Laser Based Manufacturing

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Module # 04

Lecture # 13

Process Parameters and Their Effects on the Performance of Laser Forming

Hello everyone. I welcome you all to the third lecture of Week 4 and in this week, we are studying laser-based forming.

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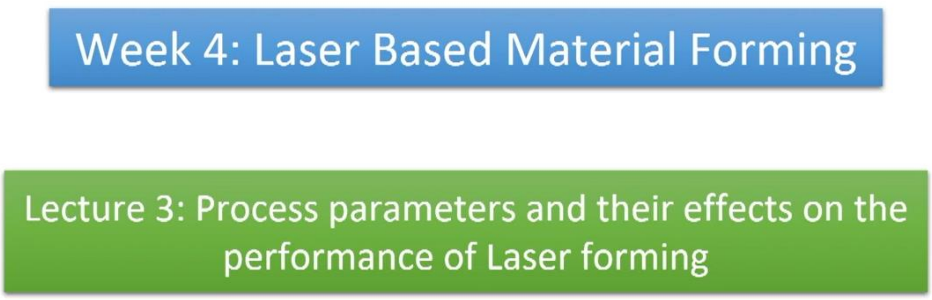

In previous lectures, we have seen the fundamentals of laser forming, various mechanisms involved in laser forming and how these mechanisms can be used in practice to solve or to apply, or to develop various products in the manufacturing. We have seen temperature gradient mechanism, upsetting mechanism and buckling mechanism. We have also seen various advantages associated with laser based forming, their limitations and various applications.

In this lecture, we will be studying in details what are the various process parameters involved in laser-based forming and their effects on the performance of the laser based forming. Let us begin our discussion on various parameters in forming and their performance related effects.

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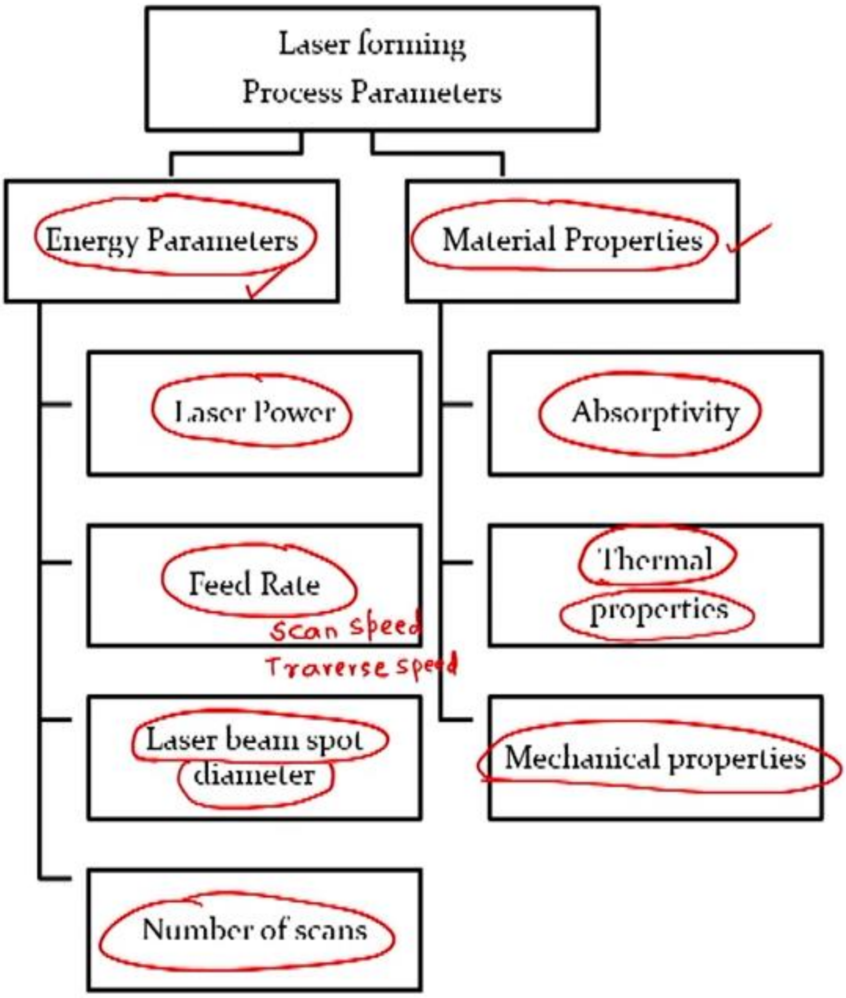
Process parameters



The parameters which are affecting the laser based forming are categorized into two groups. The first category is energy-based parameters. When we apply the laser beam over the work surface, we are applying the photon energy which is converted into thermal energy. There is energy transformation and what are the various parameters which are affecting the performance related to the energy that we are going to see. The next group is the material parameters of the work material on which the laser we are applying.

In energy related parameters the first important parameter is laser power, then the second one is feed rate or scan speed, in some of the literature it is also called as traverse speed, laser beam spot diameter which is controlling the intensity or the flux of the thermal energy which is being applied on the surface of the work part and number of passes of lasers on the work part. As far as material properties are concerned the absorptivity, which is very essential to be taken into consideration when we develop the laser based forming system or when we compute the laser based forming system angles during the deformation process. Thermal properties such as thermal conductivity, specific heat, these are the material properties need to be considered and the strength of the material, that is the mechanical property also is affecting on the laser beam bending process. In addition to this, the material geometry parameters are also affecting and the most prominent parameter is the thickness of the material geometry.

