

Laser Based Manufacturing
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Lecture – 14
Surface Treatment and Application of Lasers

Hello everyone. I once again welcome you to the NPTEL MOOC course on Laser Based Manufacturing. We are starting Week 5. We have completed four weeks, we are half way through the course on Laser Based Manufacturing. In our previous weeks, we have seen the fundamentals of lasers of the lasers are getting generated, what are the various prominent applications of lasers in the industry and we have seen three basic applications.

First is in material removal that is the laser based material removal. Second application we have seen in joining two different materials maybe of same type or of different type dissimilar materials then we have seen the lasers can be applied to deform the materials permanently plastically and in the fifth week of this course we will be studying how the lasers can used to improve the surface properties of various parts and products.

This week we will be studying applications of lasers in secondary or tertiary type of manufacturing processes where the parts are already been manufactured by using some primary or secondary manufacturing processes such as machining, welding or the forming application and now we have to improve the surface properties of some of the parts or some portion of the parts or the products.

How lasers can help us to modify the surface properties of these parts, that we will be studying in this week. Let us begin our discussion on laser-based surface treatment. Here surface treatment, we will be studying by using the thermal energy which is generated by using the photon energy of the lasers. In this first lecture we will first try to understand what is the meaning of surface treatment? And how the lasers can be applied to treat the surfaces metallic surfaces that we will be studying in this lecture.

Well my friends heat treatment is a very basic process which is often being used in the manufacturing industry. We are generally producing the parts by using machining or forming and we are generating the parts of accurate dimensions, good quality like surface quality.

But during the transformation of raw material into finished product there maybe chances of having some internal stresses generation or there maybe some problems on the surfaces and when we use these parts for the application then there maybe chances of having propagation of cracks, micro cracks which are there on the surface or there maybe chances of having failure of the parts due to low level of mechanical properties.

So, we have manufactured the parts. Now, we have to enhance the mechanical properties to certain extent maybe on the surface itself which is getting applied with the variety of forces or that temperatures in actual applications or in its real applications.

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Heat treatment

- Heat treating a precision machined component -> controlled heating and cooling process that alters the physical properties of the metal to obtain a specific requirement.
- It is used to increase strength, hardness, and wear resistance.
- It is also used to relieve the internal stress, improve machinability, and improve electrical or magnetic properties, or increase ductility and softness.



<https://brofurnaces.com/wiki/vacuum-heat-treatment-2.html>

So, heat treating is a precision. Heat treatment of precision machine component, how it is possible. We have to use heat we are using thermal energy. We are heating the components by applying the thermal energy and we are allowing that heated component or part to cool down. During this process of cooling we are getting relieving of some stresses we are getting generated during the process of its manufacturing.

During this process of heating and then cooling; the cooling maybe rapid cooling or the cooling maybe the gradual cooling. There is enhancement in the mechanical properties of the material and we can choose a particular mechanical property and accordingly we have to choose the heating temperature and the cooling process or the methodology for the cooling.

We will be seeing variety of heat treatment process in our next few slides. Heat treatment in general increases the strength of the material it also improves the hardness and wear resistance and as I mentioned right now it is also used to relieve the internal stresses which are generated during its manufacturing. The heat treatment also improve the machinability.

It improves the ductility, the flow stresses are reduced and the product or the part can be easily machined. Moreover, the heat treatment is also helpful in improving the electrical as well as magnetic properties to enhance the ductility and softness. On your screen you can see a variety of precise components which are generated so lot of gears you can see on your screen and these micro, macro size gears of various types are used in the industry.

The process of their manufacturing is complex. Moreover, improving the process of their mechanical properties is much more complex. We have to apply in a controlled fashion the heat energy and we have to apply the steps meticulously to cool it down to get the required properties.

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Heat treatment

It involves 3 basic steps:

1. **Heating:** the metal is heated to a specific temperature where the structural properties will change.
2. **Soaking:** the metal is maintained at the specified temperature until the entire part has been heated evenly.
3. **Cooling:** the metal is cooled back to room temperature at a specified rate.



