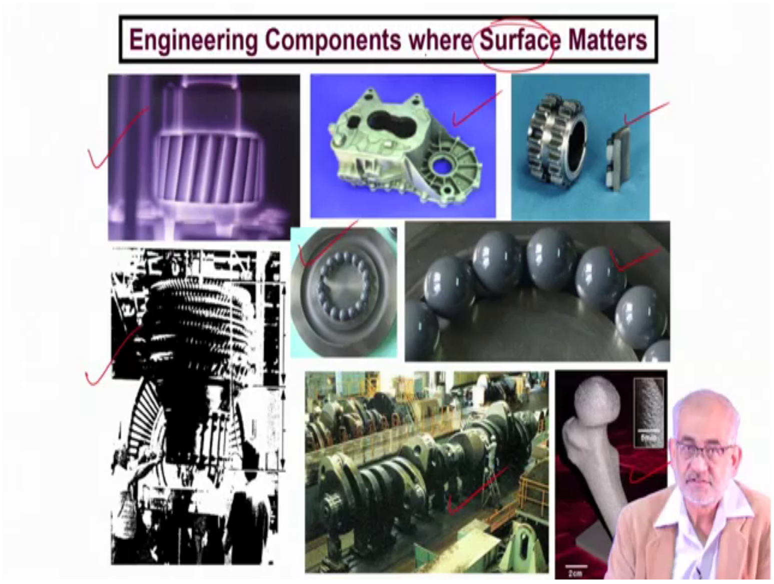

Now, why we actually are interested in overall surfacing this is the same view graph you would have seen in the very beginning at the introductory lectures and please I just want you to remember that in all these components be it a gear or a turbine engine component or this highly rotating bearing assembly or these ceramic or metallic balls that are part of the ball bearing assembly, an engine block or a sprocket or a nozzle or the camshafts or these automatic implants.

In all these cases they are very different compositionally, they may metallic, they may be ceramic, they may be steel, there may be aluminium or they may be silicon carbide or alumina titanium various kinds of metallic materials ceramic materials even polymeric materials.

And shape size or the interaction in terms of the forces acting on them or the environment in terms of temperature oxidative atmosphere or reciprocating wearing condition, fatigue conditions, high RPM rotations, interaction with body fluids.

So, all these combinations of various conditions they are very very different component wise. Yet there is one thing in common that all these components when they undergo failure the failure usually initiates from the surface. And that is purely because of the fact that the intensity of stress interaction with the surface is maximum and also the invented effect intensity at the surface is again higher than any other car parts.

So, the core does not experience as much stress intensity or environmental attack intensity as the surface experiences. So, surface always undergoes failure or is prone to undergo failure before other components actually or the core of the material undergoes. So, we need to take care of the surfaces, we need to protect the surfaces against wear, friction, corrosion, oxidation various other kinds of surface damages.

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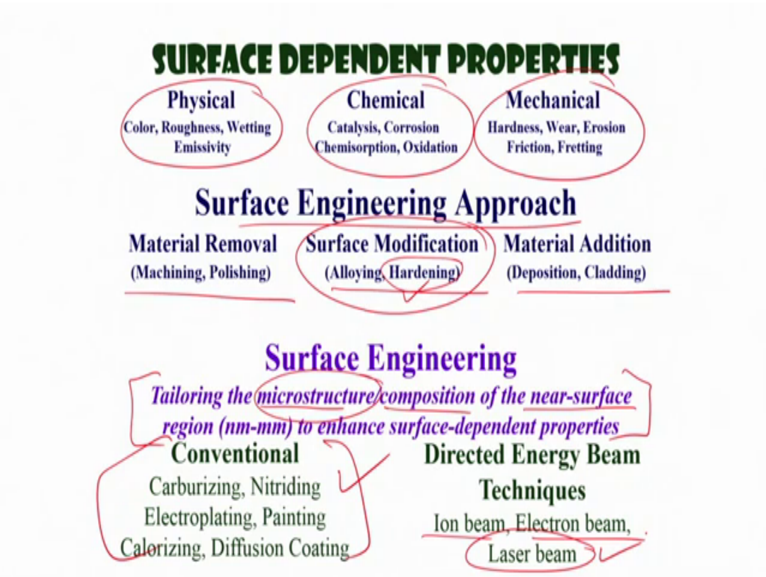