Let us see the effect of these parameters one by one.

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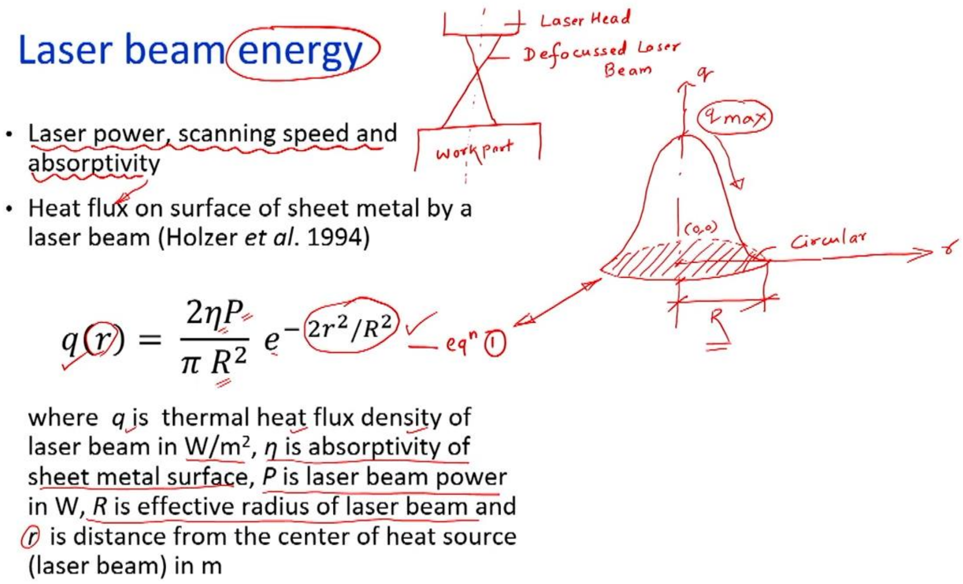

The first group of properties, that is the energy based property and in energy based property we can see that these three parameters are controlling the application of laser based energy over the work part. Laser power, scan speed and the absorptivity of work material. The laser power, scan speed and absorptivity of the work material is controlling the heat flux, which is. applied on the work part and that heat flux is generating the required thermal stresses and plastic strain during the laser forming process and it is generating the plastic deformation.

Now how to compute the laser heat flux? You know, in general there are various assumptions or there are various considerations about the application or the shape of the heat flux or the distribution of heat flux over the work surface. Prominently, the researchers and the engineers are considering the Gaussian distribution of heat flux over the work surface during laser based application. We have seen in our previous lectures that a defocused laser beam is getting applied over the work part. Let us consider this is a defocused laser beam which is applied on the work part. This is laser head, and this is defocused laser beam. The defocused laser beam has certain diameter over the work part surface.

This laser energy is being applied in the form of a cone shape defocused beam here and it has a diameter over this surface. When we apply the defocused laser beam over the surface we can see that at the center of that defocused laser beam area, the maximum amount of laser heat energy will get dissipated and as we move along the radial direction of that area of laser beam application, the laser beam energy will get reduced. It follows a Gaussian distribution, it follows the normal distribution. This Gaussian distribution of heat flux can be represented by the equation which is shown on your screen. This is equation (1). This equation (1) is having the heat flux and it is a function of r, that is the radial distance along the work part. Nu (ŋ) is the absorptivity, P is the laser power, R is the laser spot radius and e is the exponential function of r square (r^2) by R square (R^2).

Let us see the meaning of this. As I have just now said that q is the thermal heat flux density and that is in Watt per meter square (W/m^2). Nu (ŋ) is the absorptivity of the sheet metal surface, P is the laser beam power and R is the effective radius of the laser beam. whereas r is the distance from the center of the heat source. Here we are approximating the laser in a Gaussian beam, something like this. This is the Gaussian surface and this Gaussian surface (it is a bell shaped surface) is having the area and this interaction zone or interaction area is circular. This is the axis and this is the coordinate r, so along this direction the heat flux is reducing, this is the q max (q_{max}). This is the axis q and the maximum value of the heat flux is at the center, and as we are moving away from the origin or (0, 0) towards the r, then the heat flux is getting reduced and it is following the Gaussian distribution.

Here this is the effective radius of laser beam interaction with the work part. This is the particular equation which is describing this. In general, in laser based forming we are using this Gaussian distribution of heat flux for our computation. There are certain models they are using the uniform distribution of heat flux as well.