<https://www.industrialheating.com/articles/96355-heat-treating-automotive-parts>
Photo credit: cherezoff/Creatas Video® / Getty Images Plus via Getty Images



<https://www.industrialheating.com/articles/96355-heat-treating-automotive-parts>
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The heat treatment process it basically involves three steps. The first step is heating, the material is heated up to a specific temperature where there is a change in structural properties of the material. We have to heat the material by applying some energy that may be generated due to the gases. We have to burn the gases and get the thermal energy or we can use the induction heating as well electrical heating or we can use the direct application of the heat energy through the radiation as well.

Then we have to soak the material. Soaking is a next step. In this step the metal is maintained at specified temperature until the entire part has been heated evenly. We are increasing the temperature and we are allowing the temperature to get uniformly distributed among the part, among the various portions of the part and afterwards we are cooling the work part.

During this process of cooling we are getting the enhanced temperature of the work part to the room temperature, to the ambient temperature at a specified rate. Cooling rate is very much essential to be maintained. It is decrease in the temperature of the component per unit second in general.

Now, what are the various applications of the surface treatment? You might have seen that we are using various machines, mechanisms around us or in the industry as well. And there is relative motion between variety of linkages or parts of the machine elements or mechanisms. Now, when there is a relative motion when there is a contact so there is a wear and tear of the parts, there are generation of stresses of the parts and due to that the chances of failure of the part should be more. Consider the very basic element that is the bearing balls or rollers which are used in the transmission of power we are using bearing.

That bearing surface is heat treated their properties are enhanced. On your screen; two different types of products are shown that is set of gears and the bearing elements. These are the bearing elements which are coming into contact with its bearing surface and their rolling and not only their rolling they themselves are carrying the weight as well they are transmitting the power as well.

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Heat treatment: **Hardening**

It is used primarily on steels and steel alloys. It can also be used on some grades of aluminum.

There are 4 basic types of heat treating for steel:

Hardening: It is used to harden the material and make it stronger. But the ductility of the material will decrease (ie becoming more brittle).
Need for tempering after hardening.

Methodology:

- The material is heated to a high temperature slowly -> soaked in a particular temperature for a specified time -> cooled quickly by plunging them into water or oil.
- This rapid cooling in a liquid is called quenching.

Now, let us see what are the various heat treatment processes being used in the industry. The first and very prominent heat treatment process is hardening process. It is primarily used to process steels and steel alloys. It can also be used to process or to treat some of the grades of aluminum as well. There are basically five basic types of heat treatment processes that is the hardening is first and we do have three more processes that we will see in our later slides.

What we are doing in the hardening? We are hardening the material as the name suggest we are increasing its hardness, we are making the material stronger, but what is happening during this process of hardening and making the material stronger that the material may lose its ductility, its ductility will reduce the material will become brittle material. To regain its ductility to certain extent we are going for another heat treatment process that we call tempering operation.

By hardening we are increasing the hardness of the material and then subsequently we can go for tempering to regain to certain extent the ductility of the material. So, what is the methodology to carry out this hardening operation? The material is first heated to a high temperature slowly. It is to be noted that the heating is carried out in a slow manner with low pace.

Then we are soaking the heated material at a particular temperature for a definite time, for a definite duration and then we are cooling it quickly and the cooling would be carried out by plunging the component or the part into water or oil. It all depends upon what the type of

material that we are using. If the material is getting oxidized easily then we are using the oil as well to reduce its temperature to the normal temperature.

When we are rapidly cooling the material that process is called as quenching operation. This is very fundamental information some of you might have already been studied in your second year metallurgy course as well. When we cool the material at a very rapid cooling rate that is called as the quenching operation.

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Tempering ✓

- Hardening increases the internal stresses in a material.
- The tempering will relieve those stresses.
- Methodology has similar 3 steps process as of hardening, however it is carried out at lower temperatures.
- The cooling process for tempering is almost always done in air and not a liquid.

increase → heating
Soaking
Cooling

Then next type of heat treatment process that is tempering process. During the process of hardening there are chances of increasing the internal stresses as well and we have to reduce these internal stresses and for this purpose we are using the another heat treatment process that is tempering process. This process is relieving the stresses the internal stresses and basically it has three steps and these three steps are very similar to the hardening process.