So, this again we would have discussed that we said there are various properties surface dependent properties physical, chemical mechanical and I have just listed a few representative properties under them. So, when we want to improve upon any of these physical, chemical or mechanical properties we adopt the surface engineering approach and we have already discussed we do it by material removal by modification or by addition.

Now, we in today's lecture we are going to concentrate on this part, where we actually are only modifying the surface without changing dimension and that to a subset of that which will essentially be hardening or annealing only requiring change in microstructure and no change in composition.

So, the overall scope of surface engineering is what we have discussed beat nanometer or few millimeter from the surface we call it near surface region and we modify the microstructure and composition or both in today's application using laser will be whirring. So, we will only change the surface microstructure and we will see how it can improve the surface dependent mechanical properties.

So, we are not discussing the conventional process we have already done it at length in the past, we are not even considering ion beam or electron beam we are considering only laser beam which is a direct energy beam as a clean source of non contact heating.

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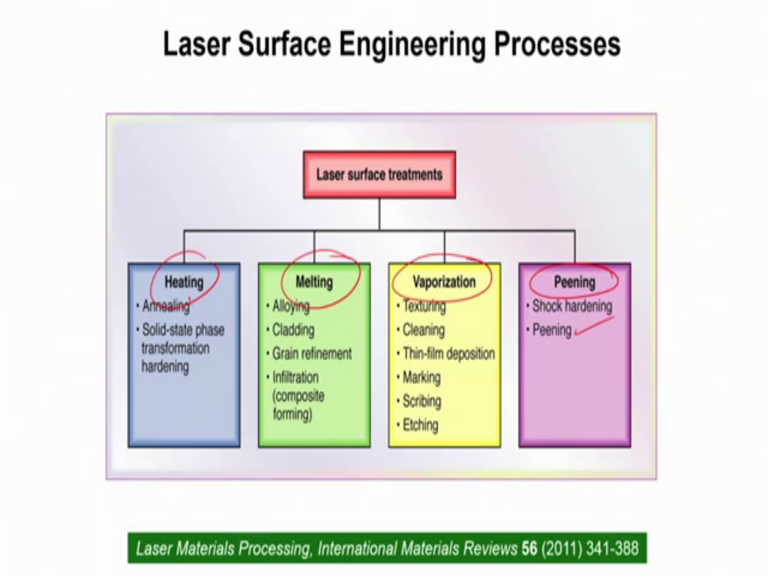

So, the overall scopes can be only heating, can be only melting. So, this is heating without any change of state this is heating with change of state, this is also heating with change of state and this is in solid state yet the rate of heating is so large that will create a very large amount of stress on to the surface. So, this is kind of a shock peening or shock hardening kind of applications.

But these are the more common types of applications, but please remember we can do many of these processes like annealing, solid state hardening, grain refinement texturing, even maybe marking or scribing all these processes without shock peening, shock hardening all these processes only through change in microstructure and no change in composition.