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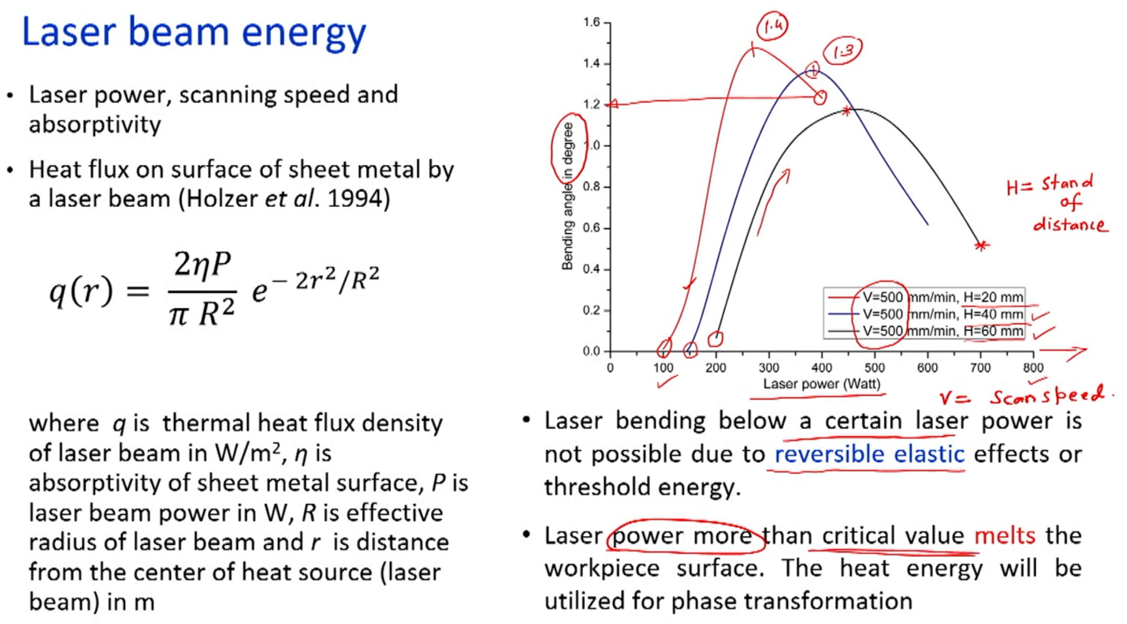

Now let us see what is the effect of this laser beam energy over the bend angle. On your screen you can see a graph and this graph is of bend angle. The bend angle is recorded in degrees and we are having laser power along the X-axis. The laser power is varied from 100 Watt to about 800 Watt and we are recording the bend angle for a constant scan speed. Here the constant scan speed that you can see, it is about 500 mm/min and H is the standoff distance, H is the distance of the laser beam head from the surface. This is H is the standoff distance and v is scanning speed.

Now, if you just look at this variation of bend angle with respect to laser power, the red color graph is showing that the bend angle is increasing with the laser power, for 100 W there was no bend angle, you just notice here for 100 Watt there was no bend angle, there was number deformation occurring. As we increase the laser power to 200 Watt we got around 1.4° of bend angle, considerable bend angle for one pass. But interestingly, if we increase the laser power further, the bend angle was reduced. You just note it down the bend angle increased and then it reduced.

Then we have increased the standoff distance we went for H is equal to 40 mm. Again, the trend is very similar for about 150 Watt of laser power there was no bend angle and we got a sufficient bend angle, significant bend angle when we took it up to 300 Watt and that is about 1.3°. But then it reduced as we increased the laser power to 400, 500 and further to 600 Watt. Then again, we tried to have another trend for H is equal to 60 mm. We got a similar observation. For 200 Watt there was insignificant bend angle, there was very small bend angle that was recorded. The bend angle increased with increase in laser power. It attained its peak over here and then again it is reduced. This is a peculiar characteristic that we noted and what is the reason for that? The reason behind this or this particular trend is attributed to reversible elastic effects. When the laser power is less and when the scan speed is. sufficiently enough, then we may not get the sufficient thermal stresses, which will give us the plastic deformation. These reversible elastic effects are due to low laser power, we are applying less energy and due to that the stresses which are getting generated are of lower side and these are providing the reversible elastic effects, there would be elastic deformation and after the laser will pass over the surface, the work part will regain its original size and shape.

But we want the plastic deformation, we have to work in the irreversible zone where there should not be any recovery of the work part dimension. But interestingly, if we apply more laser power, so here if we apply more laser power than the critical value or the threshold value, then also it is creating problem and the problem is of phase transformation. When we apply more laser power there is a phase transformation of material from its solid-state to the liquid state and the entire thermal energy which we are applying will be consumed for the phase transformation only. There is no energy would be utilized for the plastic deformation and due to that the bend angle will get reduced as you increase the laser power above the critical limit. It is non-linearly behaving. The laser power is non-linearly acting upon the bend angle. Therefore, it is very much essential or we have to be very careful in choosing the laser power during the laser bending operation.

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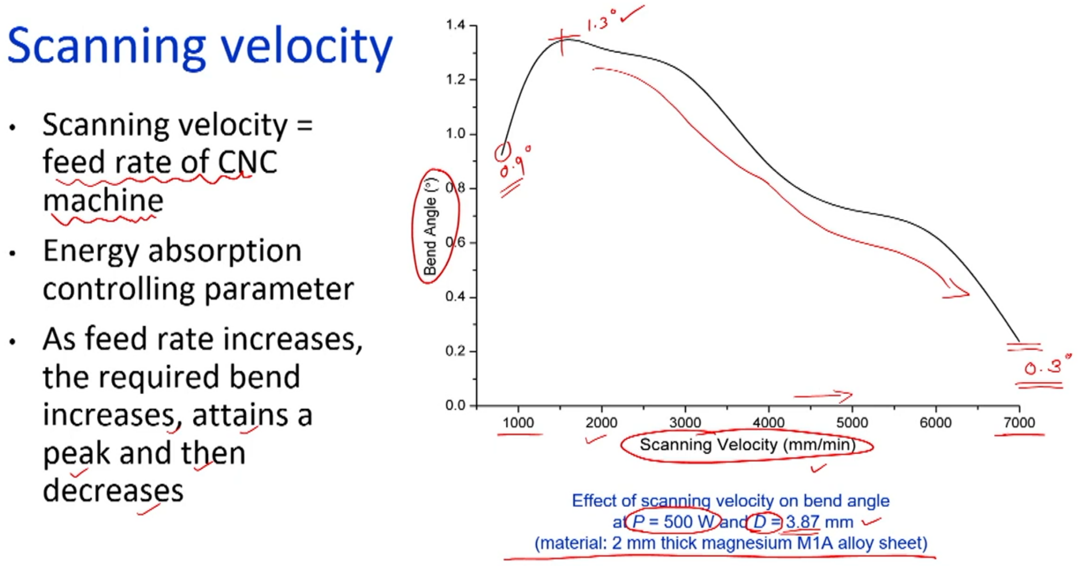