Hardening process we have seen that there is increase in the temperature that we call heating then soaking and the last step that we have seen is cooling. In tempering as well, we are following the same three steps. However, the prominent or the fundamental difference between the hardening and tempering is that the temperature which is getting enhanced it is not up to the temperature that we are increasing in hardening.

The maximum temperature to which we are heating up the work part or the material during tempering is lower than the maximum temperature that we are heating up in the hardening. That is the difference; so maximum temperature is lower in tempering operation and the

cooling process which we are carrying out in tempering operation is always done in air not in the liquid.

We are not cooling the part in water or any oil, we are cooling the part in air itself. These are the two differences between the hardening and tempering. First is the maximum temperature and the second one the medium of cooling. In hardening, we are using water or oil and in tempering we are using air for the cooling operation.

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Annealing

- It is used
 - to increase ductility of the materials (making the metal less likely to crack)
 - to relieve stress, or soften the metal.
- It is generally considered the opposite of hardening.
- **Method:**
 - the metal is heated very slowly to a specified temperature
 - held the metal at that temperature for a specified amount of time (soaking)
 - then air cooled slowly- usually by leaving the parts in the furnace as it cools down normally.
- With low-carbon steels, the temperature for annealing is high, and as the carbon level increases, the temperature for annealing will decrease.

The third process of heat treatment which is used in the industry is annealing operation. In this process we are increasing the ductility of the material so that the material will likely to have less cracks which is very much essential when we are producing or machining shafts which are rotating continuously and these shafts are transmitting the power. You consider if there is a micro crack and during the application of fluctuating loads these micro cracks will get propagated and there are chances of having catastrophic failure of the entire system.

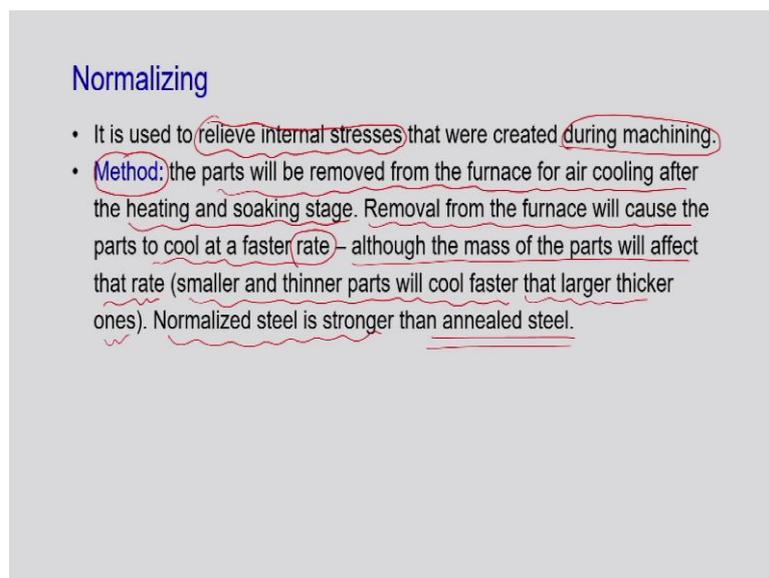
It is very essential to have softening of the material so that we can reduce the chances of having the micro cracks. Moreover, there is reduction in the stresses is also envisaged it is desired. The process of annealing is also considered to be opposite to the hardening process. The methodology is there on your screen. In this process, we are heating up the metal very slowly.

In hardening process we are heating up the material at a rapid rate. It is achieving the specified temperature by slow heating and then we are carrying out the regular soaking

process for specified duration and then the parts are allowed to cool in air, not in oil or a water usually the leaving the part in the furnace as it cools down normally. We are not talking out the parts out of the furnace. We are allowing the parts to get cool down inside the furnace itself.

When we want to anneal the low carbon steel we are annealing it at temperatures which are quite high in comparison with the high carbon steels. When we try to anneal the high carbon steels or we can generalize the statement if we increase the carbon percentage inside a ferrous material then the temperature for annealing will get reduced. We can work at a low temperature when the carbon percentage is high.