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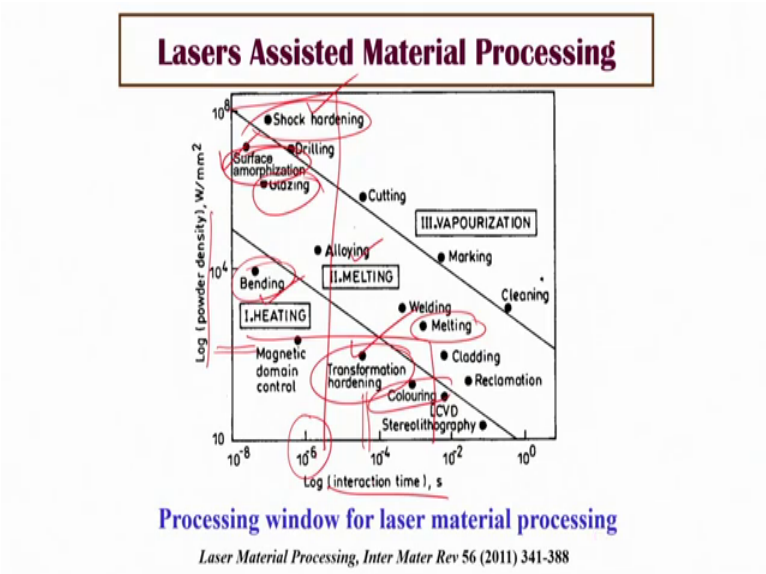

We have already discussed this, so we can go and heat remain within below the melting temperature or we can cross the melting temperature, but not across the boiling temperature. So, in the process we can do processes like bending which is a forming process we are not discussing that today, we are going to discuss transformation hardening maybe a bit of coloring or surface amortization not blazing, now all these processes actually do not require any change in competition right.

Now, when we are talking about that we have to again recall the important parameter important point that we are only talking in terms of power density and interaction time and combination of this. Say for example, when you want transformation hardening you actually do not need to apply very high power density.

So, relatively lower amount of power density, but the interaction time would be sort of moderate. On the other hand if you want shock hardening or shock peening, then you are talking about extremely high power density, but for a very short period of time.

So, then the domain is only this much whereas, for hardening we are talking about a domain like this. So, just by controlling power density in an interaction time we can achieve either transformation hardening or shock hardening or even surface immortalization or various applications like that. So, in principle we must recall that two parameters independently can be varied the power density and interaction time and that is exactly what we will do in order to change the microstructure.

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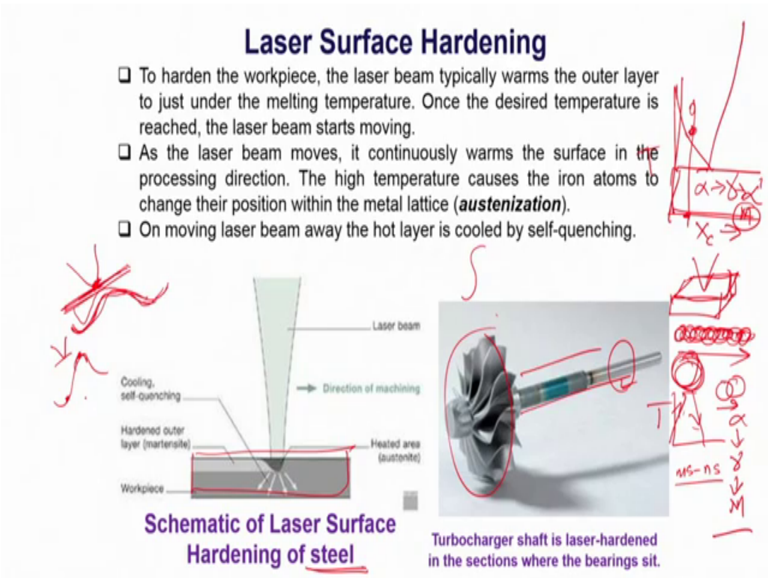

So, let us take up some examples. See in case of a steel we are aware we just need to recall the basic phase transformation principles of steel we all we need to do is to if you recall the steel part of the phase diagram. So, this is the part of iron cementite system and if we take a composition somewhere in the medium carbon range say about 0.4 weight percent carbon steel.