Now let us see the effect of scan velocity or scanning velocity. Scanning velocity is also called as the feed rate of the CNC machine. In technical terms we are calling the scan velocity or scanning velocity. However, in the CNC technology term, we are setting the feed rate during the operation. It is the energy absorption controlling parameter, it is controlling the absorption of energy. As the feed rate increases, the required bend angle increases, attains a peak, and then it decreases. We also got a similar observation here as well. On your screen you can see the bend angle is plotted against the scanning velocity, scanning velocity is taken into mm/min and the bend angle is in degrees. On X-axis you can see the scan speed or velocity is varying from about 1000 mm/min to 7000 mm/min and the bend angle that we could notice over here is about 1.3°. This process parameters are used for a constant laser power application of about 500 Watt and the laser spot diameter was 3.87 mm. The material used was magnesium M1A alloy sheet and the thickness of that sheet was about 2 mm.

Now if you look at the graph, we can notice that for 1000 mm/min we got around 0.9 degrees, that is a moderate bend angle. To achieve the more bend angle, we increase the speed, we went for 2000 mm/min, we achieved a very good bend angle per pass that is about 1.3°. To gain more bend angle, we further increased and that is 3000, 4000 and so on. It has been noticed that the bend angle was reduced and it even reduced to our primary or initial value of 0.9 and it reached to a very minimal, very insignificant bend angle of 0.3°, which is of no use. Why is this has happening? With increase in the scan speed, initially we could get good TGM, that is a steep temperature gradient was achieved, but to get more bend angle we have increased the scan velocity and as we increase the scan velocity there was not sufficient time of interaction of laser beam with the work part and due to this less interaction time, there was no proper dissipation of heat, which is at least required for the plastic deformation. Too much of the faster speed is not required in the significant or the successful bend, laser based bending operation.

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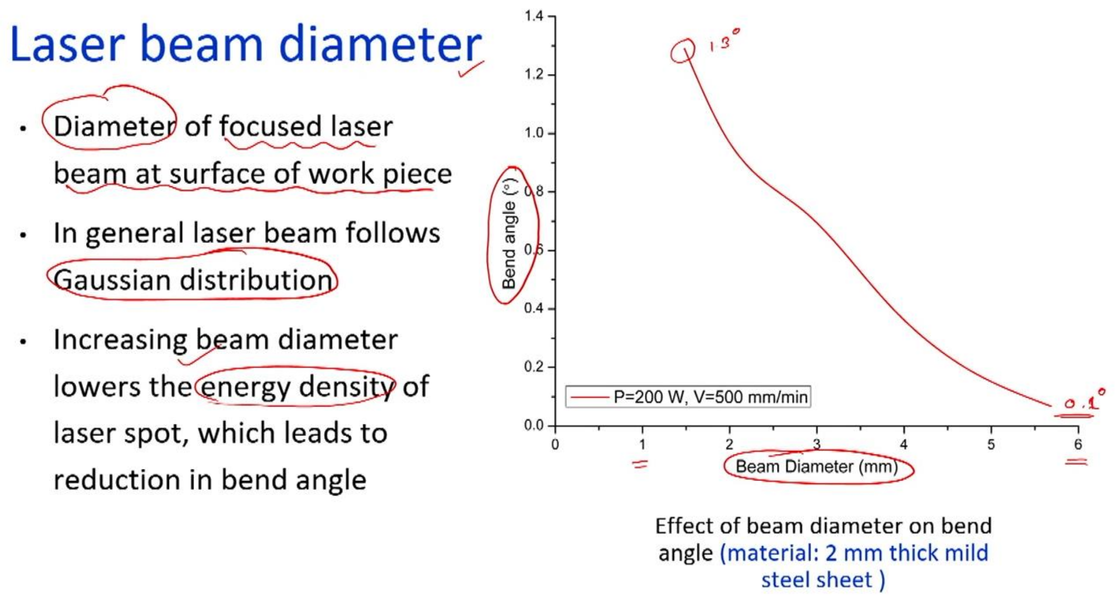

The next parameter is laser beam diameter. And this laser beam diameter is the diameter of the focused laser beam on the surface. As the name suggests, is the diameter of the laser beam on the workpart surface. As we have seen that in general the laser beams are following the Gaussian distribution, if we increase the laser beam diameter, certainly the energy density will get reduced when the power is constant. If the power is constant, if you increase the diameter, certainly the density will get reduced and that will certainly affect the bend angle as well, there would be reduction in the bend angle. This has been shown on your screen. You can see a plot of bend angle with respect to the beam diameter. As we increase the beam diameter from 1 mm to about 6 mm, it is noticed that the bend angle is almost linearly reducing from about 1.3° to 0.1°, that is of very low value or insignificant value. Here we have to carefully choose or select the laser beam diameter to get the required bend angle. Of course this has to be associated with the other two parameters, the laser power and the scan velocity.

