Laser Based Manufacturing

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Module # 05

Lecture # 16

Laser Surface Alloying

Hello friends, I welcome you all to the third lecture of Week 5 of NPTEL MOOC course of laser based manufacturing. In this week we are studying laser-based surface heat treatment processes. In our previous lectures we have seen that treatment by using heat, how the material properties are getting improved, the fundamentals of heat treatment and we have also seen how lasers are helping to improve the surface properties of parts and products. In the second lecture of this week, we have seen hardening process by using lasers in detail that we have seen.

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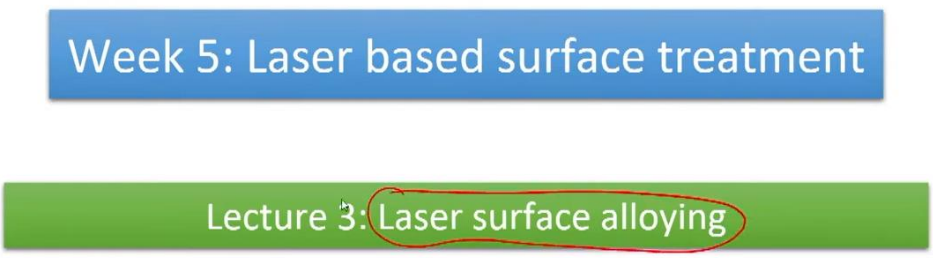

Well, in today's lecture we will be studying the next surface treatment process, that is laser surface alloying. Laser surface alloying is a very prominent and useful surface treatment process and how it is helping to improve the properties of the material that we will be studying.

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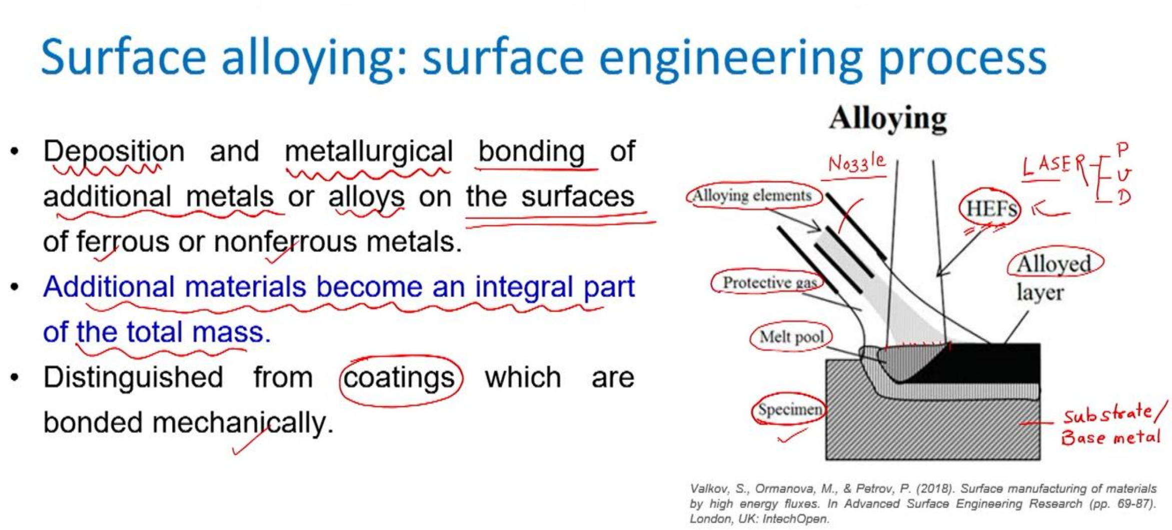

Surface alloying is basically a surface engineering process. Here we are depositing a foreign material and that foreign material may be in the form of powder, or it may be in the form of wire and then we are carrying out the metallurgical bonding of this additional metal foreign material over the surface to the substrate. This is the deposition and metallurgical bonding of additional metal or alloy on the surfaces of ferrous or non-ferrous material. Why it is essential to carry out such operation of the surface alloying? As we have seen in our previous lectures as well, in many of the mechanical engineering applications there is sliding contact of various elements of mechanisms and during this sliding there is wear and tear, many a times there are formation of cracks and that cracks may get propagated and there is a failure of the part.

Now, instead of disposing the entire part, can we repair that part? Can we re-manufacture? Can we re-engineer that particular part? so that we can save the part which might have consumed lot of resources such as energy, manpower and of course, the money instead of disposing the critical parts, can we repair them and utilize for further application? can we enhance their life during the operation? Here we are using a laser-based surface alloying, whatever the worn out parts are there that can be repaired or maintained by using alloying with the materials which will provide hardness, wear resistance and corrosion resistance.

During the process of alloying, basically the additional material will become an integral part of the total mass and it is distinguished from the coating. In coatings in general, the material is getting bonded mechanically, and alloying is the process in which the deposited material will get mixed thoroughly with the substrate material and we are getting entirely different composition. As we are getting entire different composition, the material properties of that composite of that material would be different than the added material and the substrate material. In this way we can generate a layer which may have the improved properties., enhanced properties of the surface.

How to carry out this particular operation by using lasers? On your screen you can see a schematic of a laser-based alloying. Here you can see we have taken a specimen or substrate or even we can call this as a base metal. Then, as we have seen that we want to have the thorough mixture of deposited material with the substrate material, we need to have an energy source which will generate thermal energy. In laser based surface alloying we are using lasers. The lasers parameters are chosen in such a way that power, velocity and diameter are chosen in such a way that we will be getting high energy fluxes, very high energy fluxes are essential to increase the temperature of the substrate material as well as the deposited material above their melting point temperatures. When there is an increase in the temperature of base material and the deposited material above the melting point temperature, then these two materials will get mixed together and after passing the laser over the surface, this mixture will get solidified at the same place and in this way we are getting an alloy over the surface of a definite thickness.

Here you can see how to apply the alloying element? To apply the alloying element we should have certain arrangement and that arrangement is called as nozzle. This is the nozzle and through this nozzle we are applying the alloying element at the site of application, at the place of application of the laser beam. Here the alloying element will come, the laser will melt that alloying element, it will also melt the specimen and there is a formation of melt pool. The melt pool is formed and as the laser is passed over then we are getting the alloyed layer. Now to protect the molten metal from oxidation we are using some gases inert gases, protective gases that in general the argon is used as the protective gas.

