Laser Based Manufacturing

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Module # 04

Lecture # 11

Material Forming and Fundamentals of Laser Forming

Hello friends. I welcome you all to the Week 4 of NPTEL course on Laser Based Manufacturing. Till now we have seen two basic applications of lasers in manufacturing. First in material removal and the second one in joining operations. Now, in this week we will be studying a very useful and prominent application of lasers in forming that is the material forming application.

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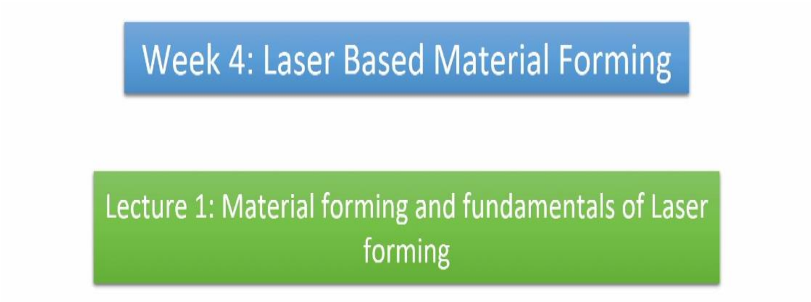

Let us begin our lecture. This is the Lecture 1 of Week 4 and it is on material forming and fundamentals of laser forming. At the start of the lecture, we will be studying little bit of various types of material forming and then we will start discussing about how lasers can be utilized to deform the material using the photon based thermal energy.

Well my friends the material forming is one of the primary manufacturing processes. We know that casting is one manufacturing process which is widely used as a primary process to convert the raw material into semi finished product. Material forming is another process where we are using the raw material again to make the semi finished products, for example, thin sheets of metals. These thin sheets of metals are further utilized to manufacture the skins of the systems, for example, an automobile system.

To manufacture the skin of the system we are using the roll sheets and these roll sheets are manufactured by using material deformation process, material forming process where we are carrying out the permanent plastic deformation of the work parts or work sheets.

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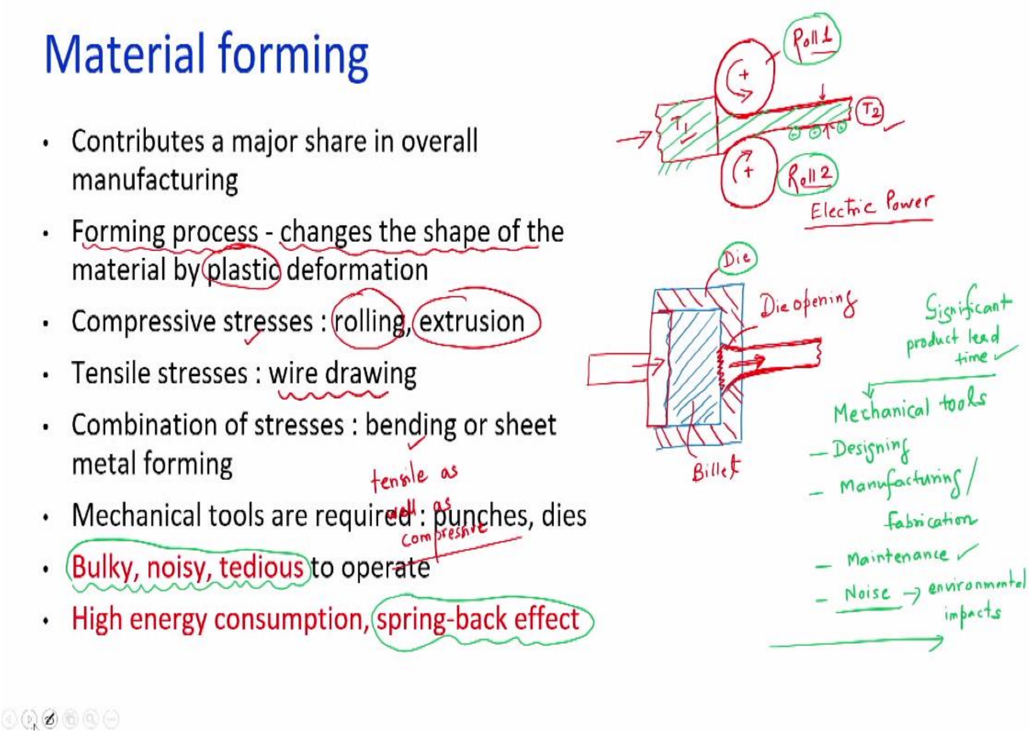

Material forming is contributing a major role or major share in overall manufacturing processes. Casting is prominent as well as the forming is also equally prominent in the manufacturing processes. Then the machining comes into picture which can be considered as the secondary manufacturing process during the part development.