So, using if this is the component we are talking about. So, this component may have a certain depth or thickness, but we use a laser beam only from the surface and this beam can move all the component can move. So, that we heat here; we heat here and gradually the heated zone moves along y x direction and each time during the irradiation the temperature of this region will undergo a rapid heating and then maybe a little bit of residual time and again will cool down.

So, this heating and cooling process is entirely confined to this region for the period of time of interaction and this time of interaction can be very very low anything like a millisecond to even nanosecond. So, in this short period of time there is rapid heating and rapid cooling. So, in the process we please remember this is the composition, so this is basically the carbon amount and this is the temperature.

So, in this rap in this short period of time we are dealing with this alloy and the alloy from room temperature will go to this temperature or maybe this temperature. And in the process we will undergo a transformation from ferrite to austenite and subsequently this austenite will transform by rapid quenching by rapid its self quenching into martensite.

So, when we cool it, when we move the beam away; when we move the beam away to the next position. So, during this period the cooling cycle starts and this cooling is a self quenching cooling and because of which this series this kind of a sequence happens ferrite transforms to austenite and on austenite on fast quenching undergoes martensitic transformation. We must have adequate carbon, we otherwise we do not get say a sufficient hardening effect on to the portion we have actually irradiated.

So, let us say this is a shaft and this is the turbocharger. So, we want these corners and the skin to be hardened, also the shaft portion to be hardened such a way that from the surface until I mean towards the core certain depth should transform to martensite. And when transforms to martensite not only it hardens it also creates residual compressive stress onto the surface.

So, in the process we actually ensure better wear resistance, better fatigue resistance and all these normal circumstances you would do conventionally, you charge the whole thing, so the whole component you charge inside the furnace. Now, you unnecessarily heat the entire volume you do not need to heat and then when you subsequently quench the whole component there will be scopes of lot of dust distortion or bending or a undue oxidation discoloration and so on.

But, when you use a laser beam, so typically if you just consider this pointer. So, this pointer it moves like this and this is how exactly the laser beam also will move. So, this component will rotate, the shaft will rotate; the shaft will rotate and then the shaft rotates the stationary beam the beam remains stationary, but as the as the shaft rotates the beam also moves along the surface. And in the process point to point you actually continue to heat and the heating zone transfers.

So, this is how you actually do it very fast and at the same time you can allow the system to undergo rapid change of microstructure from one crystal structure to another. In case of steel we just this change of phases from one aggregate one type of an aggregate at room temperature to higher temperature and then subsequent cooling during cooling. So, another transformation leads to significant improvement in various trends hardness and other things.

So this could be a circular section this could be a rectangular section or shape or with complex shapes like this with a geometry which is curved geometry and so on. The advantage of using laser is that if this is the surface we are talking about and if I know this is my beam diameter, I can make sure that the beam diameter at the surface is always is in focus and if it requires instead of flat if we are dealing with a curved surface.

So, I will have to basically trace exactly this contour of the surface using a computer aided mechanism I mean controlling the beam. So, using that cad trained beam delivery system I even if the contour or the shape changes I can still make the beam move up and down exactly to make sure exactly to ensure that the focal focus point remains in contact or remains exactly at the same position with respect to the surface.

So, in the process the heating cycle will be exactly the same, otherwise if the beam remains exactly at this level and you have a curved surface, then; obviously, when this trough region is under the beam, then the heating level will be much lower compared to this crest position when you have when the distance between the beam and the peak position is very close by.

So, this is very important for us to make sure that we actually maintain the identical position of the focus with respect to this of substrate surface. So, in principle this is certainly possible with steel we can certainly do with many other elements many other systems.