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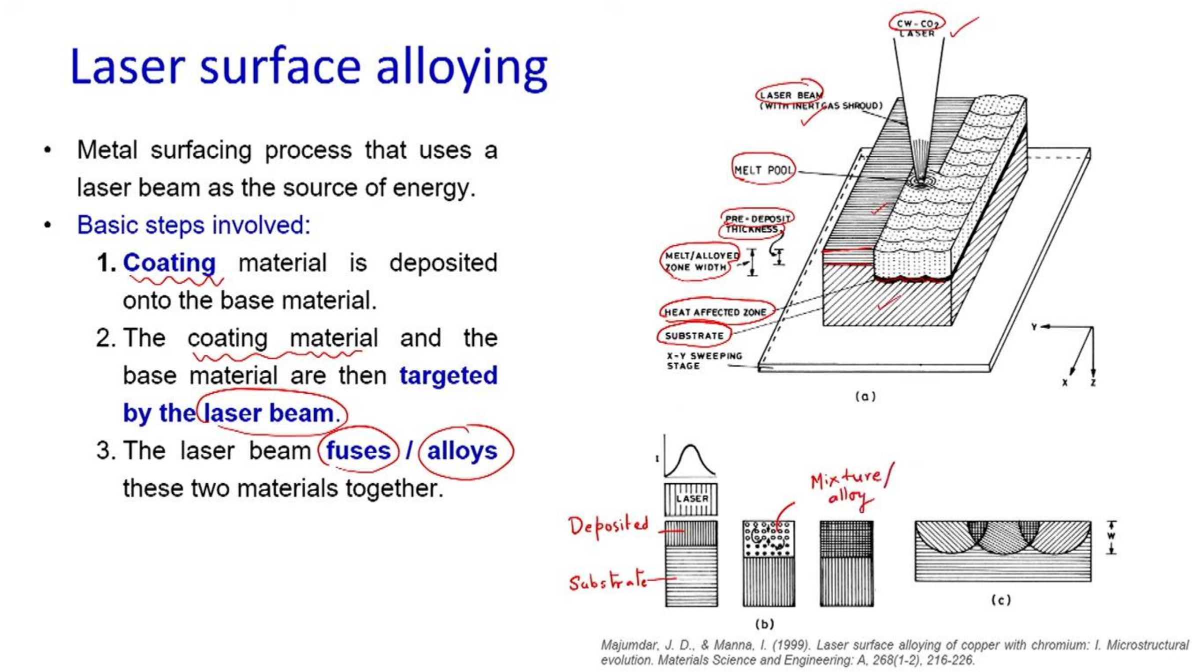

Now there is another way also to have the laser-based surface alloying. Instead of having a jet of particles of foreign materials, we can deposit or we can paste the foreign material over the surface and then we apply the laser beam or the surface. This is the second method or the second way to alloy the foreign material over the substrate material.

On your screen you can see the second arrangement. In this arrangement you noticed here, we have got a substrate and then there is the pre-deposit and it has certain thickness. This is the pre deposited foreign material of certain thickness and then we are applying the laser beam. Of course, the laser beam has the inert gas. In this case you can see a CO_2 continuous wave laser is applied.

Now what is happening when we apply the continuous wave of CO_2 laser? There is increase in temperature and formation of melt pool of the deposited material as well as the substrate material and there is re-solidification of the mixture over the surface. We also got some heat affected zone. Wherever there is a transition of the alloyed layer with the substrate material, we get another zone that is called as the heat affected zone. Here the peculiarity of alloying is that we get an entirely different mixture and its properties are entirely different, however, the thickness of alloyed layer is comparatively less.

The steps involved in laser surface alloying are there on your screen. We have to coat the material first and then we are irradiating the coated material by the laser beam, which we have already seen and then there is a fusing or alloying of the foreign material with the substrate material. Schematically the same thing have been shown over here, this is the substrate material, this is deposited material and this is the mixture or the alloy that we got.

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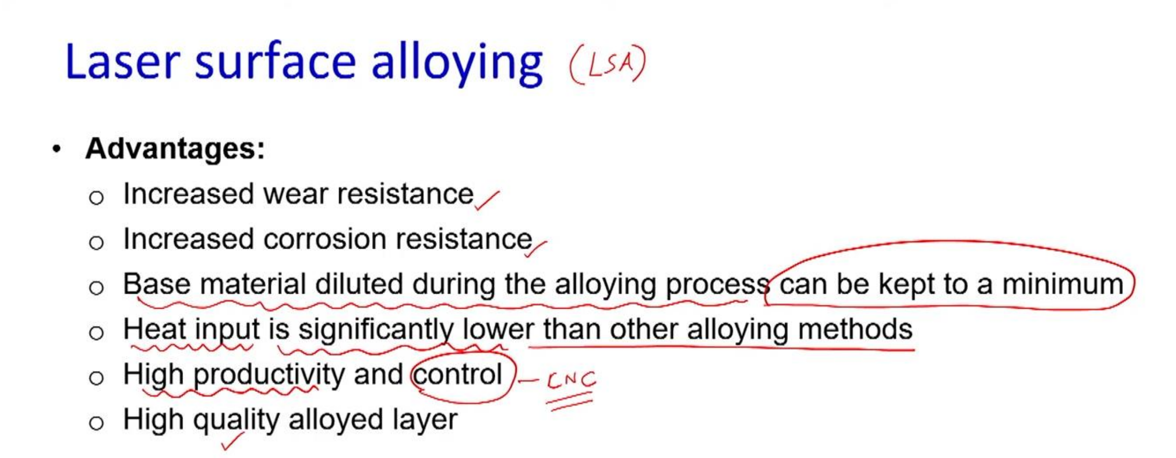

Now let us see what are the advantages of the laser surface alloying. This laser surface alloying, which is abbreviated as LSA offers increased wear resistance, increased corrosion resistance, the base material diluted during the alloying process can be kept to a minimum, this is the peculiarity or an important characteristic of the laser surface alloying, that the dilution can be kept minimum in laser based surface alloying. There are other surface alloying techniques: thermal energy based surface techniques - thermal energy based surface alloying techniques such as the thermal spraying where there would be uncontrolled dilution of substrate material with the deposited material. But in this case we can controlled the dilution, we can control the mixing of the substrate material with the deposited material by having the controlled area irradiation. That is the advantage of laser based surface alloying.

