

Laser Based Manufacturing
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Module No # 06
Lecture No # 26
Effect of Coatings, 3D Laser Forming and Micro-Forming

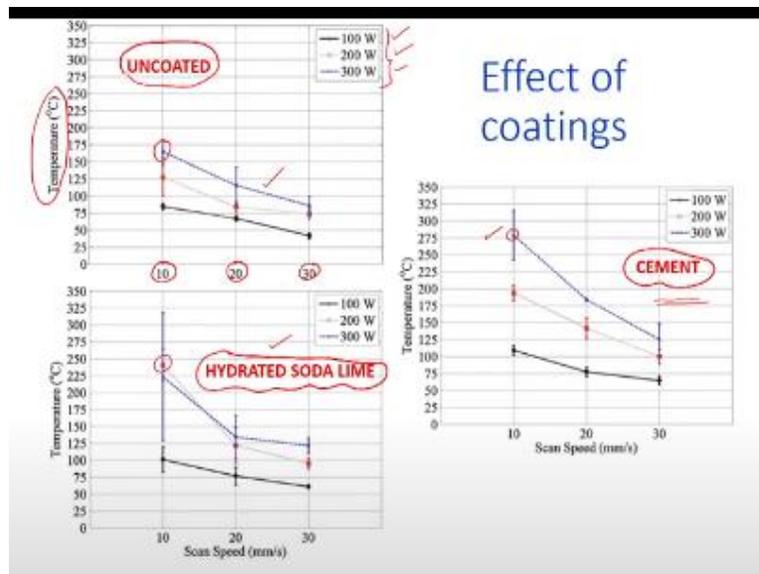
I welcome you all to the second lecture of week 8 of NPTEL MOOC's course on laser-based manufacturing. This is the last week and we are seeing the advancements in laser-based manufacturing. In the first lecture of this week we have seen the laser assisted material forming. Now we are looking at some other advancements in laser-based material forming in this lecture.

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Let us begin our lecture. This lecture 2 is on various effects of the coatings on the improvement of the productivity of laser-based forming. Moreover, we will also be studying the various techniques or the irradiation strategies being used for 3D laser forming. At last we will have some discussion on micro forming how can we generate micro features on the work parts using lasers.

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In our previous class we have seen that there is need to enhance the absorptivity for enhancement in the productivity. And this absorptivity can be increased or can be improved by applying certain coating. In normal situation the rust or the dust or the grease on the material itself it is sufficient to enhance the absorptivity. But for certain materials such as aluminum or the polished material it is essential to apply a coating to increase the absorptivity.

In the literature we can notice that lot of work has been done. People have used hydrated soda lime or they have used cement or the graphite. And by applying the hydrated soda lime or the cement or graphite, experimental studies were carried out. And by using the thermocouples the temperatures were measured during the laser based forming operation. that results are there on your screen. , this is the result number 1 which is for uncoated work parts.

On the x axis we have taken the scan speed, this is the scan speed and it is in mm per second 10, 20, 30. On y axis the temperature is recorded and this temperature was recorded by using thermocouples and data acquisition system. 3 levels of powers were used to find out the effect of coating on the bend angle, first level is 100 watts, 200 watt the second level, and 300 watt the third level.

You just notice for uncoated material the maximum temperature was around 175 degree Celsius for 300 watt of power, and which is achieved at 10 mm per second. When the interaction time was

less the power was high about 300 watts the maximum temperature was reached about 175 degrees Celsius. Now for the same process condition if we apply the hydrated soda lime then you just notice that temperature recorded was increased, it went up to more than 225 degree Celsius.

For the same process condition when cement was applied then the temperature was further enhanced to 275 degree Celsius. the conclusion of this experimental study is that when we apply certain coating when we try to improve the absorptivity by using coating the cement is the better option or better material that to be coated on the work part. And the cement material is easily available and we can easily coat the cement on the work parts and that will save a lot of energy the laser beam energy to get the required Bend angle.

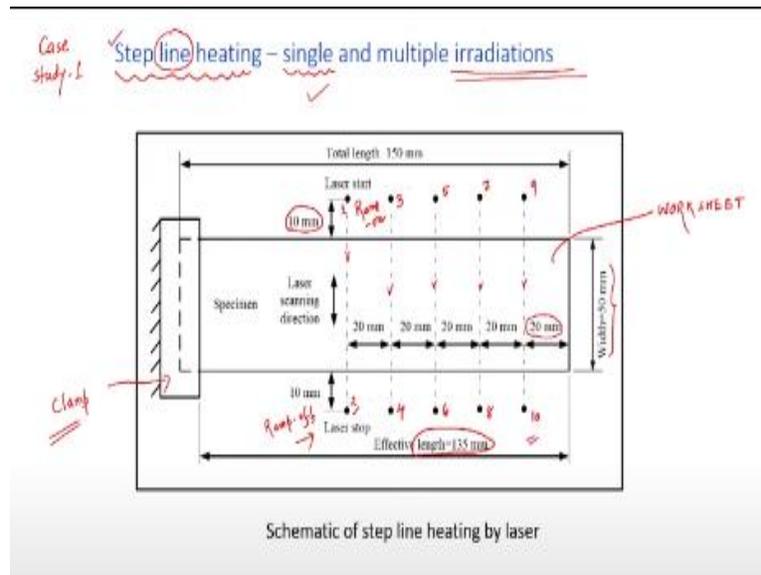
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Well the next point of discussion is how can we have the 3d laser forming. In our all previous discussions we have seen a linear irradiation, linear laser heating and with that linear laser heating we could get certain bend angle. Now for the industrial parts we have to generate some 3d shapes 3d complex shapes and what are the various things which are essential for the 3d laser forming.