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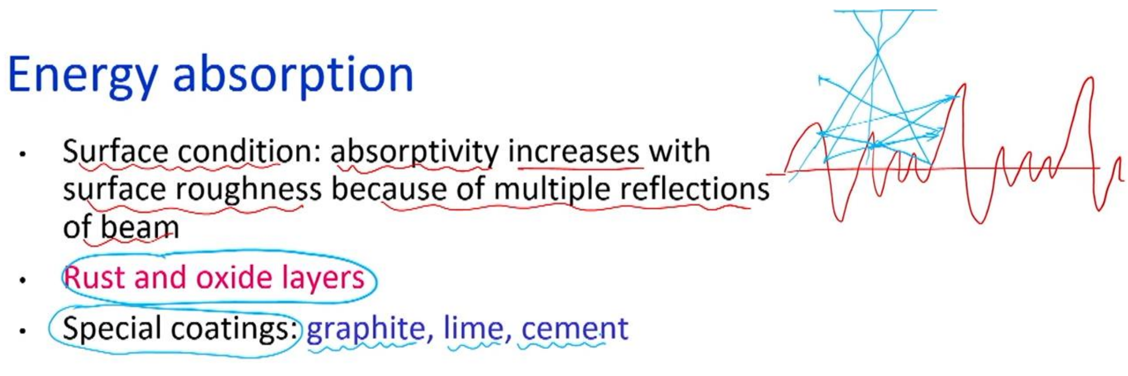

Now next parameter is the absorption or energy absorption. And it is dependent upon the surface condition. The surface condition is affecting it. It has been noticed that the absorptivity is increasing with surface roughness, because of multiple reflections of the beam. As we know that the surface is not perfectly flat, it has crests and troughs. If you just observe the surface in microscope, you may get this kind of undulations of the surface. When a laser beam is applied over the surface, let us consider a beam is applied over the surface, this is the defocused beam which is applied and the energy has been applied. Now there may be reflections from this end, so it will go here and then the reflection will come over here and from here again it will come back and again it will move to this direction and it will move out. In a similar way the other rays of the laser will get struck over here they will get reflected. These laser rays are getting reflected multiple number of times and as there are multiple number of times the rays are getting reflected, they may get struck up, they may get strike to the crest of the surfaces and due to that there will be more energy absorption over the work surface.

Then the energy absorption is also based upon the rust and oxide layers. The industrial parts may have some rust, they may have some oxide layers which are laid down to protect its surfaces. When we use rolled sheets with these oxides and the rust layers during the operation, they will get more absorption of the laser beam energy. When we are dealing with the reflective surfaces, we have to increase its absorptivity. In these cases, deliberately we are applying certain material that is graphite or lime or the cement so we can have a spray of graphite or cement over the surface and these coatings will certainly improve the absorptivity.

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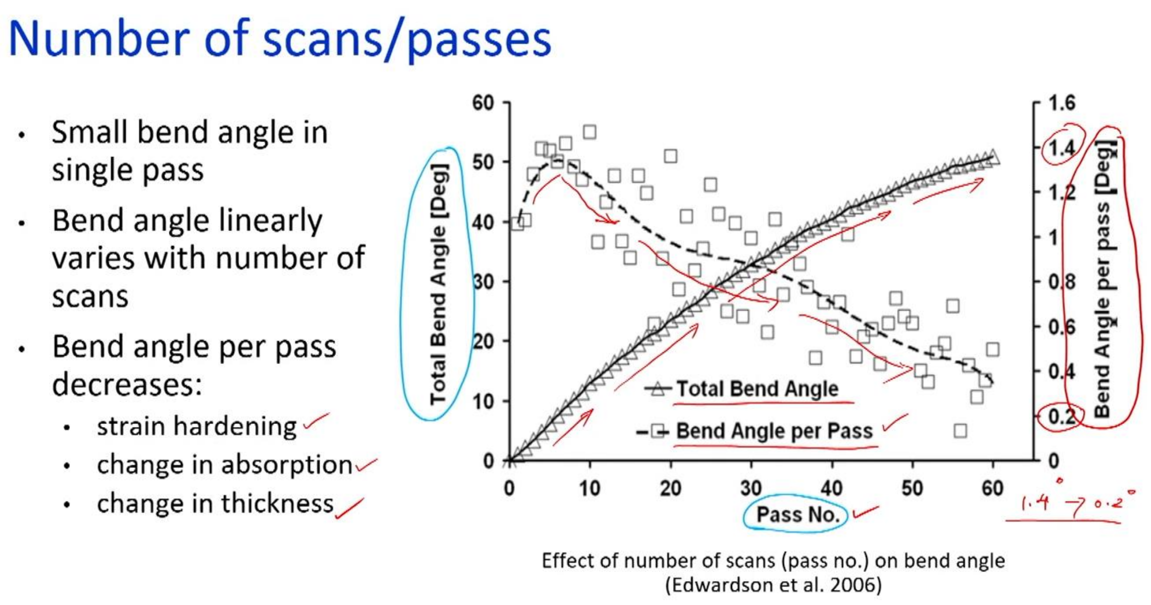

The next parameter is number of scans or the passes. It has been noticed in all our discussion till now, that laser bend angle is very small per pass. We have seen that it is about 1° or 1.4° per pass. Now to increase or to have the macro-level of bending, to have sufficient bending of the metal sheets, we have to irradiate the surface multiple number of times. In that case we are using this parameter to gain more bend angle, that is a number of times we have to scan the laser beam. And it has been noticed that the bend angle is linearly varying, linearly increasing with number of scans. We are applying multiple number of times, more energy we are putting in in the workpiece material and we are getting more bend angle.