The heat input is significantly lower than the other alloying methods. In other alloying methods, such as the thermal spray or plasma based surface alloying, we have to apply enormous energy and that energy will be utilized for the coating as well as changing the material properties, but that is affecting the material properties of the substrate material even because there would be high HAZ high heat affected zone and that can be reduced by having the control irradiation. Therefore the heat input is comparatively low in the laser based surface alloying.

The productivity is high and we can easily controlled which we have already seen by using CNC technology. And we can get a very high quality alloyed layer by using laser based surface alloying.

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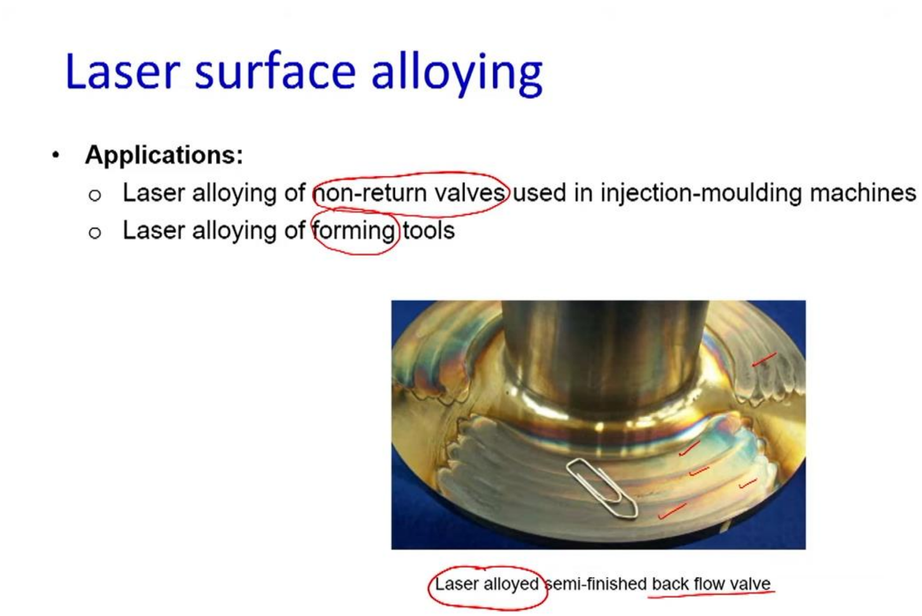

Now let us see what are the various applications of laser surface alloying. The LSA is providing very prominent application in repair and maintenance of critical parts. For example, the non-return valves of injection molding machine which are very critical, but somehow due to the continuous utilization of this non return valves there may be wear and tear of the valves and we can apply the required coating by using lasers and we can save that particular non-return valves and we can enhance its life. Then forming tools, are again exposed to high friction and there is a wearing of this forming tools, here as well the laser surface alloying can be helping us. One picture is there on your screen, this is a back flow wall and here you can see it is a laser alloyed, the surface is laser alloyed, this surface you can see over here and by applying the lasers and specific powder over it, the required material performance can be achieved.

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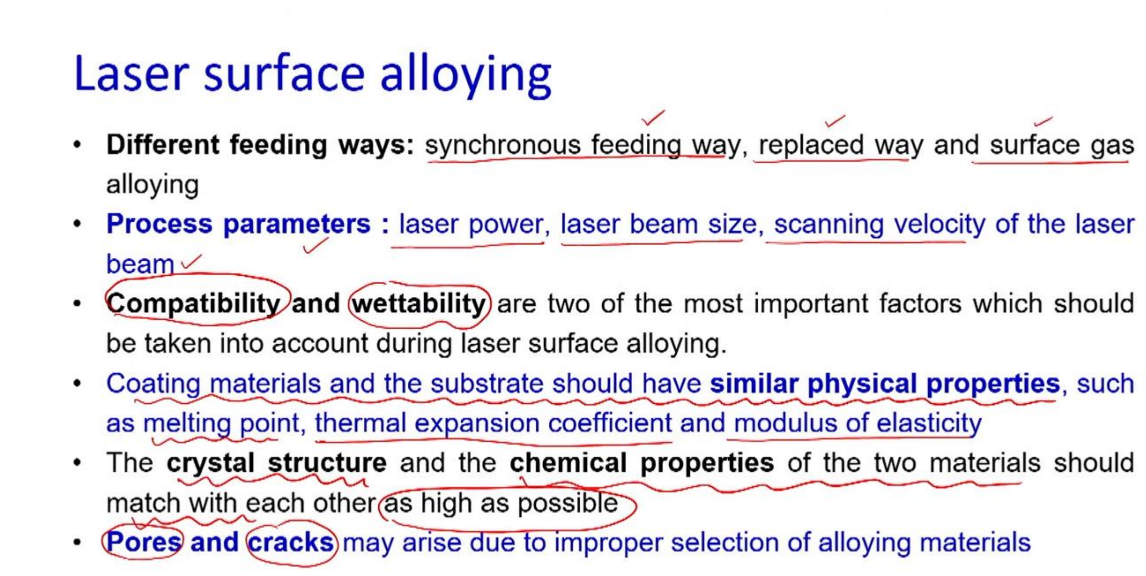

As I have pointed out in my previous discussion as well, there are various ways through which we can apply the foreign material or the material that to be deposited on the surface. Basically, there are three ways to apply the material. First is synchronous feeding way, the second one is replaced way and the third one is surface gas alloying. We will see the meaning of these three ways of applying the foreign material in the next slides.

Before that, let us see what are the various process parameters which are affecting the performance of LSA and these are the regular parameters such as laser power, laser beam size and scanning velocity of the laser beam. We have already seen the meaning of all these parameters in our previous classes and we will be also looking at some of the experimental results in next few slides.

Moreover, the powder which we will try to deposit on the surface, its properties, in particular the compatibility of that foreign powder that to be deposited on the substrate material that is one point and the second one is wettability. Wettability is the property of the liquid to get held on the solid surface. As we are liquefying the solid material it may be in form of the particles or maybe in wire form we are liquefying the solid material and that that to be there on the surface of the substrate material to get it solidified. If the wettability is low, if the adherence of the liquid material on the surface is low, then it will spill and will not get the proper re-solidification and will not get proper laser surface alloying. These two parameters, the compatibility and wettability, has to be taken into consideration when you choose the foreign material or the particles that to be deposited.