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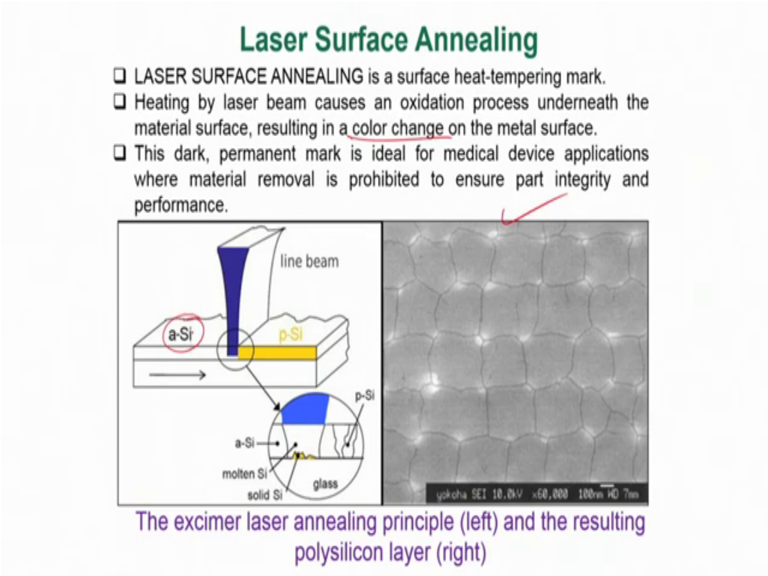

In fact, we do not necessarily have to always undergo ferrite austenite kind of phase transformation, even we will show some examples where we are able to take it to very fast cooling to take it to surface melting limited melting on to the surface followed by resolidification of this molten layer and that also can produce significant amount of hardening, but that we will discuss later.

We can also do semiconductor annealing or basically annealing of even metals or nonmetallic systems and in the process we actually can change the color to a certain extent by way of allowing certain limited amount of oxidation. Maintaining the thickness of this oxide layer and the composition of the oxide layer we can bring in various kinds of colors through an oxidative process. But otherwise we actually can also make micro structural changes like for example, this silicon wafer initially if it is in amorphous condition by way of laser beam heating we can convert this into a poly crystalline aggregate like this.

So, by changing from amorphous to poly crystalline aggregate we can make lot of changes in terms of not only appearance, but also a transport properties and color and electrical properties.

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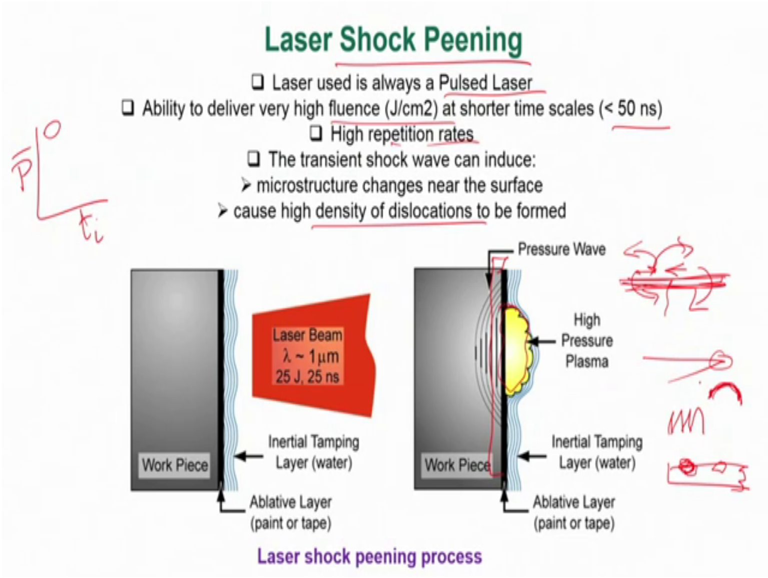

Now, another very important process is a shock peening. So, I told you that in terms of power density and interaction time, if you choose a region which is very high power density, but very small interaction time. So, of the order of few tens of nanoseconds or so, but your power density is a mega watt per centimeter square or even higher.

So, in that short period of time you actually can create a shock wave on to the surface. So, in order to create that shock wave first you would create a layer you will cover it up with some. So, it is a polymeric membrane with certain chemicals or certain substances which can undergo very quick vaporization. So, we use a pulsed laser and we allow the very high fluence in terms of, so this in terms of energy or it can be in terms of power is watt per centimeter square for very small period of time.