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Normalizing

- It is used to relieve internal stresses that were created during machining.
- **Method:** the parts will be removed from the furnace for air cooling after the heating and soaking stage. Removal from the furnace will cause the parts to cool at a faster rate – although the mass of the parts will affect that rate (smaller and thinner parts will cool faster than larger thicker ones). Normalized steel is stronger than annealed steel.

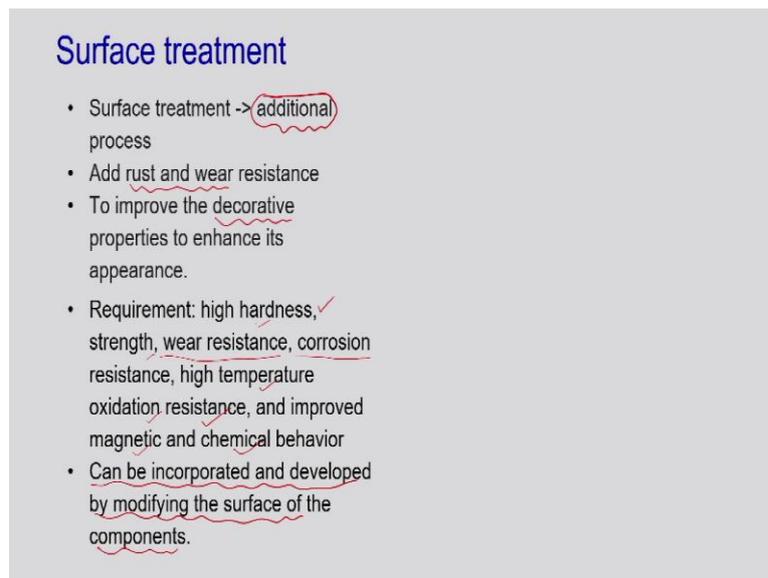
The next process is normalizing. It is again used to relieve the internal stresses that are created during machining operations. As I mentioned in machining operations we are cutting the fibers, we are cutting the grains and due to that there is generation of stresses and that stresses are relieved by using the normalizing operation. What is the method of normalization?

The parts will be removed from the furnace for air cooling after heating and the soaking stage and the removal from the furnace will cause the parts to get cool at a faster rate. In normalizing operation we are not allowing the material to get cool down in the furnace. We are taking it out from the furnace and allowing the part to get cool down in the air so there would be rapid cooling of the material in the normal air in ambient atmosphere.

Although, the mass of the parts will affect that rate. Of course, the cooling rate is dependent upon the mass of that particular part or that product. Smaller and thinner parts will cool faster than that of the larger or the thicker ones. So, that is very obvious. Normal or thinner parts will get cool down due to less mass associated with them. Normalized steel is stronger than annealed steel.

So, the hardness or the material properties of normalized steel is comparatively high than the annealed steel.

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Surface treatment

- Surface treatment -> additional process
- Add rust and wear resistance
- To improve the decorative properties to enhance its appearance.
- Requirement: high hardness, strength, wear resistance, corrosion resistance, high temperature oxidation resistance, and improved magnetic and chemical behavior
- Can be incorporated and developed by modifying the surface of the components.

Now, let us summarize the basic heat treatment processes that we have seen. We have seen that the heat treatment processing is an additional one to the fundamental manufacturing processes or transformation processes that we are using. By carrying out the surface treatment we are increasing the rust or wear resistance of the surface of the parts which is very essential.

Moreover, the surface treatment is helping to improve the decorative properties, the appearance of the work parts. Then there are other benefits of doing the heat treatment, surface treatment and these are enhancement in hardness, strength, wear resistance, corrosion resistance, temperature oxidation resistance, magnetic and chemical behaviour of the parts or products.

And the surface treatment as we have seen that can be carried out by modifying the surface of the components by variety of processes. Conventional process we have seen that it is

induction heating or the furnace heating and then carrying out the cooling operation of the parts. When we have seen the previous heat treatment processes, these processes are changing the material properties or mechanical properties of the entire product or an entire workpiece.

Entire the workpiece, but in certain cases we have to just modify the surface of the part, surface of the product and there are various techniques being used in the industry.