The coating materials and the substrate should have similar physical properties such as the melt point, thermal expansion coefficient and modulus of elasticity. These things are to be seen when you carry out this LSA, they should not be exactly similar or exactly matching, however, there has to be certain agreement between the properties of the deposition material and the properties of the substrate material. Their melt point has to be near to each other, their thermal expansion coefficient and the modulus of elasticity should be matching, they should not be exactly same, but at least with certain margins, say about 5% should be related to each other. The crystal structure and chemical properties of the two materials should also match to maximum extent to have the proper laser surface alloying. And if we don't select the material properties properly, then there will be chances of having pores and cracks during the laser surface alloying which is quite obvious, which is very similar to the laser based welding that we have already seen in our previous lecture.

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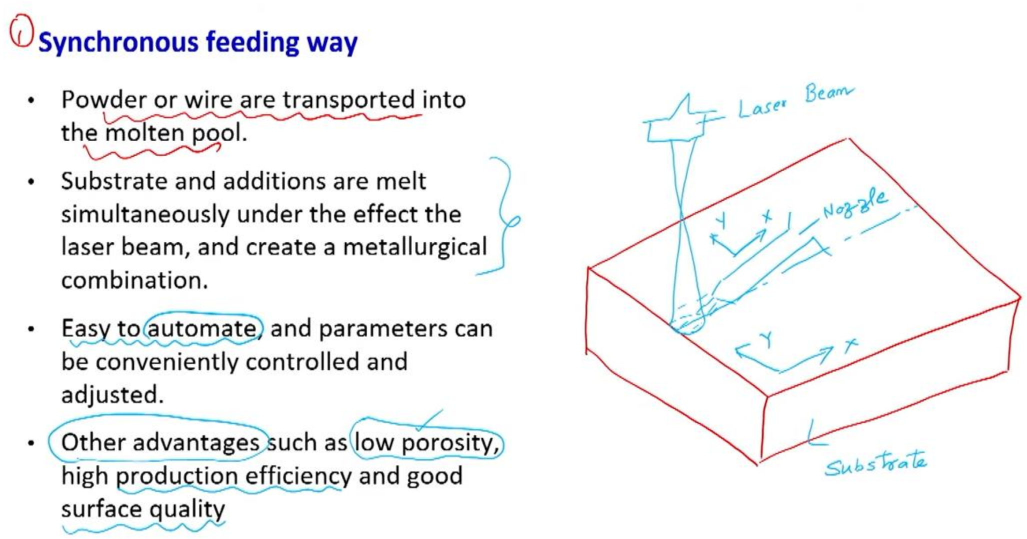

Now let us see what are the various different ways of feeding the deposition material over the substrate material. The first feeding way is synchronous, synchronous means that the movement of feeding nozzle is synchronized with the laser movement or the movement of the feeding nozzle is synchronized with the movement of the substrate the other way round. The laser head is moving or the substrate is moving. When we have the synchronization between the nozzle and the substrate material or the laser that we call the synchronized feeding way. The powder or the wire are transported into the molten pool.

Let us consider that we are having work part over here. Now, we have to apply the additional material along this axis. Here consider we have taken a laser beam. This is the laser beam and this is the substrate. Now let us assume that the substrate is moving in X&Y direction. Now to have the feeding, we can have a nozzle over here and this nozzle which is feeding the foreign material and this nozzle is also moving in X&Y, moving in XY plane in a similar speed in the same speed of the substrate movement. In this way we can easily carry out the deposition and alloying. This kind of movement is now easily done by using CNC based controllers and other advantages of this particular feeding that is synchronous feeding is that since we are controlling movement by using electronics, we can have the smooth deposition, efficient deposition and that is leading to low porosity, high production efficiency and good surface quality.

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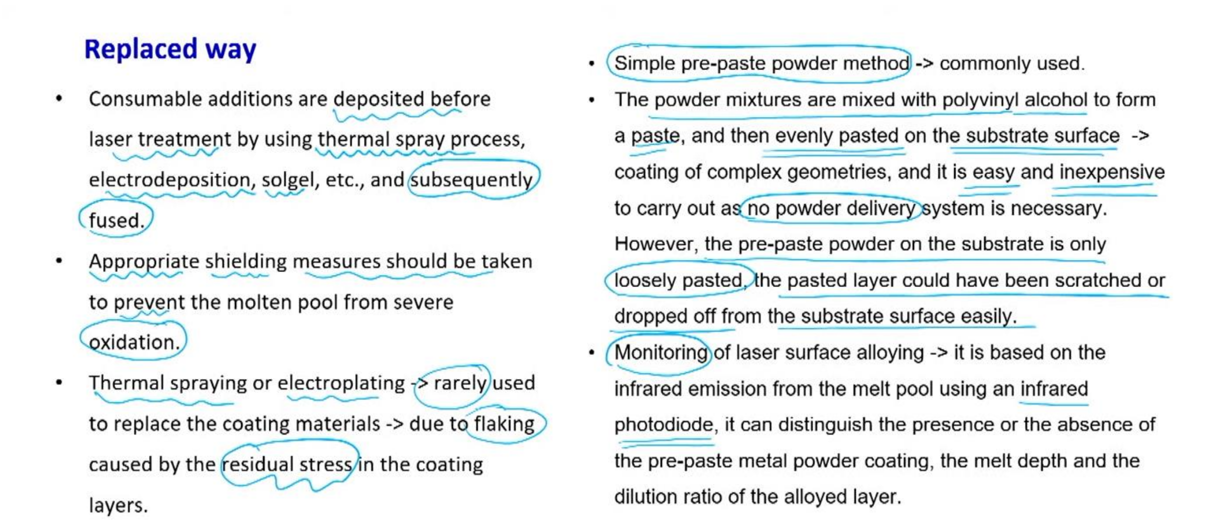

But as I mentioned in my previous slide as well, there is another way, we can have the replaced way. In this mode of feeding, the consumable additions are deposited before the laser treatment, we have to deposit the consumable addition over the work part and this may be done either by using thermal spray process or electrode deposition or solgel kind of method and afterwards we are fusing it by applying the laser beam. Then subsequently we will be fusing that to the substrate by using laser beam process. Here we need to take care the shielding, appropriate shielding measure should be taken into consideration to avoid the oxidation.