The fundamental point here is the scanning strategies. in our previous discussion we have seen that the linear scan is the simple way of applying the laser beam energy and we can get some deformation. That deformation is not uniform along this the scanning line. Then we can go for the parabolic or the curvilinear irradiation. can we have permutation and combinations of these various paths various scanning strategies to get our required 3d complex shape done.

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Let us see some of the work related to this. here is the case study one, and this case study one is for step line heating. the meaning is very simple we are heating the work part in steps and the heating is done in a linear way. the linear heating in stepwise manner can lead to some sort of complex shapes that we will see now. Moreover, we will also vary the number of irradiations. We can have a single irradiation pattern or we can have the multiple irradiations at same location.

Let us see what happens with single and multiple irradiations for step line heating. on your screen the scanning strategy is shown over here. this is the clamp in which the work part is fixed this is the worksheet. this worksheet is of having 50 mm width and the length of the worksheet is about 135 mm. Now during the operation of the line heating the steps are taken of 20 mm each we are having step 1, 2, 3, 4, and 5. in 5 steps let us see what is the shape is getting generated.

Now there is override or we can call this as ramp on and ramp off of the laser this I can call ramp on and ramp off of the laser and that ramping on or ramping off distance is about 10 mm this is the ramp on and this is the ramp off. laser is starting at this point; point number 1 and it will get irradiated along this path it will stop over this and again we are having the laser from this point number 3 to 4, then 5 to 6, 7 to 8, and 9 to 10.

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Case study-1

Step line heating – single and multiple irradiations



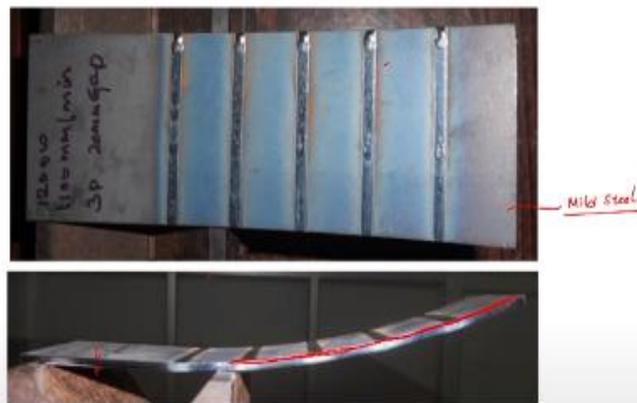
Deformation of plate for multiple step line heating at 1 cycle of irradiation.

Now on your screen you can see the irradiated work piece and these irradiations were done for only one cycle. one cycle irradiation with power of around 1200 watts and scanning velocity of about 1100 mm per minute. When we apply this process parameters you can notice that there is certain non-linear deformation of the work part, in this manner there was a bend but that bend was in a non-linear fashion. Now let us enhance or let us increase the number of irradiations and see what happens.

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Case study-1

Step line heating – single and multiple irradiations

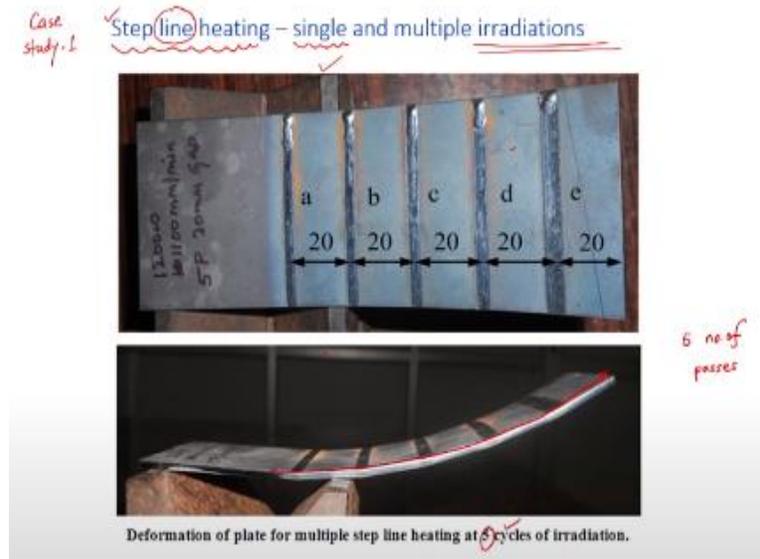


Deformation of plate for multiple step line heating at 3 cycles of irradiation.