In forming operations, we are changing the shape of the material by carrying out the plastic deformation and to obtain the plastic deformation of the work material we are applying the forces. In certain cases even we are increasing the temperature of the material by applying the heat energy such as forging operation. There are various types of stresses being used in the material forming. Consider the compressive stresses. When we use compressive stresses we can roll or we can reduce the thickness of the work sheets. Rolling is very useful and an important application in the industry. It is a plastic deformation operation.

We are having two rolls and these two rolls are used to reduce the thickness of the metal sheet. In rolling operations we are using two rolls. Roll number 1, these are made up of metals, these are metallic rolls. Roll 1 and roll 2. There is designated gap between these two rolls. Certainly these gaps between two rolls could be less than the thickness of the input material. Now, consider we want to reduce the thick sheet of about T1 and this is getting driven by the roll 1. Roll 1 will drive the roll 2 by taking this sheet inside the gap between roll 1 and roll 2. At initial level, we have to push the sheet inside the gap between two rolls and then there are rolls are being driven by electric motor - electric power and as we apply the electric power this power would be converted into mechanical energy and that mechanical energy will be utilized to deform plastically the thick sheet into a thin sheet. Here the reduction in the thickness from T1 to T2. Here we apply by using these two rolls the compressive stresses and that compressive stresses are helping us to reduce the thickness from T1 to T2.

There is another process that we call extrusion process. Extrusion process is used to again make various shapes and to reduce the dimensions of the work part. In extrusion process, we are using dies, and let us consider a die which is getting designed and developed. Now, here we are putting up the billet material. Billet is the raw material, this is the billet material, this is die and this die is having opening. This is the die opening, this is billet. We are applying mechanical force on these billet material by using a ram. This is a mechanical element that we call ram, we are applying the compressive forces, we are applying forces on the billet material and due to these forces there are generation of compressive stresses and wherever the gap is there wherever the opening is there through that opening the material will get deformed. It will be flown out of the gap or the die opening.

In this way the extrusion is also considered as the compressive stress based deformation process, where we can manufacture variety of shapes based upon the shape of the die opening. You can extrude the bars of circular cross section rectangular cross section or any geometric cross section you can extrude the bars of metals.

Instead of applying the compressive forces if we apply the tensile forces or tension in this process that is called as the wire drawing. In wire drawing if we pull this material by using certain mechanism through the opening of the die then that process can be called as the wire drawing operation.

Let us consider that we want to manufacture a wire of about 10 mm, we have made a die of 10 mm and then we are pulling that material through the die. At the other side of the die there is a billet material. When we apply the tension and by using this tension we are generating the required product that is called as the wire drawing process.

In certain applications we are applying both the type of stresses that is called as bending and when we apply both the stresses that compressive stresses as well as the tension or the tensile stresses and the application of both the stresses in combination is called as the bending operation.

Bending here we are applying both tensile as well as compressive, but if you note in all these cases we need to have some mechanical systems. In rolling operation we have to design rolls, we have to take care of the rolls, there is a wear and tear of the rolls, design, development of the rolls, then fixtures for the rolls as well as fixtures for the work parts. All these things are to be designed and are to be manufactured or fabricated before start of the actual production. In a similar way, in die ways extrusion as well, the design and development of die is a crucial. We have to manufacture the die first and then use it for actual operation. There are other operation such as forging. In forging operation, we are increasing the temperature of the work part above the recrystallisation temperature and then we apply the mechanical forces.

The mechanical forces are applied by using mechanical systems and then we required the required shape. That also required some sort of die and the punch system to get the required shape.