The thermal spray or the electroplating is rarely used in replaced way, basically because of flaking. We can thermally spray the additional material over the surface or we can even have the electroplating, but during the application of laser source there may be chances of flaking due to the residual stresses which are there during the thermal spraying or the electroplating. A simple pre-paste powder method is commonly being used. Instead of going for the complicated process such as the thermal spraying or the electroplating, we can go for the pre-paste powder method. In this method, the powder is getting mixed with polyvinyl alcohol to form the paste. And then we are evenly applying that paste over the substrate surface.

Now another advantage of having this pre-placing the powder over the substrate material or pre-pasting of the power powder over the substrate material is that we can process geometrically complex work parts. Consider we are having a turbine blade and we have to carry out maintenance operation, repair operation by using LSA that is a laser surface alloying. Here the application of the powder, deposition powder is easy. You just paste it over the surface and then you apply the laser beam energy. In that way it is easy and inexpensive as well as we do not require any special equipment such as the powder delivery system, its control, all these things will get removed and that will save a lot of money as well. However, the pre-paste powder on the substrate is only loosely pasted, which is the disadvantage of this method, that the powder is getting loosely pasted, there may be chances of having removal of the powder when we apply the laser source. The powder may get scratched, or it may be dropped off when we process the substrate material. We have to be very careful when we apply the laser beam energy on the pre-pasted powders.

Now how to control or how to monitor? To monitor the removal of the pre-pasted powder over the surface by using infrared photodiode. Some experimental setups were developed where the pre pasted powder was continuously monitored during the application of laser source by using the infrared photodiode. And when there is an absence of the powder due to dropping it off, that will be sensed, and at that moment itself another layer of the powder was applied and we can have the efficient laser-based surface alloying.

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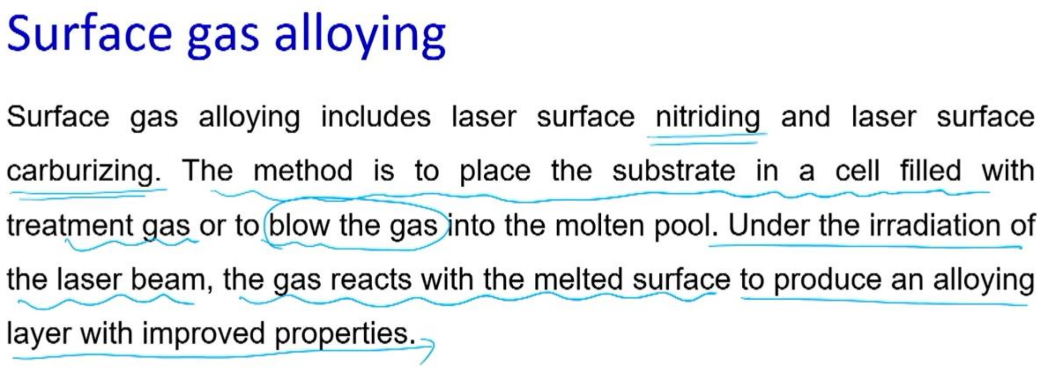

Now let us see the next type of alloying process, that is a surface gas alloying process. In this type of feeding system, we are not using the deposition in the form of any powder or not in the form of any pre-pasting of the material. Here the deposition material is in the form of gases. Nitriding and carburizing, as we know very well, in this case the laser surface nitriding or laser surface carburizing can be done. We are taking the substrate material inside a chamber; we are applying the gas of nitrogen or the carbon and then we apply the laser beam energy. When the laser beam energy is interacting with the substrate material and during the process of the interaction the particles which are there in the form of gases that will get deposited on the substrate material. In that way, we are depositing the particles present in the form of gas on the substrate material, during the laser surface processing and that we call the surface gas alloying.

In this method, the substrate is placed in a cell filled with the treatment gas or we can even have the blowing of the gas over the material where the laser is getting applied. We are blowing the gas wherever the laser is getting interacted with the substrate material, where the melting of the material is getting occurred. Under the irradiation of the laser beam, the gas reacts with melted surface to produce an alloying layer with improved properties.

In this way we can have the feeding of the material either by using powder which is flowing through the nozzle or by pasting the powder over the surface or we can have the surface alloying by using the gaseous type of material.

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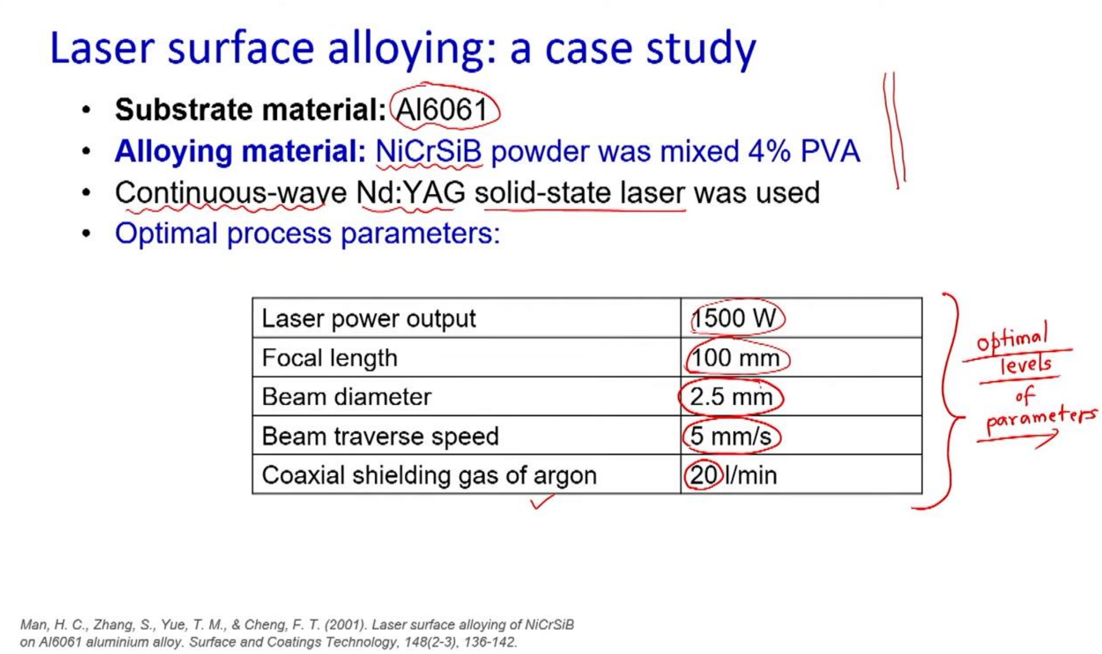