Now when we increase the cycles the number of irradiations at the same line for all the steps to 3 1 to 3 is enhancement and you just look at the shape that we are getting. Now the sheet has been bent in a very non-linear fashion and that may lead to some sort of complex shape some sort of

other curvilinear shape we can give to the very thick plate. you just notice the thickness is significant and the material is steel material it is particularly the mild steel material which is having sufficient strength. And that material we are bending by using lasers without any contact of mechanical tool.

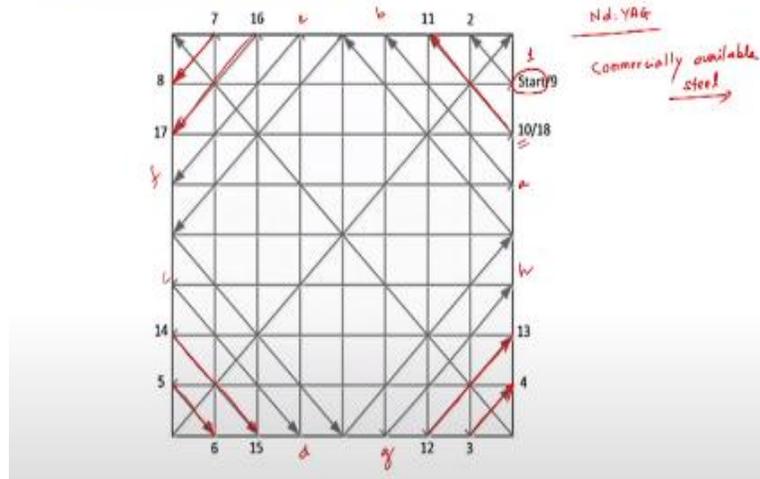
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Now let us go further and increase the number of irradiations. Now in this case you can notice that the number of irradiations is enhanced to 5. 5 number of passes and for 5 number of passes you notice the shape that we have got. it is a very similar to a bowel shape that we can get if we irradiate it on the other side of the work part as well. it will lead to some sort of saucer or the bowel shape in this case we have done only the linear heating. can we have the transverse heating as well to this linear heating then the part will have much more complex shape.

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Laser irradiation strategy proposed by Yang et al. (2010) to form a dome shaped surface (400 W)

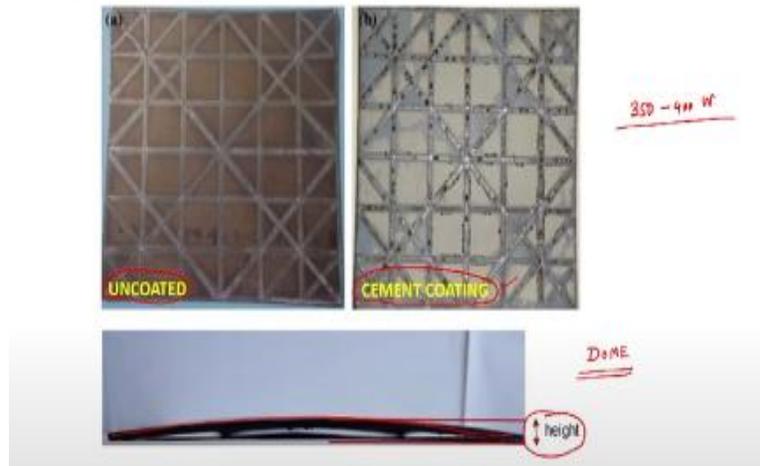


To study such kind of deformation the Yang et al they have carried out or they propose some sort of strategies for the deformation. these are done on Nd: YAG laser machine for commercially available steel. all the process has been followed that the plate was cleaned by acetone then they applied a coating of graphite or cement and then the laser irradiations were carried out. you just notice how the lasers were irradiated this is the start point. From point 1 that is a start point 1 to 2.

This is the first irradiation was carried out then 3 to 4 then 5 to 6 and then 7 to 8. The second round of irradiation were started from point number 10; 10 to 11 here you notice 10 to 11 is the second irradiation then 12 to 13, 14 to 15, and 16 to 17. in a similar manner the irradiations patterns were decided and these were applied after the point number 17. Again, the irradiation was started from this point A to point B, then C to D, then E to F and G to H.

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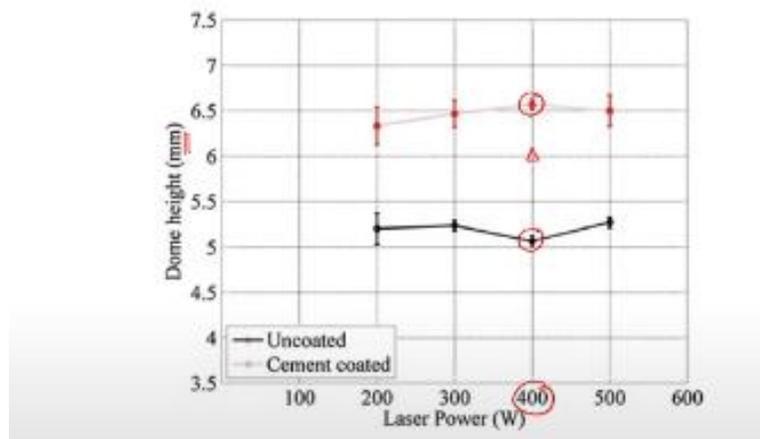
Laser irradiation strategy proposed by Yang et al. (2010) to form a dome shaped surface (400 W)



After scanning in this way, the deformed sheet is looking something like this. here you notice there was a dome shaped pattern was generated when we apply around 350 watt to 400 watt of the laser power when it is applied then there is a certain height was received and that shape was something like a dome. , dome shaped work part was developed. It was tried with uncoated material uncoated sheet and it is also tried with a cement coated worksheet. For cement coated worksheet of course, the Dome height was considerably large with respect to uncoated sheet.