So, we actually allow certain bursts of laser irradiation at very high frequency, very high reputation rate and that creates that immediately vaporizes the content inside between the membrane and the surface the solid surface. So, with vaporization this portion expands and if it expands then if it is prevented to go beyond a certain point on to the right, then; obviously, it creates a huge pressure inside and this pressure creates a shockwave.

So, you create a plasma which tries to expand and you confine the plasma within certain volume and that creates a shock wave and this shock wave is a very transient one. And but nevertheless can create can actually cross immediately very high stress level which can cause certain plastic deformation create certain amount of dislocation density and in the process can make the surface harder and most importantly make the surface develop certain residual compressive stress.

So, the reason why we actually create residual compressive stress is because of creation of this high dislocation density onto the surface. But the beauty of the whole process is its not like a mechanical deformation process by rolling or by short peening or something like that, the beauty of laser assisted shock peening please remember this we are talking about shock peening and not short pinning. So, the shock peening actually allows very thin layer we are talking about a very thin layer which is typically few tens of a micrometer or even less.

So, the dimension there is no dimensional change, there is no compositional change, there is no distortion yet the surface develops fairly high few hundred mega Pascal's of residual compressive stress. So, and just to remind you the utility of such residual compressive stress is that if this is the surface and if you create deformation onto the surface, then essentially you create residual stresses which are sort of acting towards each other.

So, if there is a crack form for whatever by whatever reasons may be due to fatigue or wear or something, this crack first has to overcome this residual compressive stress and then convert this into residual tensile component and then only the crack can propagate. So, under normal circumstances when you create such high residual compressive stress on to the surface near surface region they act in a way to prevent crack formation or crack propagation and that helps the component to acquire higher resistance to wear, fatigue or any amount of mechanical damage to the surface.

And this is done by laser in a very precise manner, so if you have for example, a component a short teeth of a gear component or sharp edges of a cutting device or in a semiconductor you want a small region to be heated and leaving rest of the regions unaffected.

So, very precisely you can heat treat only this portion the dimension of which could be a few micrometers and remaining 90 percent 99 percent of the surface can be left unaffected. So, here also you can affect only this very precise corner of the cutting device or the shear component or some sharp edges or maybe the cup the curved portion of the acetabular cup can be given this kind of a treatment to create residual compressive stress. And you can do that very precisely exactly at where you want and avoid heating other zones where you do not want.

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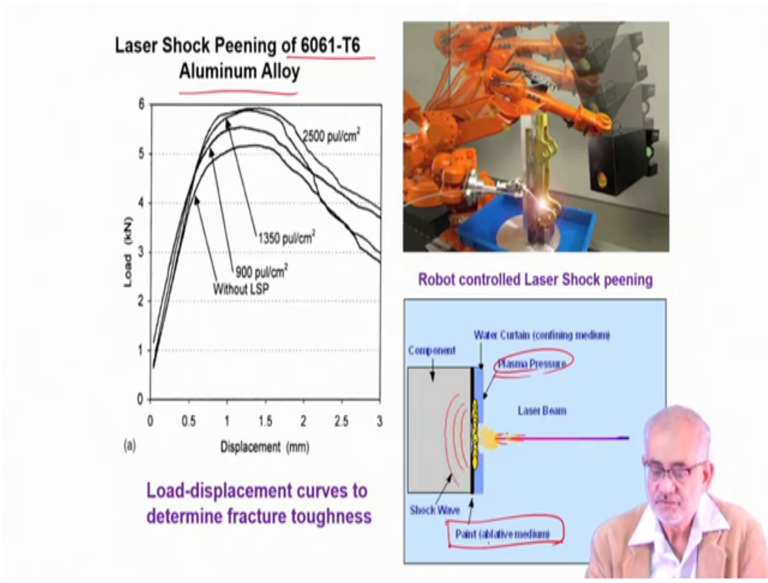

So, this is the advantage of a such kind of shock peening and this is the kind of machine and this is what you are seeing here is on aluminum alloy and these are aluminum alloy and this is how the shock wave propagates because of the creation of this temporary plasma pressure that we create by way of this kind of laser irradiation.