But there is a peculiar observation regarding the gross bend angle that we are getting and the bend angle per pass that we are getting. On your screen you can see a plot and this plot is the total bend angle with the number of passes and it also has the bend angle per pass in degrees with number of passes. It also has the bend angle per pass with number of passes. In the same graph we are getting two curves; one curve for the total bend angle and another curve is for bend angle per pass.

Let us discuss the total bend angle with the pass number. Here you can see this is the curve for the total bend and as it has been noted here, the total bend angle is increasing with pass number, and you can see the total bend angle is linearly increasing with the pass number. The number of passes is up to 60.

Now the next is bend angle per pass. We can see here the bend angle per pass is increased little bit and then it started reducing. This is a very peculiar observation, very typical observation that we are getting over here. The bend angle per pass is reducing. That bend angle per pass was about 1.4° or around 1.5 or 1.4° at the initial level and it reduced to up to 0.2 degrees. Here you can see it is reduced to 0.2 degrees, so it is varying from about 1.4° to 0.2°, very interesting. Why is this happening? When we apply the laser irradiated surface multiple number of times, then there are the problems of strain hardening. We are treating thermally the surface for multiple number of times; the material properties are getting changed. The bend angle per pass is decreasing and it is attributed to the strain hardening, change in absorption, as the surface quality or the surfaces are getting changed so there is little bit of melting will also occur and melting and redeposition will lead to some sort of reflection; the absorption will also reduce, and change in thickness as well, there is a change in thickness so more volume is there for heat conduction and due to more volume for the heat conduction, less would be the deformation for the same amount of heat power that we are applying, for the same amount of heat flux density that we are applying.

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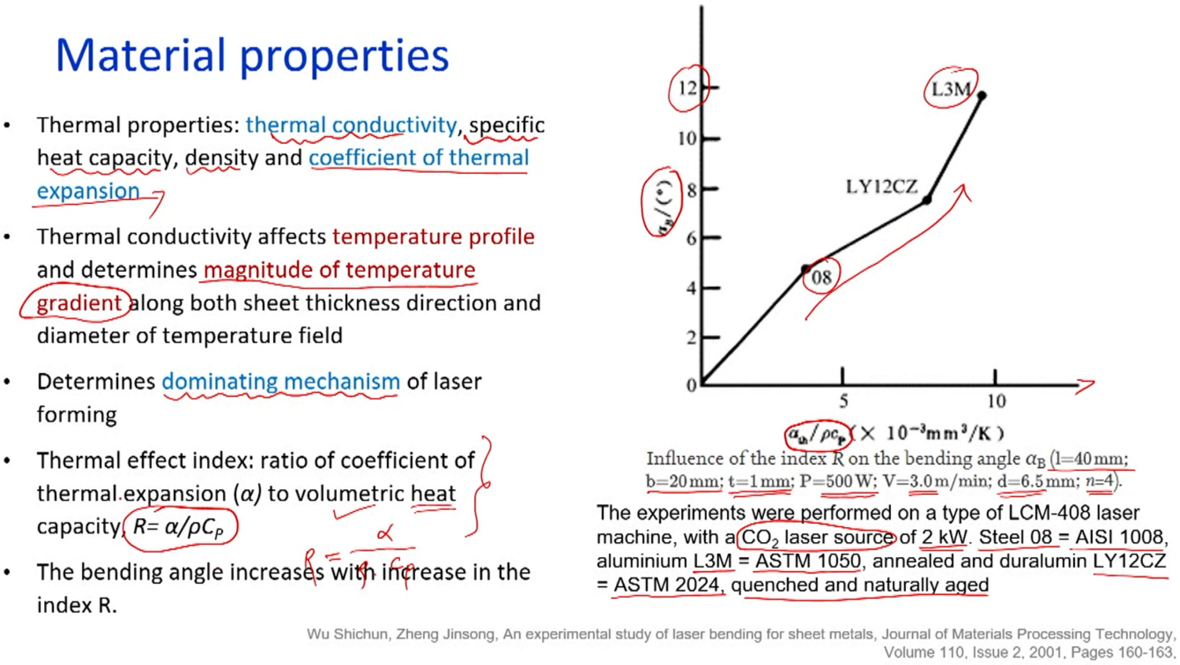

Now next group of parameters which are affecting is the material properties. And as we know that the thermal conductivity, specific heat capacity, density and coefficient of thermal expansion are coming under the thermal material properties. As far as laser bending is concerned, the most prominent thermal property that is thermal conductivity is affecting the temperature profile. It is determining the magnitude of TGM, it is deciding the magnitude of temperature in thermal gradient mechanism-based laser bending. As we have seen that if. more the thermal conductivity, we may not get sufficient bend angle and that is due to less temperature gradient. If you are using stainless steel sheet of 2 mm and a copper sheet of 2 mm, the temperature gradient in stainless steel sheet would be more than the copper sheet because of the less thermal conductivity that SS is providing to us for the same process parameters and for the same geometry of the work part.