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Laser irradiation strategy proposed by Yang et al. (2010) to form a dome shaped surface (400 W)

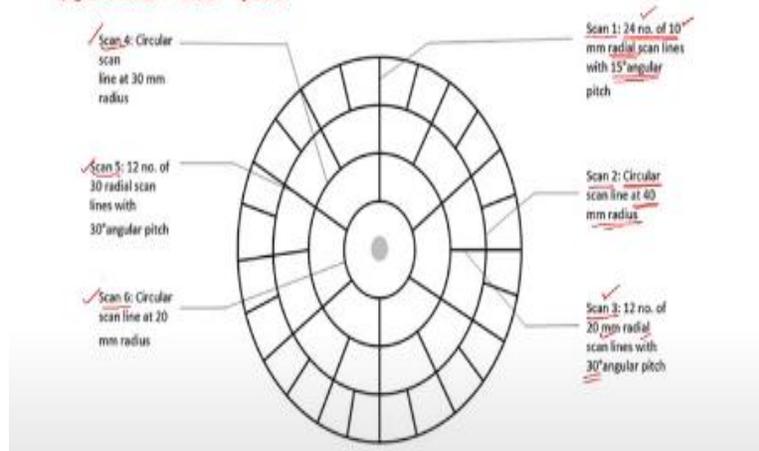


here you can just notice the dome height for the cement coated sheet was around 6.5 mm in comparison with the uncoated sheet and it was around 5 mm; 5 mm to 6.5 mm is the enhancement

for about 400 watts. There is a considerable enhancement in the dome height when we apply the coating that is of the cement.

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Forming of bowl shaped surface as per the laser scan scheme proposed by Chakraborty et al. (2012)

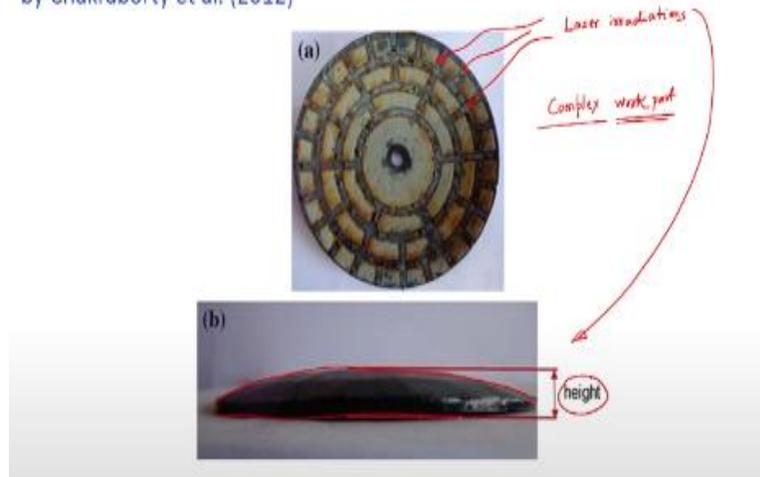


Well there is another way of carrying out the irradiation that is there on your screen and that has been suggested by the Chakraborty group; Chakraborty et al of 2012. And they suggested a scan pattern to generate again a dome shaped cavity a complex shape and that scan pattern is on your screen. what is the scan pattern? the scan pattern number 1 is suggesting to have 24 number of irradiations and these irradiation lengths is around 10 mm and these irradiations are radial scan lines with 15-degree angular pitch.

So, 10 mm of radial lines with 24 number of irradiations that to be applied that is a scan 1 after that scan 2 is having circular scan line, and that circular scan line is of 40 mm radius. that is this 40 mm radius circular scan line. The third group of scanning comprises 12 number of 20 mm radial scan lines with angular pitch of 30 degrees. In a similar way the scan 4, scan 5, and scan 6 group of radial scanings and the circular scanings were applied.