So, this is typically the load displacement curve, so when you actually apply such shockwaves, then you temporarily cross the yield strength of the material locally very very confined region and that is how you create certain dislocation density, but this deformation is so small volume that there is no overall distortion or change of shape of the material.

So, it is important that we actually choose the right kind of paint and then have an impervious membrane through which we can actually use the laser beam to irradiate.

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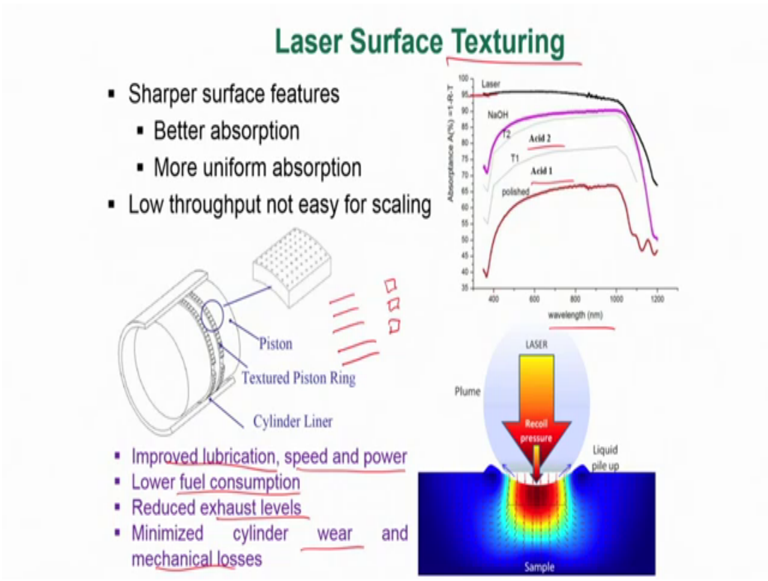

We can also do texturing which means we actually this texturing is different than crystallographic texturing. So, we are not orienting the crystallites in certain crystallographic directions, here we are basically creating certain pattern on to the surface. So, certain tiny little holes or small markings at regular intervals or certain grooves at regular intervals. Now, all these cuts or grooves or dents actually creates a very nice geometric pattern onto the surface, which improves the lubrication allows higher speed of rotation, power also produces fuel consumption so, for any rotating parts particularly let us say the engine blocks and so on.

Now, the pistons the exhaust levels are reduced and most importantly the wear and tear or the mechanical losses on the surfaces is reduced and this is done. So, actually when you do this with a laser you actually create very localized evaporation from the surface or deformation from the surface. Now, for in case of mechanical system this deformation is spread wider in case of laser it is confined to very very small level.

So, you can do for example, using certain electrochemical process or chemical process by using certain acids and so on, but with laser you actually can reach a very higher level of absorbance and hence the effect is much higher and is can be done over a very wide range of a wavelength incident wavelength.