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Surface treatment

- Surface modification techniques
- Thermochemical coatings (nitriding, carburizing, cyaniding)
- Electrodeposition ✓
- Spray coatings (flame spray, thermal spray coating, plasma spray coating, etc.)
- Physical vapor deposition (PVD) } Depth
- Chemical vapor deposition (CVD) }
- Laser surface modification (LSM) }

And these are thermomechanical coating. We can coat, we can apply the required material or the material which is providing us the required mechanical or surface property and these processes are nitriding, carburizing, cyaniding. By addition of the nitrogen or by having a layer of carbon we can improve the mechanical properties. There is a process of using electrical energy that is electro deposition process for enhancement in the properties of the surface.

We are spraying the required material by using flame that we call flame spraying, thermal spray coating, we are using plasmas as well for having the required coating of the material on the surface and then there are advance coating method such as physical vapour deposition and chemical vapour deposition which are often used in the industry to improve the surface properties.

However, the problem of PVD and DVD is the depth, PVD is a physical vapour deposition and CVD is a chemical vapour deposition the depth of dilution of the foreign elements in

over the substrate is very low; it is in microns at the max. PVD is being used to coat the materials in nanometric level, but for macro level applications on the shop floor or on the road condition, real life condition when we want to have the dilution depth of the coating in micrometers or in certain cases the millimeters.

We have to use some process and that process is the laser-based surface deposition; laser-based surface modification. When we are using lasers to have the controlled modification of the work parts that is LSM surface modification using lasers.

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Laser based surface treatment / modification

- A surface treatment -> to harden or clad surfaces of ferrous metals
- Hardening : a laser beam with a high power density heats a small area on the surface of the workpiece
- Changes to the atoms in the lattice of the material (austenite).
- As the beam passes to another spot on the surface, the heated area is rapidly cooled by the surrounding metal -> self-quenching
- Rapid cooling -> stops the lattice from returning to its original arrangement
- Results in a very hard surface structure : martensite.

The diagram illustrates the laser-based surface treatment process. A laser beam is directed at a workpiece, creating a heated area (1) and a self-quenching area (2). The laser beam is shown as a blue line with a red tip, labeled 'Laser Beam'. The workpiece is a rectangular block, labeled 'Work part'. The heated area is labeled '1' and the self-quenching area is labeled '2'. The diagram shows the laser beam moving across the surface of the workpiece, creating a series of heated and self-quenching spots.

Now, let us look at how lasers are helping we will have a detail discussion here. Laser-based surface treatment or modification it is basically hardening process or it is also a cladding process. It can be a hardening process or it can be a cladding process of ferrous material. So, let us see the hardening of the work part or the work surface by using lasers. Here we are using the regular laser.

However, the laser power must be high enough to heat up the work parts. We are applying the laser beam energy and we are generating the high-power densities over a small area of the work part and then we are allowing it to cool it down. In a very similar way that we have done in our hardening process. In hardening, however we have heated up the entire body of the part or the work material.

But in laser we do have the advantage of having controlled heating and cooling of certain material, certain portion of the work part. However, the process is very similar heating it up

and allow it to cool it down. During this process of hardening there would be changes to the atoms of the lattice of the material that is the austenite. During the process of laser irradiation these things will happen.

And as the beam is passing over as the beam passes it crosses the work part to another spot, to the next destination of the laser beam on the surface, the heated area will rapidly cool down due to the surrounding metal. These we have already seen in our laser based forming as well. We are scanning the work part for a very small region, but the surrounding work part is at a normal temperature it is a ambient temperature.

It is a comparatively very cool with the heated surface. During the process of the laser application for surface modification as well. There is heating up rapidly and cooling it down rapidly due to the surrounding part. This unique attribute or characteristics of the laser is called as self quenching. It is having the self quenching capability, characteristics. Here as we can see that suppose we are having a work part.

And there is a laser beam energy that we are applying. Consider a defocus laser is getting applied over the surface. This is the laser beam defocus laser beam that we are applying, this is the work part. Laser is moving in this direction and during this movement there is a change in the lattice of the material austenite and as the laser spot is getting changed to its next spot. Consider in this case it is going to the next spot from one to two.