In all these cases, it is essential to note that there is a need to have mechanical tools and there are things required for designing of the mechanical tools, their manufacturing or fabrication of the tools, maintenance and their effects or there maybe side effects of these processes such as noise or environmental impacts.

Now to resolve some of these issues or to resolve some of these problems with this mechanical tooling which also prominently required considerable or significant product development time, significant product lead time. Lot of time is required in development of mechanical tools, maintenance is very high and it may also have lot of noise as well, environment impacts would also be there. To tackle some of these problems, the engineers, scientists started using thermal energy in non-contact way that is the flame bending. You apply the thermal energy by using the flames and by using these flames you can deform the material and the advancement of the flame bending is laser based bending or the forming.

These mechanical tools are bulky, noisy and tedious and we are trying to resolve these issues by using some advanced technologies. Moreover, the mechanical tools may generate some sort of spring back. There may be some sort of recovery due to the elastic deformation of some of the materials and that spring back effect will certainly affect the product quality.

Consider during bending it is envisaged, it is expected, it is desired that we should get about 30 degrees of bend angle, but due to spring back effect we may not achieve exactly 30 degrees, we will get 28 degrees, but if that product would be utilized for some precision application, in that case it is very essential for us to have the exact 30 degrees in these cases. That is not possible by using the mechanical bending. How to resolve these issue to have the exactness in getting the deformation? that can be done by using some advanced techniques such as the laser based energy application.

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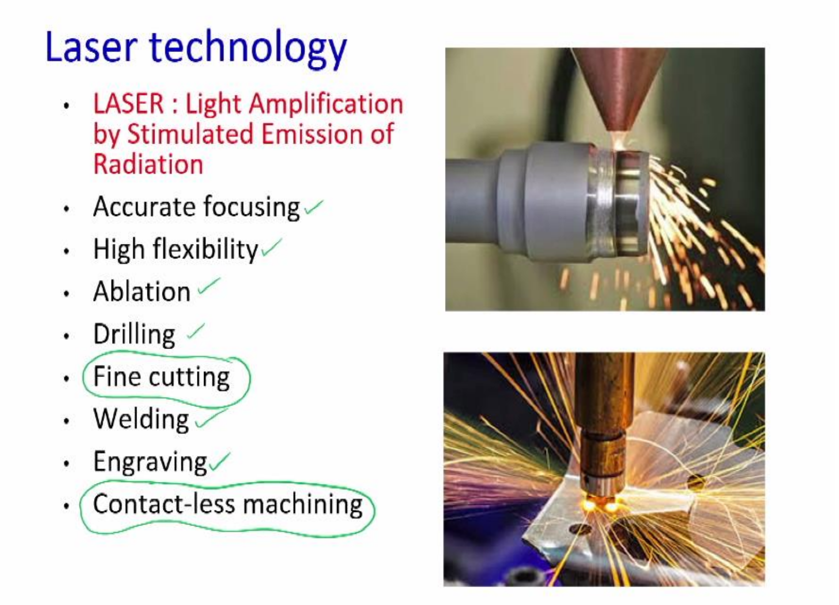

As we have seen in our previous lectures, lasers are having a prominent advantage of accurate focusing. It has another advantage of providing very high flexibility of application and we have seen ablation based laser material removal in our previous class, drilling techniques and it is also providing a very fine cut due to controlled application of laser beam energy at a very finer spots or along a path with precision.

We have also seen that welding is also getting benefitted by lasers when we want to connect two dissimilar materials, when we want to join two different materials of different thicknesses. Engraving is also getting benefitted, we will be seeing the engraving operation in the next week. The biggest advantage of lasers as far as material removal is contactless machining. We have seen some of the problems with the mechanical based material removal is the contact operation.

Whether there is a contact, there is a friction, there is noise, there would be vibration, there would be wear and tear and it will consume lot of energy as well. Can we have a contactless material forming? and the solution is by using lasers.