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Forming of bowl shaped surface as per the laser scan scheme proposed by Chakraborty et al. (2012)



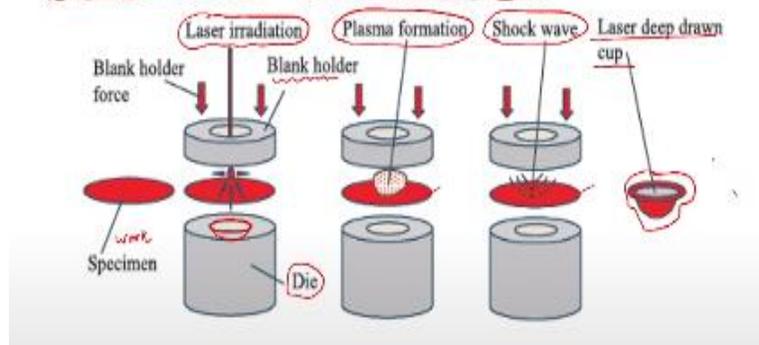
And after applying these scans you can notice a very good quality dome shaped complex work part was generated. this is a complex work part with various irradiations patterns. all these are the irradiations, all these are the irradiations, laser irradiations and after applying these laser irradiations, we got a dome. if we put this work part upside down we can easily measure the height of the dome. in this way when we apply or when we employ various scan strategies we can easily manufacture 3D complex shapes. In all these situations we are using continuous wave of laser beam.

Now if we want to manufacture very small size features or the micro or meso size features on the work parts then how to generate such kind of features that is called as the laser based micro forming.

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Laser micro deep drawing

- Creation of a shock wave ✓
- Nd:YAG Laser with a maximum power density of 1.7 GW/cm^2 -> thermal damaging and mechanical deformation



One such application we will be seeing that is laser micro deep drawing. here the deep drawing operation would be carried out by using the shock wave, we have to create the shock wave. We have to create a energy wave and that energy wave will be applied on the work part and there is a need to have a dye as well. here the shock wave is applying the pressure on the work part and the deformation would be carried out against the dye.

in this way we can generate very small size micro size features or micro size work parts. let us see. we have to create the shock wave by using a pulse laser. Nd: YAG laser with a maximum power density of about 1.7 gigawatts per centimeter square it is leading to the thermal damaging or it can create some sort of mechanical deformation. Now this arrangement can be seen on your screen here we are using a dye, this is the dye and the dye has a shape that to be produced.

This is the shape that to be produced and that shape is created in the dye. We are putting the specimen this is the work specimen a very thin sheet or it can be a foil that metal foil is put on the dye. And to hold that specimen to hold that foil during the shock wave operation we are using a holder that is called as blank holder. this blank holder will be kept on the specimen we are applying a certain force as well to ensure that the work specimen is not getting shifted or it is not getting displaced during the application of the shock wave.

We are using a laser irradiation for a short duration and that laser is producing a shock wave. And that shock wave is applied on the surface of that foil or the specimen that is deforming that particular specimen. the deformation would be constraint or the deformation would be carried out

by the shape of that particular dye. here you can see when we apply the laser there is a creation of plasma and that plasma is creating the shock wave and after that we are getting the deep drawn cup. There is application of mechanical force generated by the shock wave and that force is drawing the sheet metal foil or the specimen in a cup.

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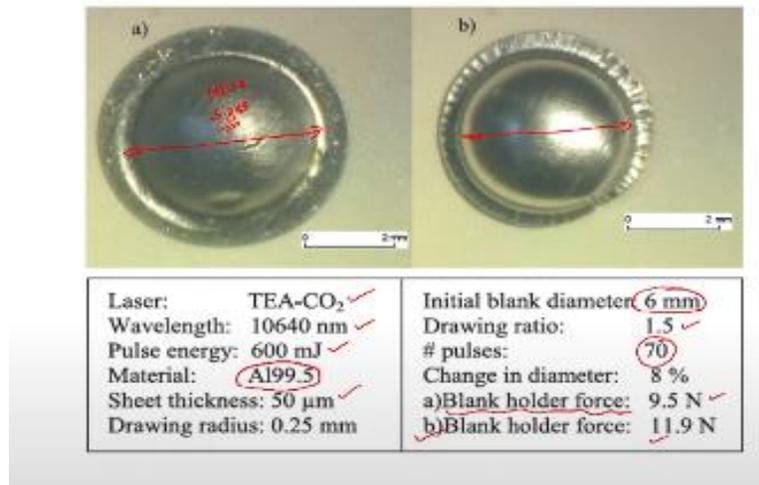
Laser micro deep drawing

- one or several short laser pulses hit the specimen with a focus located at the blank surface
- high energy density of the laser radiation -> ionization of the close by atmosphere -> plasma formation -> propagation -> shock wave

In this case one or several short laser pulses will be hit at the specimen with a focus located at the blank surface only on the blank surface one or several number of short laser pulses are applied and that is creating the drawing operation. The high energy density of the laser radiation is ionizing the environment or it is ionizing the area near to that work piece, and that creates the plasma so that ionization of the air particles will lead to plasma formation, and that plasma is get propagated and it will generate a shock wave, we will be using the shock wave for our intended purpose.