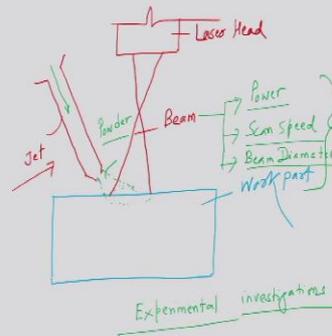
There would be rapid cooling and this rapid cooling is called as the self quenching. So, what will happen what would be the benefit of the rapid cooling? These rapid cooling is stopping the lattice from returning to its original arrangement and this is resulting in hard surface structure that is martensite. This peculiarity of getting it cool down due to the surrounding large area or volume during the laser-based operation.

It is a rapid cooling due to the surrounding area will lead to generation of martensite which is the hard-surface structure. In this way by having the controlled heating and cooling during the laser surface operation we can enhance the hardness. In the next slides we will see how the hardness got increased by the laser processing.

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Laser based surface treatment / modification

- A surface treatment -> to harden or clad surfaces of ferrous metals.
- For cladding, the high temperature of the laser helps bond tracks of injected powder with the surface of the workpiece.



The next process is cladding process. In cladding process we are depositing, we are adding a foreign material over the laser process material and due to the addition of the foreign material there is change in properties, surface properties of the material. For cladding the high temperatures of the lasers are helping for bonding the tracks of the injected powder. Here we are injecting a powder and to have the bonding of these injected powder with the substrate we have to increase the temperature.

And the lasers are helping here to increase the temperature of the substrate as well as the powder that to be bonded. Here if suppose a work part which is to be cladded. We have taken a work part here and let us have a laser the high power lasers are in general used Nd:YAG or CO₂ lasers maybe in a continuous mode or in a pulse mode. This is laser head and this is the beam.

Here we are having a jet and through this jet the powder that is to be bonded is applied. This is powder. The laser beam is applied in such a way that it should generate the temperature which is more than the melting point temperature of the work part as well as the powder. So that power and scan speed is to be meticulously chosen for getting the required temperature. Powers, scan speed, and the beam diameter.

It would be a very interesting experimental investigation to find out the required properties and to find out or to derive the optimal levels of process parameters to get the required properties. There would be a little bit of depression may create and there maybe some sort of bead formation will also happen over here to enhance the properties of the surface.

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Attributes	LSA	Electrodeposition	Thermal spray	CVD	PVD
Dilution	High	Nil ✓	High	Nil ✓	Nil ✓
Bonding strength ✓	High	Low ✓	Moderate	Low ✓	Low ✓
Heat-affected zone ✓	Low	Nil	High	Low ✓	Low ✓
Coating thickness ✓	Moderate	Moderate	High	Low	Low
Repeatability ✓	High	Low	Moderate	High ✓	High ✓
Controllability ✓	High	Low	Moderate	High ✓	High ✓

Laser Surface Treatment, Anas Ahmad Siddiqui and Avansh Kumar Dubey, DOI: 10.5772/intechopen.91800

On your screen we have got around five different processes. The first process is the laser surface modification. Second one is electro deposition, third one is thermal spray coating, CVD and PVD. Five processes have been taken and let us see where the lasers stand. As far as the attributes are considered we are considering here the dilution; the dilution depth, the strength of the bonding, HAZ heat affected zone, the coating thickness, the repeatability and the controllability.

If you consider the dilution the laser based process is standing high in comparison with the other processes. Of course, the thermal spray coating is also equally providing the dilution depth. As far as electro deposition and the CVD or PVD the dilution would be nil. As far as the bonding strength is concerned, the bonding strength in laser-based processes are found to be very high.

However, the thermal spray coating is providing the moderate level of bonding strength and the electro deposition CVD and PVD are at very low level. The third one is the heat affected zone and it is desired to have the low value of HAZ during the thermal energy-based processes. HAZ is found to be very low because of controlled irradiation of the laser beam energy for very small area during its processing.