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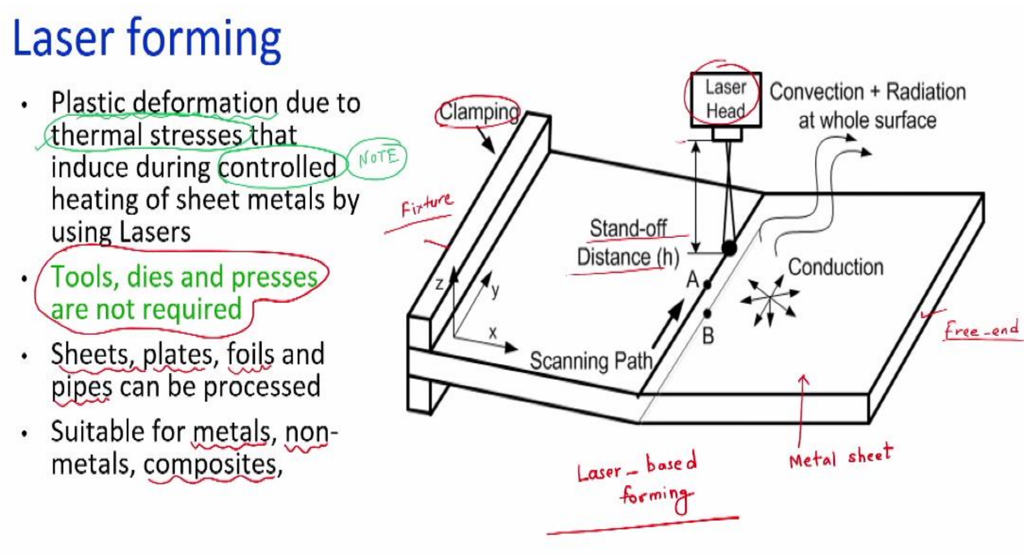

Let us see how lasers are used to deform the material. It is possible to deform the material by using lasers. We can generate the plastic deformation and that plastic deformation is generating due to thermal stresses. If we generate thermal stresses above the yield strength of the material then that stresses can give us the enough plastic strain which may be converted into the permanent deformation.

And these thermal stresses are generated due to the controlled heating. Here it is very essential to note down there has to be application of controlled energy. If the energy is more, then the material will get ablated, there would be cutting instead of deformation. During the experiments we can easily notice that if there is increase in laser power, if there is increase in heat input the material will start getting melted, there is a phase transformation from solid to liquid material, that is not desired and it is to be very carefully taken into consideration when we apply the process parameters. The lasers are to be applied with power and speed in such a way that there should not be any melting and there has to be only pure deformation without melting, then and then only we can generate a good quality deformation by using lasers.

Now, let us see how lasers are deforming? We have taken one work sheet. This is metal sheet and these metal sheet is clamped in a fixture. This is fixture at one end and the metal sheet has a free end. This is free end and this is the clamped end. Now, we are using a laser beam here to generate the deformation or to get the deformation we should apply sufficient or enough power. We can apply CO_2 laser or we can use Nd:YAG laser as well during these application. There has to be certain safe distance between the laser head and the point of application that is the top surface of the metal sheet and this is called as the stand-off distance. Then we can either move the work part with respect to the laser head or we can move the laser head with respect to the work part either way it is possible.

When we apply or when we scan the energy from one end to another end of the metal sheet, the metal sheet gets deformed - that is the laser based forming and how it is possible that we will see in our coming slides. Laser based forming by controlled application of laser based energy over the work surface and by using the CNC based technology.

Now, here the prominent advantage of laser based forming is that no tools, dies or presses are required. We are completely removing the mechanical tooling only the clamps or the fixtures for the workpieces are required which are very simple and readily available. There is no need to design especially the clamps or fixtures during these laser based processing.

Laser based processing find applications for the deformation of sheets, plates, foils, pipes. All these form of metals, all these types of forms such as sheets, plates, foils and pipes can easily be deformed by using the lasers. Lasers are found to be very suitable for metals, non metals, composites, even glass also can be deformed by using lasers.