The temperature gradient is all dependent upon the thermal conductivity. And there is a ratio which is being used in the industry that we call the Thermal effect index and this Thermal Effect index is the ratio of coefficient of thermal expansion (alpha, α) to the volumetric heat capacity. This is thermal effect index (R) is alpha (α) divided by the volumetric heat capacity, which is defined by the product of the density of the work material and its specific heat.

Now let us have a sort of little more discussion on this R (thermal effect index). It has been noticed that when R is more or when R is increasing, when the Thermal effect index is increasing, we are getting more bend angle. This was observed by experimental investigation. That is there on your screen, here you can see the parameter R (Thermal Effect index) on X-axis and on Y-axis is the bend angle.

Now these experiments were carried out on a CO_2 laser machine - CO_2 continuous laser source of maximum power of 2 kW and three different materials were selected or three different materials were used for this particular study. The first material was Steel 08 (AISI 1008 grade of steel), then the next one is L3M, it is an aluminum alloy and it is of the standard ASTM 1050 and the next one is LY12CZ material and that is of ASTM 2024, it is duraluminum, it is quenched and naturally aged. These three materials were selected for this particular study and you can see the process parameters on your screen. The length of the workpiece was 40 mm its width was 20 mm and the thickness was 1 mm. The specimen sizes are 40 by 20 into 1 mm. Laser power, which was set to about 500 Watt and the scan velocity was 3 meters per minute (3000 mm/min), diameter, that is, the laser spot diameter was 6.5 mm and the number of passes were 4. With this, it was found that as the Thermal Effect index is increasing, we are we are getting more laser power, and the steel has been compared with aluminum. Aluminum is having more Thermal effect index and due to that more bend angle was noticed with aluminum material in comparison with steel. Therefore here you can see the more bend angle for the aluminum because of its Thermal effect index.

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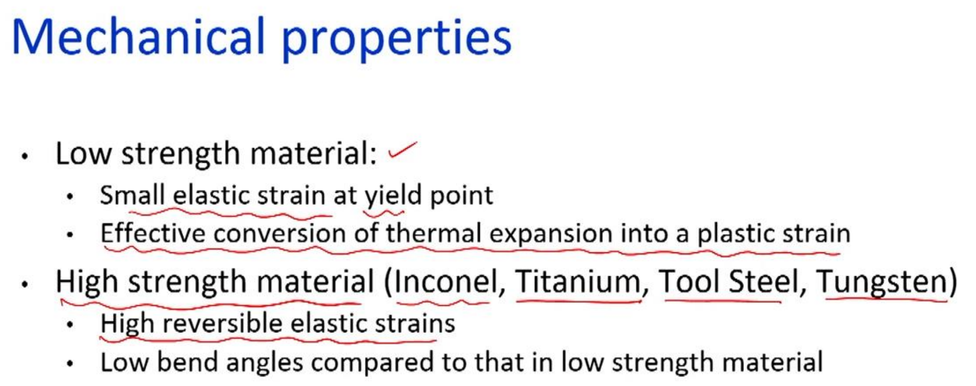

Now let us see what are the effect of mechanical properties on the laser bending performance. In industry we are dealing with multiple types of materials which are having low strength as well as the high strength. If we process the low strength material, there would be small elastic strain at the yield point and there would be effective conversion of thermal expansion into plastic strain. If the material is having low strength, we can easily deform it. And the same thing would be useful for the laser bending operation as well; if the strength of the material is low, it can easily be deformed and that is why low strength material can have more ease of deformation and under laser bending as well.

For high strength materials such as Inconel, Titanium, Tool steel, Tungsten, all these are the high strength materials they are having high reversible elastic strains and we can certainly notice low bend angles during the processing of these materials by using lasers.

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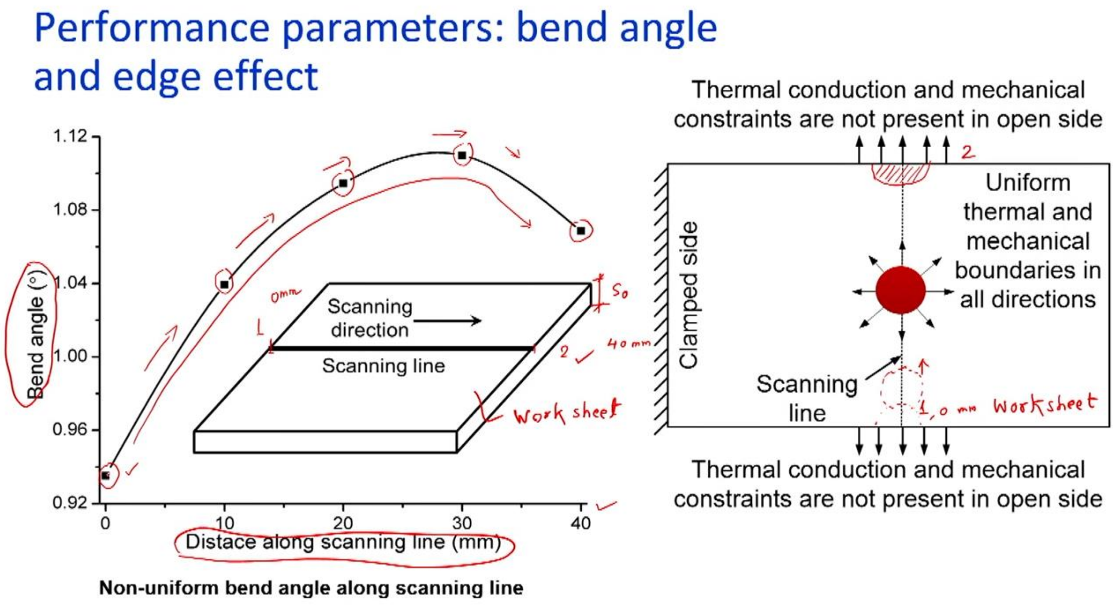