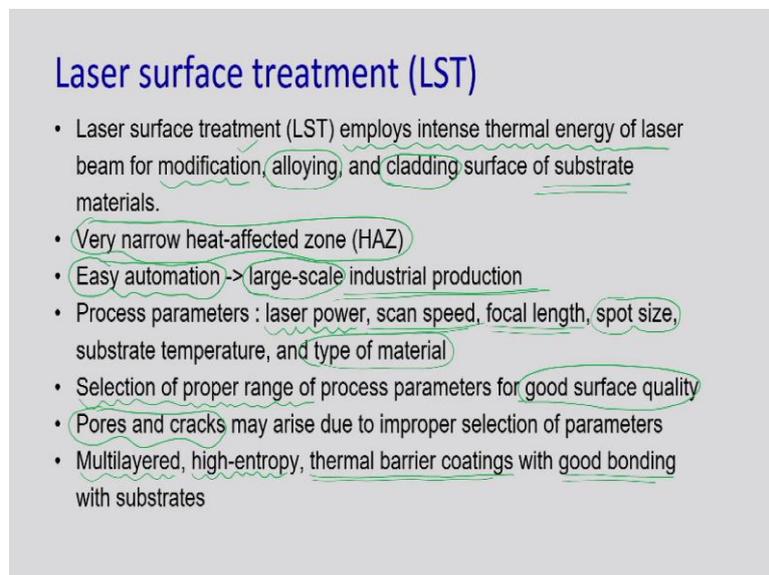
HAZ is low, the electro deposition is providing mean heat affected zone because we are not using any heat during the electro deposition. As far as thermal spray coating it is purely thermal based process, the HAZ is very high for CVD and PVD it is low. The thickness of

coating that is moderate in electro deposition LSA, however, in thermal spray coating we are getting the coating thickness in millimeters which is comparatively very high of the LSA and the electrodeposition.

In thermal spray coating we are using the heavy thermal energy; a large thermal energy to coat the materials. The repeatability is very high in lasers. However, in thermal spray coating it is moderate because the area or the volume of application is very high, the energy application will not be in that much of control as of the laser beam energy. This last parameters that we will be considering is controllability.

There also you can notice that the thermal spray coating is at moderate level in comparison with the laser-based level that is very high. CVD also we can have repeatability more and the controllability also more.

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Laser surface treatment (LST)

- Laser surface treatment (LST) employs intense thermal energy of laser beam for modification, alloying, and cladding surface of substrate materials.
- Very narrow heat-affected zone (HAZ)
- Easy automation -> large-scale industrial production
- Process parameters : laser power, scan speed, focal length, spot size, substrate temperature, and type of material
- Selection of proper range of process parameters for good surface quality
- Pores and cracks may arise due to improper selection of parameters
- Multilayered, high-entropy, thermal barrier coatings with good bonding with substrates

Now, let us summarize today's class that is on the heat treatment process, the fundamentals of heat treatment process and the basic introduction to this laser-based surface treatment. During the laser-based surface laser treatment and intense thermal energy of laser is applied and that can be further used for modification of the surface parameters or the mechanical parameters of the work material.

We can carry out alloying, we can change the composition of the work part or the surface by adding various elements by carrying out the alloying we can clad the surface. We can have a coating of surface of significant size, significant thickness over the substrate material. All

these things are possible by using the lasers. The laser surface treatment is offering us various advantages as we have already seen that the HAZ is very narrow.

It's very low which is very prominent advantage of the LST laser surface treatment processes. By using the CNC application, we can have easy automation, easy control of the laser over the work part material. So, that is why for large scale industrial application the laser-based surface treatment is finding a wide application in the industry. There are various process parameters associated with the laser surface treatment that is power, scan speed, the focal length, spot size, the laser beam diameter size, the temperature of the substrate and the type of material. Of course, type of material means its thermal property such as its conductivity, heat capacity and density, needless to say that it is important to have proper selection of the process parameters to achieve a good surface quality and if you do not select the process parameters properly certainly there would be chances of having pores and cracks during the laser processing of the material because we are melting the surface, we are adding the powder and we are allowing it to cool down.

There would be chances of having pores and when the laser process material is getting cooled down rapidly there maybe chances of having the cracks due to thermal residual stresses. The laser surface treatment is widely used to have multilayered components to process high entropy alloys to have the thermal barrier coatings with good bonding characteristics with the substrate.

So, with this basic introduction to heat treatment and the utilization of lasers for heat treatment I stop for today's class. In the next lecture, we will take up a case study on laser-based hardening of a work part. So, till then good bye! Thank you!