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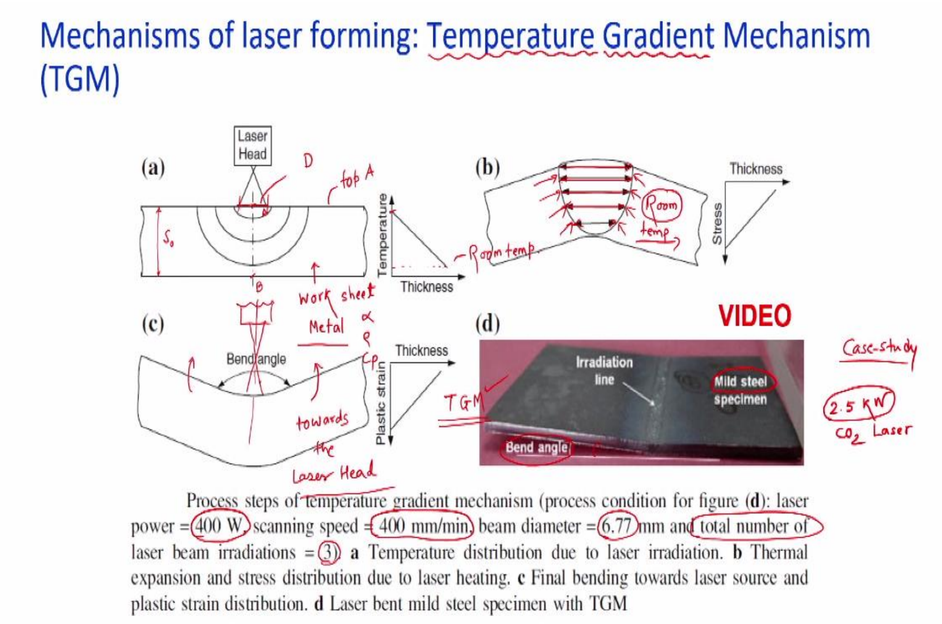

Now, let us see how exactly the lasers are deforming the material. There is a prominent mechanism that we call temperature gradient mechanism which is helping to deform the materials by using lasers. Let us see what is the meaning of TGM - temperature gradient mechanism?

Now, on your screen you can see there is a worksheet and this worksheet is having a certain thickness, consider it is having a thickness S_o. Now, there is a laser head and laser head is getting irradiated, the laser head is providing us the laser energy - the defocus laser is applied here. We are not focusing the laser on the surface, if you focus the laser on the work surface there maybe chances of having intense heat generation and that intense heat may spoil the work part, it may either vaporize the work part or melt the work part which we do not want here. Therefore we are using defocus laser during the forming operation. Accordingly you have to adjust or accordingly you have to tune or set the SOD, that is the stand-off distance. The diameter of the laser beam on the surface is D. This is a diameter D. Now this work material is considered a metal and it is having thermal diffusivity of alpha (α), it is having density of rho (ρ) and it is having specific heat capacity (C_p).

When laser is applied on its top surface, due to laser material interaction, there is expansion of top fibers and that heat energy which is getting absorbed by the top fibers that will get dissipated based upon the thermal conductivity of the work material. When the top fibers or top layer is expanded the surrounding material which is at the normal temperature, ambient temperature will oppose that expansion, they will constraint the expansion of the top fibers and due to that there is a generation of compressive stresses inside the material and due to these compressive stresses the material will get deformed. If you are able to manufacture more compressive stresses due to the constraint offered by the surrounding cooler region to the expanded fibers you are able to get the plastic deformation due to the lasers.

Now, let us consider the laser is applied. At the top surface there is maximum temperature which got generated at the top fiber. This is the top surface, top point A, so at point A we got this temperature and along the application of the laser heat, along the thickness, we are getting point B and temperature at the point B would be very low. This maybe the room temperature.

Now here the concept is that there has to be significant or there has to be maximum possible difference between temperature at point A and temperature at point B and when we are able to get the maximum difference we are generating the enough or significant bend angle during our laser forming operation. When the laser beam is applied the top surface is having maximum temperature and the bottom is having low temperature and there is expansion of fibers, the fibers are getting expanded, but the surrounding fibers, these are at room temperature or they may be having temperature little more than the room temperature.

As these are at the room temperature they will not allow these fibers to expand and that restriction or constraint is generating the compressive stresses. And when the laser is just passed over the work material after that the material will get cool down and due to this compressive stresses there is a plastic deformation will occur towards the laser head. Here the laser head and we are getting the plastic deformation towards the laser head. This is called as the TGM - temperature gradient mechanism. By using the temperature gradient between the top fibers and the bottom fibers we are generating the plastic deformation that is the TGM.