Now let us have a case study on laser surface alloying. In this case study, we have taken the substrate material that is aluminum 6061 alloy and over these aluminum substrate material, we will be trying to have a powder deposition, which is composition of nickel, chromium, silicon and boron. This process will be carried out by using continuous wave Nd:YAG solid-state laser. And after deciding the substrate material and the alloying material, a lot of experiments were carried out and it was noticed that a power of 1500 Watt, focal length of 100 mm, beam diameter of about 2.5 mm, beam travel speed of 5 mm/s and the coaxial shielding gas of argon which is flowing over a rate of 20 L/min. These are the optimal levels of parameters which are generating a good quality alloying, these are the optimal levels of parameters which are generating a good quality alloy.

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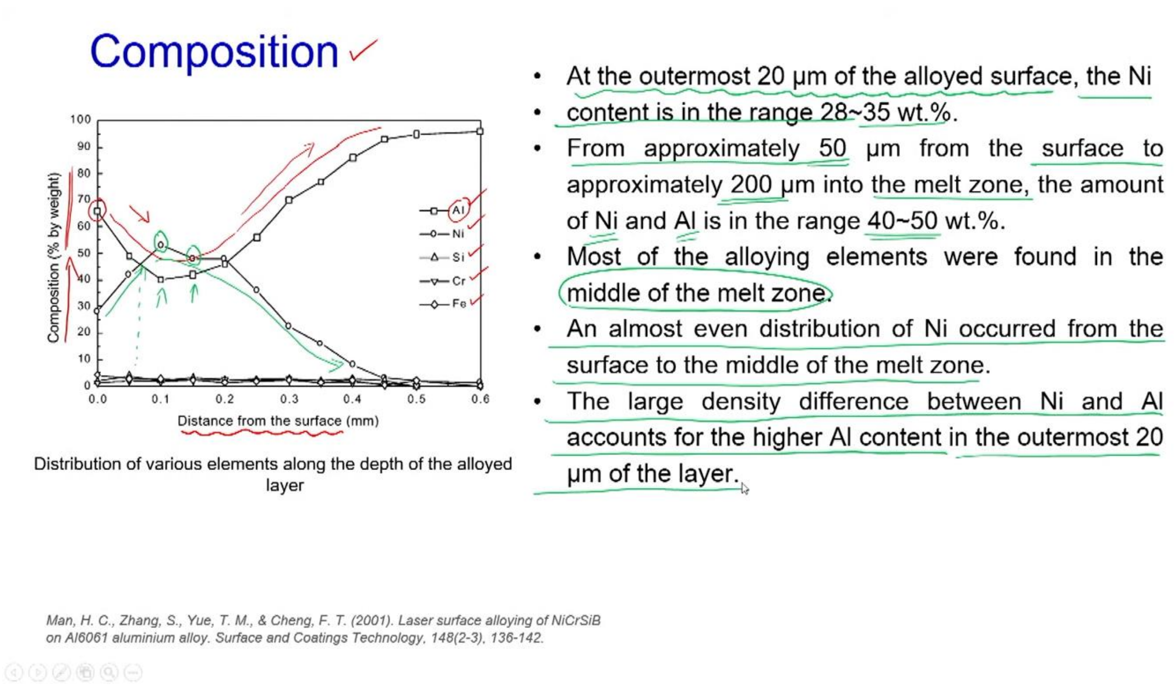

Some of the experimental results are with us, let us see what are these results. The first is composition, as we have seen that when the deposition material is getting mixed with the substrate material, we are getting a new composition that we will see now. On X - axis we have taken the distance from the surface and on the Y - axis we have taken the composition by percentage weight. This is a percentage weight we have taken. On your screen you can see various line graphs. The first is the aluminum, this empty square is aluminum, empty circle is nickel, empty triangle is silicon, the inverted empty triangle is chromium and the rhombus is for the ferrous material. If you observe the percentage of the aluminum with respect to the distance from the surface of the substrate material that graph you just notice over here at the top surface it was about 65 percentage and as we move along the thickness direction, then the aluminum percentage is reduced and then it is increased. Here it is very interesting as there is reduction in the percentage of aluminum, there is increase in the percentage of nickel as well.

Here you can see another graph, it is the graph for nickel. It is very interesting to note here, as we move from the top surface along the thickness direction, there is increase in the percentage of nickel and then there is a decrease again. At certain position or location, exactly the middle of the deposition/deposited layer or the alloyed layer, there is more percentage of nickel than the aluminum. Here you notice the more percentage of nickel than the aluminum. This is successful alloying of nickel with the aluminum. Of course, the other parameters are also there, but their percentage is minimal and it is almost constant from top of the surface along the thickness direction. At the outermost 20 micron of the alloyed surface, the nickel content is in the range of about 28 to 35 percentage weight. From approximately 50 microns from the surface to approximately 200 microns into the melt zone, the amount of nickel and aluminum was in 40 to 50 percentage of weight. Most of the alloying elements were found in the middle of the melt zone, which I have pointed out here, this is the middle of the melt zone and almost all the elements were found there and an almost even distribution of nickel occurred from the surface to the middle of the melt zone. The large density difference between nickel and aluminum accounts for the higher aluminum content in the outer most 20 micron of the layer.