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Typical laser deep drawn cups

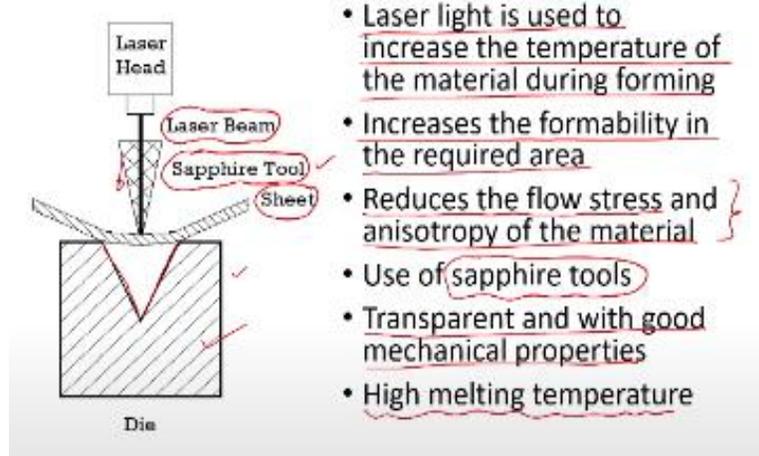


By using this laser-based methodology for deep drawing the actual drawn cups are there in front of you. you notice these cups are made up of aluminum and they were made by using a sheet and the sheet thickness is very small that is about 50 micron the drawing ratio was 1.5 and initial blank diameter was very very small that is a 6 mm. you just look at the diameter of the cup that we got it is in very small size it is in meso size.

Meso-sized cups of aluminum were formed by using this laser-based drawing operation. The number of pulses was 70 and the pulse energy was about 600 millijoule. here the laser was used a CO₂ laser and the wavelength is about 10 microns to hold the foil or to hold the worksheet at the dye a blank holder force was applied about 9.5 Newton. this is in case of a we applied 9.5; in case of b it was little increased to 11.9 Newton. successfully the cups were drawn by using laser based deep drawing operation.

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Laser assisted micro-forming



Now we can even use the lasers in addition to the mechanical force for micro forming as well. In our previous class we have seen that laser assisted forming for macro level applications but in micro level applications as well we can effectively use laser for manufacturing of complex features. How it is possible. For this purpose, we can have an arrangement. The schematic of that arrangement is there on your screen.

We have got a die. This is the metal die and this metal die has a certain shape. This is the V-shaped opening in the metal die. We are using a sapphire tool. Sapphire is transparent and the sapphire tool has been given the required shape of which we want to have the required deformation. Here a triangular shape sapphire tool is being used which is transparent and through this sapphire tool we are applying the laser beam.

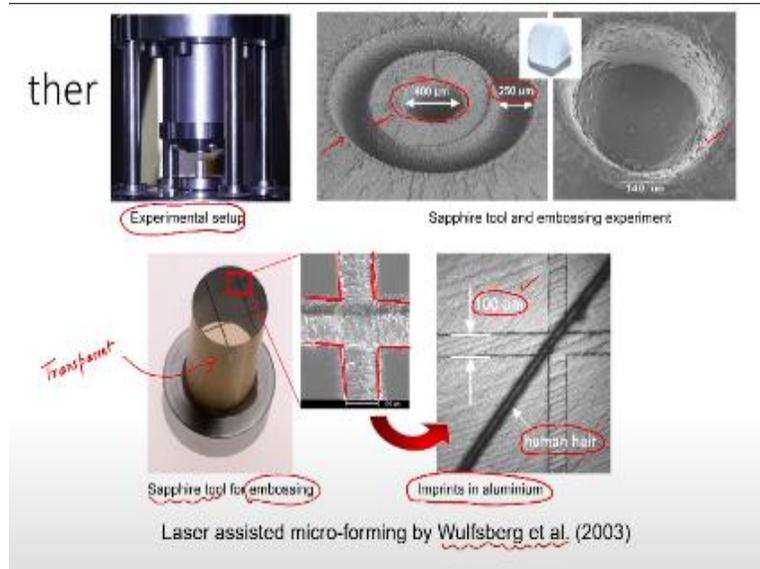
Laser beam is applied in such a way that it should only heat the work part. It should not melt the work part. The laser beam is applied which is transmitting through the sapphire tool. It will come at the work sheet which is in between the sapphire tool and the die. This is the work sheet. As the laser beam is getting applied there is a local heating and that is a controlled local heating and then we are applying the sapphire tool to get the required deformation.

It is very similar to the way we have seen in our previous class as well. It is a laser assisted material forming but for the micro level application. Laser light is used to increase the temperature of the material during the forming application. That heating is enhancing the formability in the required

area and that formability enhancement is nothing but reduction of flow stresses and anisotropy of the material and that lead to generation of the micro features.

Here we are using the sapphire tools which are transparent and having sufficient strength as well. sapphire tools are having good mechanical properties and they are transparent. Moreover, the sapphire tools are having high melting temperature.