On your screen you can see a mild steel specimen, mild steel worksheet and it has been processed by using a 2.5 kilowatt laser machine, it is a CO_2 laser and by using application of the laser it was noted a certain bend angle. Now, what are the process conditions for this case study here? This is the case study. We applied a 400 watt, the machine maximum power was 2.5 kilowatt, but we said the power of about 400 watt, the scan speed was about 400 mm per minute and the beam diameter was 6.77 mm. Here this D was 6.77 mm and we irradiated the work part thrice for three number of times we have just irradiated. When we apply the heat energy for three number of times we got a considerable bend angle of about 5 degrees.

Now, let us look at the actual deformation by watching a video. Now, let us look at the actual deformation when the laser is being applied on the mild steel sheet.

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On your screen you can see a typical arrangement that we have to create for this 2.5 kilowatt CO_2 based laser forming. This is machine bed, this is inset, we can have one more angle to watch the video. This is fixture and this is work part. Now, you closely or you carefully observe how the part is getting deformed towards the laser. Laser will come from this direction and it will deform the work part. I request you all to just see the deformation towards the laser.

Now, let us begin the video here. **(Video starts at 29:53)** The laser has come and it has started applying the energy. There is some sort of arcing you can notice and it is the burning of the slag or the dirt on its surface. One pass is over and now the second pass will go on. Now, there is more burning or arcing that maybe due to more heat that we are applying, but you can notice that there is a deformation which is getting occur. There is a deformation which has already been done. Now, the third pass is coming and now we are applying the energy for the third pass. Now, there is a deformation which can prominently seen here. This is the bending which has occurred. **(Video ends at 30:45)**

After the application of laser energy, we have noticed that there is bending which has occurred. Now, we can even analyze how exactly the bending has been done. We can compute the bend angle by computing the plastic strains by carrying out various numerical analysis such as Finite element method.

Now, let us try to find out the correlation between the thermal properties of the work material with the bend angle and the material properties as well.

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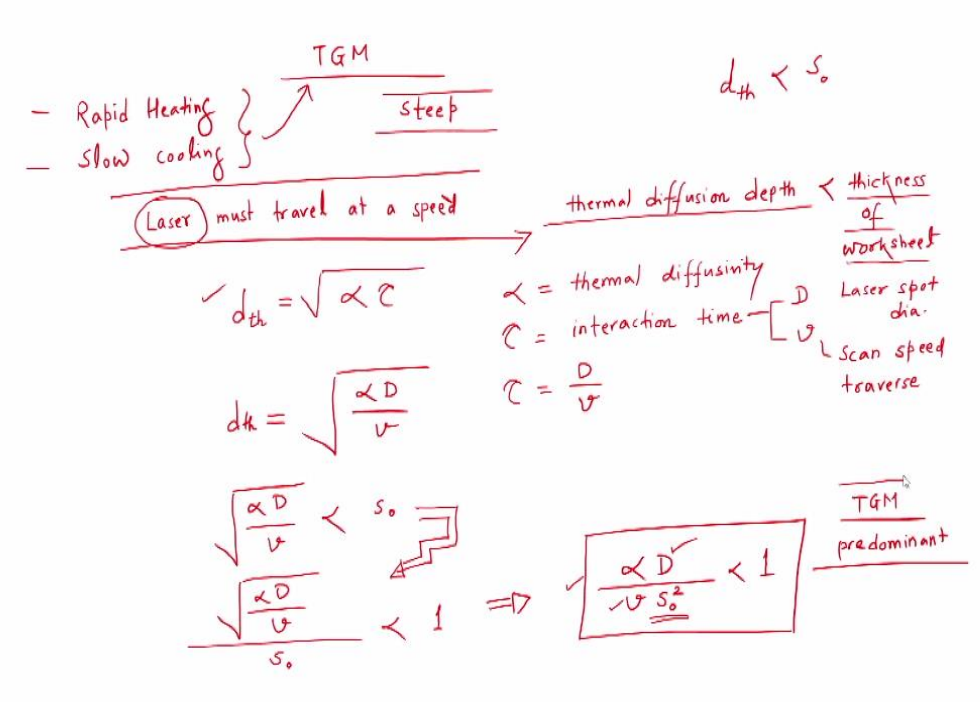