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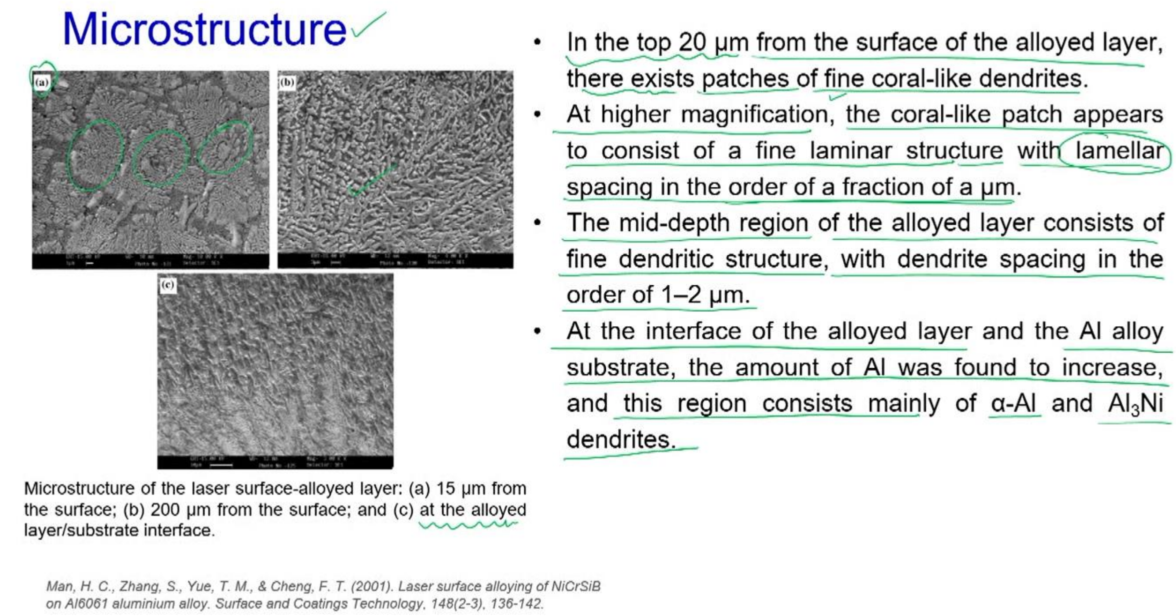

Then let us study the microstructure of the alloyed layer. The top 20 micron from the surface of the alloye layer, there exist patches of fine coral-like dendrites. This figure (a) which you can see over here, this is at the top surface, approximately 15 to 20 micron and we can notice fine coral-like dendrites. All these are the fine coral like dendrites at the top surface. At higher magnification, the coral-like patch appears to consist of fine laminar structure with lamellar spacing in the order of fraction of a micron. If you try to observe in a higher magnification this coral-like patch appears to be a fine laminar structure with a spacing and that spacing is of lamellar nature and the order of the spacing is in the fraction of microns.

The mid depth region of the alloyed layer consists of fine dendritic structure, with dendrite spacing in the range of about 1 to 2 microns. When we move in the mid depth region, this is the mid depth region microstructural graph. What it is notice? that a fine dendritic structure and the spacing is about 1-2 microns.

Now the third is, what is the microstructural graph at the interface? At the interface of the alloyed layer, the alloy substrate, the amount of Al was found to be increased. At the interface, the amount of aluminum was noticed to increase and this region consists of mainly alpha-aluminum (α-Al) and Al_3Ni dendrites. Aluminum-nitrite dendrites were noticed at the interface of the deposition material with the substrate material.

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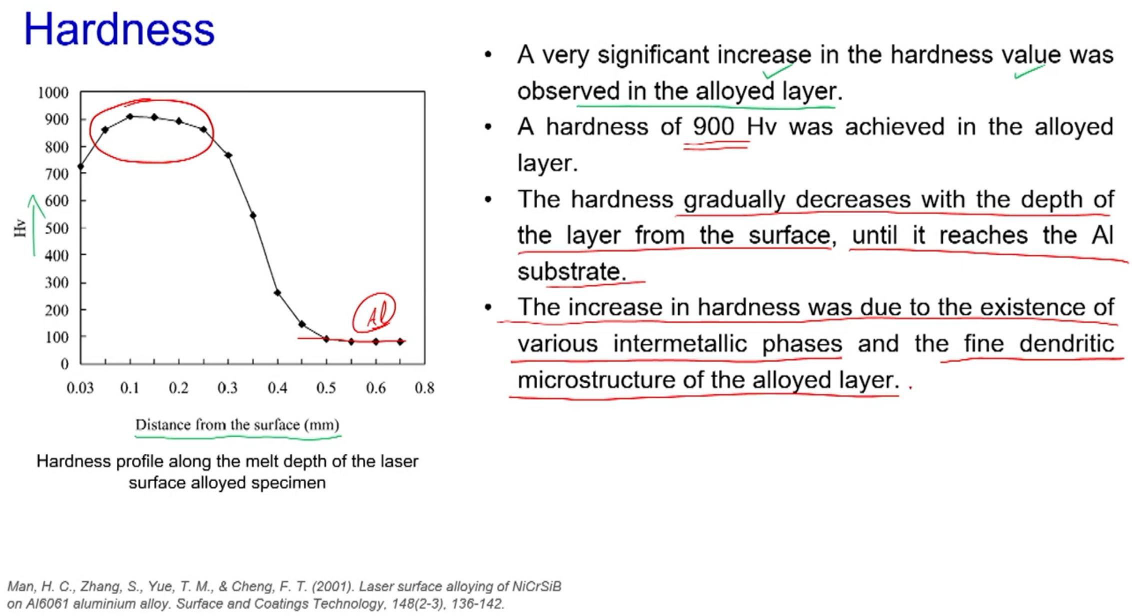

The hardness was also recorded for the alloyed layer, here you can notice that on X axis is the distance from the surface and on Y axis is the Vickers' hardness. It has been noticed that a very significant increase in the hardness value is observed in the alloyed layer, you can notice there is increase in the hardness value in the alloyed layer and as we move inside in the work piece, along the thickness direction, the hardness is getting reduced. The maximum hardness was recorded about 900 Vickers' hardness (H_v) and then gradually it decreased with the depth of the layer from the surface until it reaches the aluminum substrate, it reaches at this point and this hardness is of the aluminum substrate hardness. This increase in the hardness was due to existence of various inter-metallic phases. There are many elements that we are trying to deposit, the nickel, boron, chromium, all these are to be deposited and due to formation of inter-metallic phases the hardness was improved. Moreover, this increase in hardness was dedicated to the fine dendritic microstructure of the alloyed layer.