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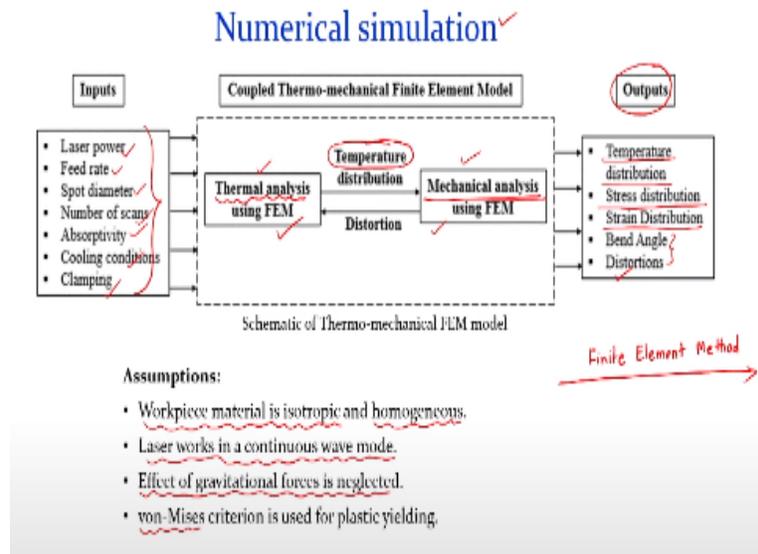


Now let us see what kind of features we can generate by using this methodology. this has been developed by Wulfsberg et al group of German scientists. this is the experimental setup. And this experimental setup is having the sapphire tool and this is being used for embossing to generate the micro channels this tool was used. as you can see that this tool is transparent. through this tool we are applying the laser beam energy and the projections which are there on its surface these projections are manufacturing the channels.

Here we are getting these projections and these projections are making the depressions on the work part. here you notice these are being done on the work part, you can just imagine we can get easily about 100 micrometer channel or 100 micrometer feature which is little larger than the human hair. these imprints have been done on the aluminum work part in a similar way we can also emboss a complex shape we just look at this complex shape the dimensions are in microns.

this is a cavity that we got of around 400 micron and a annular depression this annular depression is having width of about 250 micron. Moreover, another cavity that you can see which is about 200 micron can be easily generated by using this laser assisted micro forming operation.

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Now we can even compute the temperatures stresses or strains during the laser forming operation. for this purpose, we have to employ the hard-computing techniques such as finite element method. lot of work is being carried out to compute the stresses strains and temperatures during the forming operation. how it is possible? to carry out this operation we have to take care of the thermal analysis. And based on the thermal analysis we have to carry out the mechanical analysis of the laser forming operation.

Thermal analysis is generating the temperature and based upon the temperature we are getting the thermal stresses which are resulting into the deformation. how to compute the thermal stresses to compute the thermal stresses we have to first get the temperature and this temperature is function of various input parameters.

What are these input parameters? during our last 2 lectures one in this week and the other one in the previous weeks we have seen that laser power feed rate, spot diameter, number of scans, absorptivity, cooling condition, and clamping, all these are playing important role crucial roles to control the temperature. we have seen in the TGM as well the material properties are also affecting.

Now when we apply these input parameters we are getting temperature that will be given to the mechanical analysis module. In the mechanical analysis module, we have to apply the required boundary conditions. And ultimately the numerical simulation can lead us the temperature distribution, stress distribution, strain distribution, band angle, and various distortions or the deformations. To carry out the numerical simulation, of course, we need to assume certain things.

We are assuming that the workpiece is isotropic and homogeneous and laser is being applied in a continuous wave mode. In certain applications such as the laser shock pinning we can even model, the laser operation in pulse mode as well. The effect of gravitational forces are neglected and in general when we deal with the ductile materials we are using the von mises criteria for the plastic yielding.

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Numerical simulation

Governing Equations and Boundary conditions:

• Thermal Boundary Conditions:

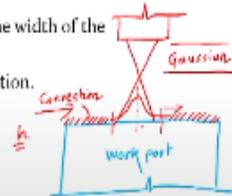
- The heat transfer problem can be solved by law of conservation of thermal energy. The temperature distribution is calculated by three-dimensional heat conduction equation as:

$$k \left(\frac{d^2 T}{dx^2} + \frac{d^2 T}{dy^2} + \frac{d^2 T}{dz^2} \right) = \rho c \frac{dT}{dt} \quad \checkmark \quad \text{Transient Mode}$$

- The initial thermal condition is given by applying room temperature condition to the worksheet.
- Gaussian heat flux moves on the top of the surface along the width of the worksheet with a velocity of 5000 mm/min.
- Boundary is modelled by natural heat convection and radiation.

$$q = h(T_s - T_a)$$

$$q = 5.67 \times 10^{-14} \epsilon (T_s^4 - T_a^4)$$



To compute the temperature, we are using the 3-dimensional heat conduction equations which is there on your screen. this is for the transient mode when we apply the laser beam energy that is generating the temperature.

$$k \left(\frac{d^2 T}{dx^2} + \frac{d^2 T}{dy^2} + \frac{d^2 T}{dz^2} \right) = \rho c \frac{dT}{dt}$$

The initial thermal condition is given by applying the room temperature first of all we have to consider the work part is at room temperature then you apply the boundary condition.

The boundary conditions may be of 3 types: the convection, the radiation, and the application of heat flux due to the laser beam. let us consider our part and this work part is being applied by laser

this is the work part and now we are having the laser. here the laser is applied for certain operation. when the laser being is applied so we have to approximate what is the pattern of the energy is being applied in.