As we have seen that in TGM that is temperature gradient mechanism we are rapidly heating the work part. There is a rapid heating and we are cooling it, but the cooling has to be slow cooling and the ultimate aim is to generate the steep temperature gradient. Steepness is very important here. So, steep temperature gradient. To get this situation the laser must travel at a speed which will generate thermal diffusion depth less than the thickness of the work sheet.

To have TGM, the proper TGM with significant steep gradient we have to travel the laser in such a way that the thermal diffusion depth should be less than the thickness of the work sheet. Let us consider the thermal diffusion depth by using a letter d subscript th. This d_{th} should be less than the workpiece thickness. It has been noticed this d_{th} that is thermal diffusion depth is approximately equal to root alpha (α) into tau (τ).

Here alpha (α) is thermal diffusivity and tau (τ) is the interaction time - the laser material interaction time and this laser material interaction time is dependent upon two factors: first one is the diameter of laser beam and the second one is the speed. This is laser spot diameter and the scan speed. In some cases it is called as traverse speed as well. I can write tau (τ) = D upon ϑ.

Let us rewrite the correlation d_{th} is equal to root alpha (α) into D divided by (ϑ) and as we have seen that our condition is that d_{th} has to be less than the S_0, that is the thickness of the work sheet. Here I can write root alpha (α) D divided by ϑ should be less than S_o. I can rewrite this equation in this format root alpha (α) D divided by (ϑ) divided by S_o that is the thickness of the sheet less $(<)$ than 1. These can further be rewritten in this way alpha (α) D divided by (ϑ) into S_o^2 should be less than $(<)$ 1 always.

When the thermal diffusivity, the diameter of the laser spot, traverse speed and thickness, when the values of the parameters in this correlation are generating this quotient or ratio less than 1, then we are saying that TGM is getting predominant. To have a successful TGM we should have this correlation get satisfied. You can choose the process parameters by varying the D and the scan speed. The S_o that is the thickness would be constant which is not in our control and the material property is also not in our control, that is the thermal diffusivity. We can modulate, we can fine tune the diameter of the laser spot at the work part and the scan speed. By meticulously choosing the D and ϑ, we can easily find out or we can easily get the TGM for our application.

Now as I previous mentioned by using numerical analysis tools as well we can predict, we can compute the stresses and strains which are generated during the operation.

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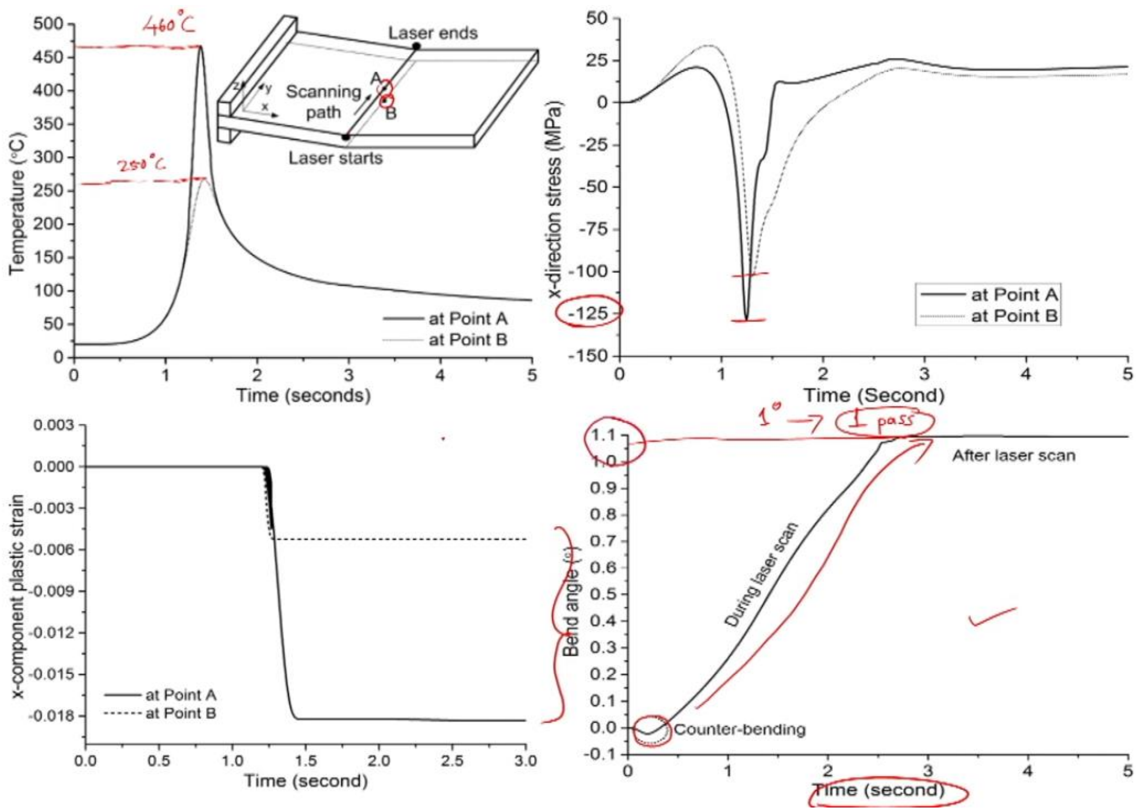