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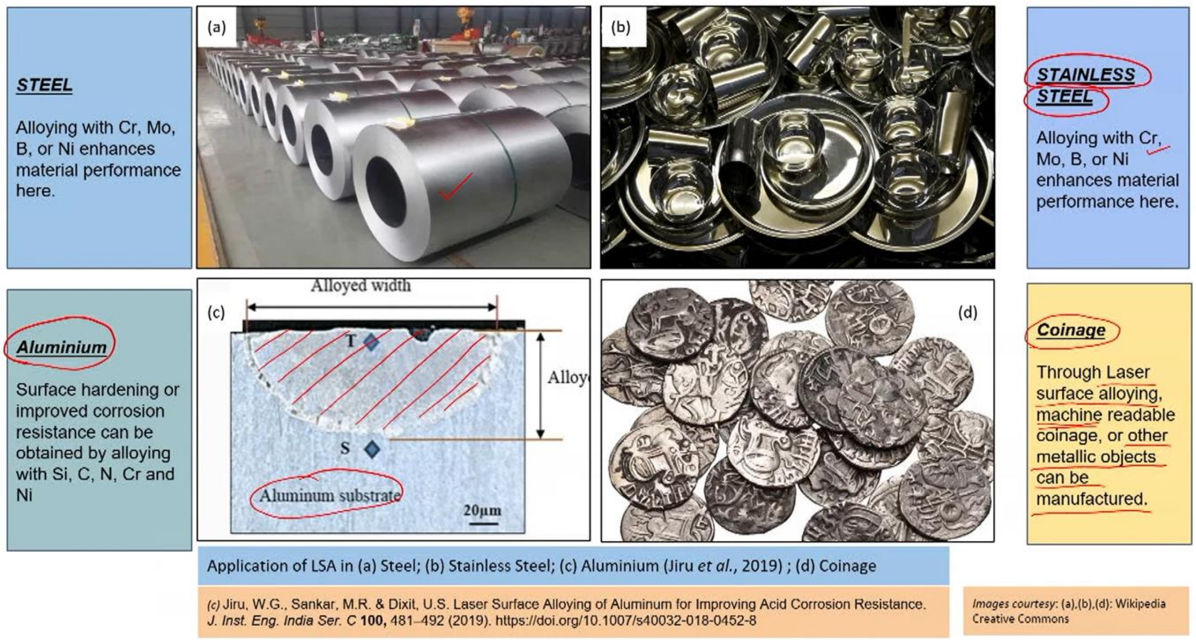

Now let us see what are the various applications of the LSA, that is the laser surface alloying. On your screen you can see the rolled sheets and when we want to enhance the material performance by applying chromium, molybdenum or boron or nickel, that is possible over this already rolled sheets by using lasers. We can even improve the properties of stainless steel utensils by applying the similar elements such as chromium, molybdenum, boron or nickel. Of course, aluminums material properties can also be enhanced. In the industry aluminum is widely used, but its wear and tear are very high. To improve its material properties, to improve the surface properties of the aluminum, we can utilize the laser.

Here you can see the alloyed region. This is the alloyed region which is looking very, very similar to the substrate with certain difference. However, the material properties inside the alloyed region is entirely different than the aluminum substrate properties. Coinage, by applying the laser in surface alloying of the coinage, we can make the coinage machine readable and the other metallic objects can also be manufactured.

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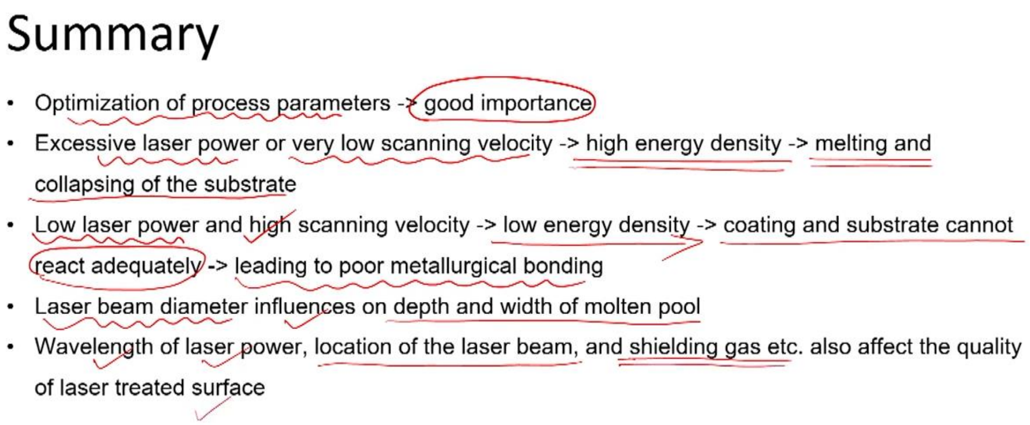

With this I would like to summarize today's lecture on laser surface alloying. We have seen the meaning of laser surface alloying, various mechanisms, various feeding mechanisms or feeding ways of the deposition material over the substrate material. After that we have seen one case study and we have seen how the material properties are improved in terms of hardness by using laser surface alloying.

Let us summarize. Needless to say here to have the efficient LSA, we need to find out the optimal levels of process parameters. I would like to emphasize here the optimization of process parameters is very much essential to have the good importance of the process. Excessive laser power or very low scan velocity will lead to very high energy density and that will lead to melting and collapsing of the substrate material. To have more surface alloying, if you apply excessive laser power and if you reduce the scan velocity, that may lead to excessive energy density and that may spoil the entire substrate material. If we lower the laser power, if you apply low laser power and if you increase the scan velocity tremendously, then the problem would be, you will be getting the low energy density and these low energy densities may not be sufficient for the coating, you may not have the proper mixture, you will not have proper melting and mixing of this deposition material with the substrate materials and there may not be adequate reaction of the alloying elements with each other, that may lead to a poor metallurgical bonding of the deposition material with the substrate material.

Moreover, the beam diameter of the laser is also influencing the depth and width of the molten metal. Of course, the wavelength of the laser power, location of the laser beam and shielding gas are also affecting the quality of laser treated surface. If the wavelength of the laser is low, there would be more absorptivity which we have already seen and that would help us to have the efficient heating of the laser treated surface - laser applied surface to get the required bonding done.

Fine, with this I would like to stop for today's lecture. In the next lecture, we will be having a short discussion on laser cladding. Till then goodbye. Thank you.