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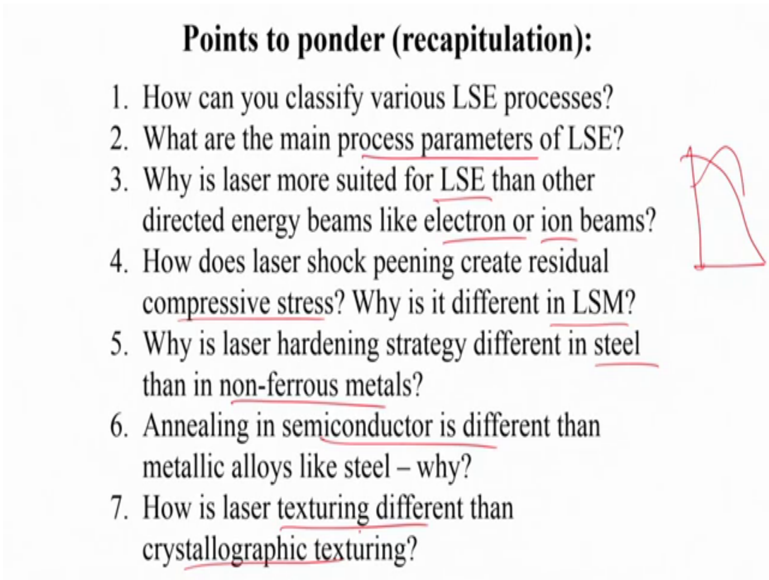

So, in order to summarize we will say that we can do various kinds of surface engineering using laser; laser surface engineering where either we change the composition and microstructure both or we change only the microstructure and not the composition. And that is possible very easily because we can control the heating rate the heating process and so on.

The main process parameters are as I said the power density and interaction time and laser is a laser fastening is more suitable than electron beam or ion being purely because of this kind of exponential decay of the deposition profile compared to Gaussian profile of electron or ion beam.

The shock peening creates a compressive stress because you actually deform locally very very thin there from the surface increase the dislocation density, but this effect is different than what happens in case of surface melting because in case of surface melting you actually create residual tensile stress because of the tendency for contraction during solidification, we will discuss that again in the next lecture. In case of steel we actually adopt the strategy of austenitization followed by martensitic transformation which is absent in non ferrous metal.

So; obviously, the strategies for hardening surface hardening using laser is going to be different in non ferrous metals we generally adopt rapid melting followed by quenching. In case of semiconductor we actually allow very transient heating in the process because of which there could be a annealing effect, annealing of the point effect density onto the surface or we can change color or instantly by way of heating we can convert an amorphous aggregate into polycrystalline aggregate.

And texturing involves creating certain surface patterns by way of creating grooves or dents or marks and so on onto the surface and this is different than changing the crystallographic distribution onto the surface in terms of crystallographic directions and planes or bringing in certain pattern in that this is more of the topological texturing than a crystallographic texturing.

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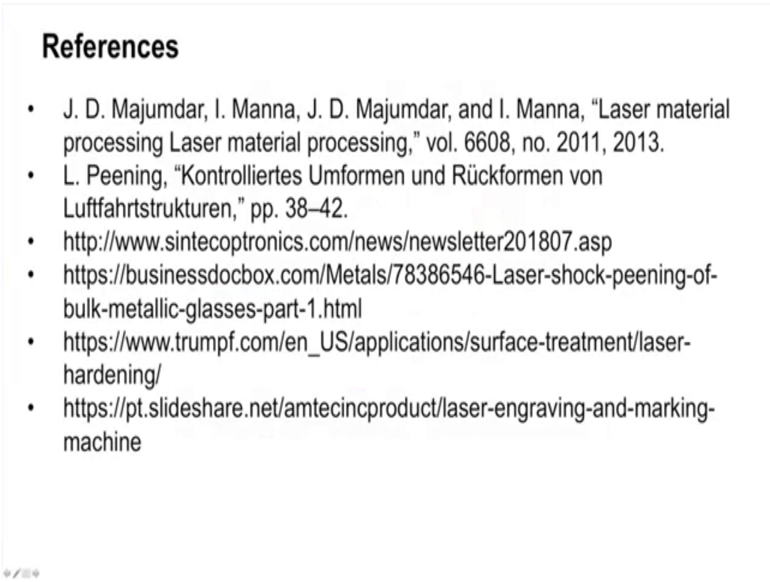

So, we will stop here and then we will move on to the next lecture where we will discuss specific examples.

Thank you very much.