Such graphs are there on your screen. The first graph here is the temperature versus time graph. The time of application of laser during the laser bending operation. Here you can see the same schematic that we have seen about the definition of laser scan. We are having a work part the laser is starting from this point and it is ending at this point. The top point or the point on the top surface is designated as point A and the point at the bottom surface is point B.

Let us find out what is the temperature is getting generated during the laser application. You can notice that during the laser operation the temperature generated at the sheet is around 460 degree Celsius more than 450 degree Celsius and at the bottom surface it is little more than 250 degree Celsius. There is significant difference between the temperature at top surface and temperature at the bottom surface which is leading to the generation of thermal stresses.

Let us look at the stresses which are getting generated during the application. You can notice the point A and point B at both the places we are getting the compressive stresses generation. The compressive are getting generated at both point A and point B. Due to this compressive stresses we are getting the compressive strain, compressive plastic strain and there is a significant difference between the plastic strain at top surface and plastic strain at bottom surface. At the top surface, there is more amount of plastic strain is noticed, is about 0.018 and at point B is less, and due to these difference between plastic strains at top surface and bottom surface we are getting the bend angle.

If you look at these particular diagram here which is plotted against the time for the bend angle, we have noticed a counter bending, counter bending means it is away from the laser beam and that is for very short duration, it is just due to the expansion of the fibers on the top surface. When we apply the laser beam energy there is expansion of top fibers and due to that there is a counter bending which is occurring, but due to the compressive forces which are applied by surrounding cooler medium there is bending which will occur towards the laser beam. And this is the increase in the bend angle that you can notice and it goes up to around one degree of bend angle for one pass.

For macro level processing, this one degree bend angle may not be that significant, but when we talk about MEMS systems - micro electromechanical systems where we need to get the micro angles, micro precision angles say about 1 degree or 1.5 degrees, there we can apply the laser bending operation. Here we can have a very small bend angle of about 1 degree by application of controlled laser heating during laser bending operation.

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Well, with this I would like to summarize the today's class. In today's class, we have seen what is the meaning of material forming, what are the various types of forces or stresses are used in the material forming, compressive forces, tensile forces, combination forces and what are the limitations of mechanical based material forming. After that how the lasers are helping us to resolve some of the issues or some of the limitations of the mechanical based material forming particularly in precision material forming.

Then we have seen in detail the TGM that is temperature gradient mechanism. In TGM, we have seen the detail procedure of getting the temperatures, stresses and plastic strain and the effect of these plastic strains to get the required bend angle. Even we have seen the correlation of material properties, laser spot diameter and the scan speed to get the dominance of TGM during the laser bending operation.

With this, I stop here. Thank you for watching this lecture. Good bye.