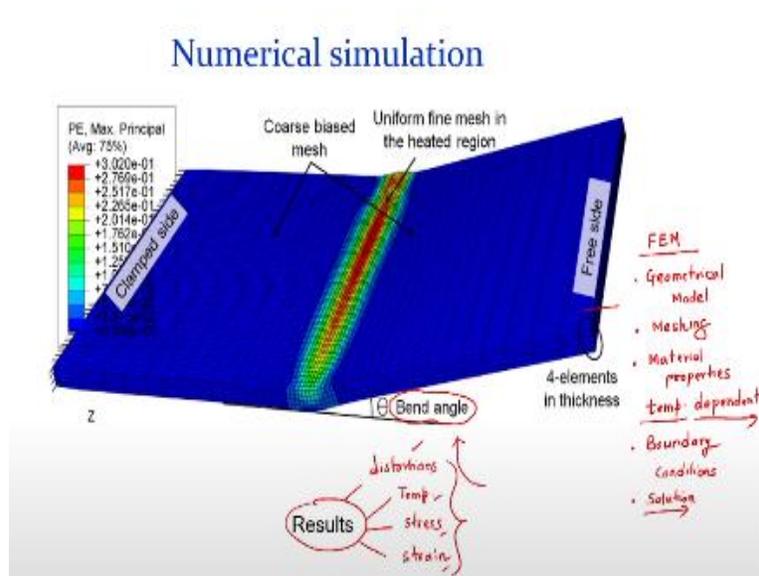
In most of the cases the pattern of energy applied or the function of energy applied is considered as the Gaussian function. The Gaussian function is that at the center of the laser beam there is the maximum amount of energy is applied and as we move along the radial direction of that bell shape the energy is getting reduced. wherever the laser beam is in contact with the work part we are considering a Gaussian beam distribution.

However, the remaining portion this portion would be in contact with the surrounding medium here we have to apply the convection. To consider the convection we have to take the h value of air. in this way you have to first decide what is the; distribution of heat flux, in certain cases people are considering this as uniform distribution as well. instead of considering a Gaussian we can consider uniform distribution over the entire area of irradiation.

$$q = h(T_s - T_a)$$

$$q = 5.67 \times 10^{-14} \varepsilon (T_s^4 - T_a^4)$$

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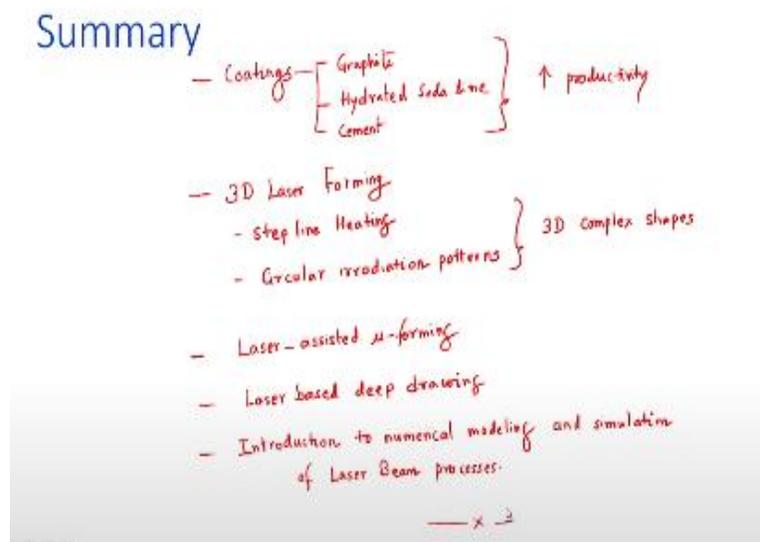
these process boundary conditions are applied on the work part and to apply these boundary conditions first of all we have to create the geometry. In FEM methodology we have to first create

the geometrical model. Then we have to mesh that model, we have to discretize this model into small element meshing. Then we have to apply the material properties.

It is always suggested to apply the temperature dependent material properties in a realistic way. as we know that the conductivity of the material is getting changed it is getting varied with respect to the temperature. temperature dependent material properties will lead you more realistic results, temperature dependent material properties. Then you apply the boundary conditions and after that you have to carry out the solution.

The solution will lead to such kind of results, these results may be temperature, stress, strain or distortions. Then by analyzing the temperature, stress, strain and distortions we can easily analyze the effect of various process parameters on the performance measures. in laser based forming the performance measure is bend angle. How much is the bend angle that we are getting that we can easily compute by using this FEM based numerical simulation.

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Fine with this little introduction or little glimpse of the using numerical simulation I would like to stop for the lecture 2 of week 8. in this lecture we have seen the effect of coatings and we have seen that the various coatings such as graphite, hydrated soda lime then cement can be used; and certainly, these coatings are enhancing the productivity. Then we have seen the 3d laser forming, in 3d laser forming we have seen the step line heating, the circular irradiation patterns and effect of this circular irradiation patterns, and the step line hitting, to get the 3d complex shapes.

Then we have seen the laser assisted micro forming, and laser-based deep drawing as well. And at last we have seen the introduction to numerical modeling and simulation of laser beam processes. With this I stop for the lecture 2 of week 8. Thank you for watching this video. Goodbye!