The next parameter is the geometry and the material or the products specimen that we are using during laser bending operation, they may have various geometry parameters. Consider we are using a rectangular sheets, and they may have length and width and it will certainly have the thickness. The sheet thickness is the prominent parameters, that also we have seen in our previous lecture when we compared three different mechanisms of laser bending. Sheet thickness is the most important parameter among the other geometry parameters. It has been noticed by Geiger et al. that the bend angle is approximately inversely proportional to the square of the sheet thickness. The bend angle is approximately inversely proportional to the square of sheet thickness. Now, during the process of application of heat energy, it was noticed that the bend angle is not uniform along the path of its application, path of the application of laser source. This is a very interesting observation noticed when we apply the laser beam over the work part.

Consider this is the work part that we do have, consider this is the worksheet of certain thickness and we irradiated this worksheet by laser from this end to this end. However, it is expected that we should get uniform bend angle from end 1 to end 2 during the laser bending operation. But during the experimental study, during the actual practice of laser-based forming, it was noticed that we do not get uniform bend angle along the length of its application.

Here you can see a typical graph of the distance along the scanning line. The distance along the scanning line is from point 1 to point 2 and it is about 40 mm, here you can see it is about 40 mm, 40 mm is the length of the scan path and on Y-axis we are having the bend angle, the bend angle is varying with respect to the scanning line.

Now when we plotted the bend angles at point 1 to point 2. Point 1 is at 0 mm and point 2 is the 40 mm. We noticed that at point 1 the bend angle is little more than 0.92° and it increased up to 1.04 then went to 1.08 and it reached to about 1.1 and then it was reduced again further to 1.08. The uniform bending was not observed, as we expected to have either 0.93 uniformly along the scan line or whatever the value, but it has to be uniform. But that is not observed and what are the reasons for that? The reasons can be seen on your screen. This is the clamped side of the work part and this is the free side. This is the worksheet which is clamped, this is clamped on this side and this is another side.

Now what is happening when we are scanning from one end to another end? At the start of the scan, say 0.1 over here which is at 0 mm, so we got some bend angle and that bend angle is due to the regular TGM mechanism that we have already seen. But when the laser beam was here, half the laser beam was outside the over surface and half the beam was inside the work surface, and due to that only half of the heat flux density was useful for the heat conduction. Ok with that, we got certain bend angle.

Now as the laser beam is moving inside, now the complete heat flux density is available for the bending operation. With that the bend angle started increasing. When there was a spot over here there was a bending which was occurring. Due to this bending some energy was getting dissipated inside the work part. The next location was getting the benefit of getting heat flux from the previous location of the laser. There was a preheating of the subsequent place, and that preheating was helping to get more bend angle, so that was noticed for further increase. And when the laser beam will come at this location at the end, here when the laser beam was at its end point number 2, again there was a halfway or again there was half of the portion of the laser area was available for heat dissipation, and due to that the bend angle was further reduced. But here is the effect of the preheating. At the start there was no preheating, the work piece was at the surrounding temperature at the ambient temperature, the bend angle at the start was less. But at the end, when there was only halfway area was available for the laser beam application, but due to preheating we got the moderate bend angle.

Here I can say at start the bend angle was low because there was no preheating and it was purely due to TGM and only half portion of the laser beam was useful for the TGM. As the beam is passing over the scan line there was increasing in the bend angle due to preheating due to available of the entire area, entire volume for the heat conduction. But at the end again, there was only half area was available for the laser beam operation TGM, but there was effect of preheating so we got a modest bend angle. However, it was not the top or the maximum bend angle which was produced, but it was certainly more than the initial bend angle. This is called as the **edge effect** and this edge effect is due to the preheating the available area of the available volume for the heat dissipation during the laser bending operation. To have the uniform bend angle, you can modulate or you can find tune this process parameters when the laser beam is traversing over the work part.

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Summary

Energy based process parameters
- Laser power
- Scan speed
- Beam spot diameter
- Number of passes

- Absorptivity
- Thermal properties → thermal effect index
- Mechanical properties
- Edge effect → quality of Laser bending operation

Fine, these are all the process parameters that we have seen at length. We have seen various process parameters such as energy based parameters and these energy based are laser power, scan speed, beam diameter or beam spot diameter and number of passes. We have also seen the other parameters such as absorptivity or material related parameters and effect of thermal conductivity - thermal parameters. We have seen the meaning of Thermal effect index, mechanical properties and an interesting thing that is the edge effect. We have seen the meaning of edge effect which is associated with the quality of laser beam during laser forming operation.

Basically, the quality of laser bending operation is dependent upon two things: the uniform bend angle along the scan path and the magnitude of bend angle during the scanning operation. These two parameters are to be considered the vital parameters when we talk about the quality of laser bending.

With this, I would like to stop for today's class on effect of process parameters on laser bending operation.

Thank you for watching this video. Thank you. Goodbye. See you in the next lecture.