Laser Based Manufacturing

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Module No # 05
Lecture No # 25
Laser-Assisted Material Forming

Hello everyone I welcome you all to the last week of NPTEL MOOC course on laser-based manufacturing. This is week 8 that is the last week in previous weeks we have studied the fundamentals of lasers and their applications in a variety of manufacturing processes such as material removal, joining, additive manufacturing and forming. Moreover we have also seen the application of lasers in manufacturing automation.

, in this week we will be studying some advancement in the application of lasers in manufacturing processes. Let us start the lecture 1 of week 8. As I mentioned this week is dealing with the advancements in laser-based manufacturing and in the first lecture of this week we will be studying how lasers can be utilized to improve or to enhance the productivity of material forming.

In one of the previous weeks we have studied the laser-based material forming but there were certain limitations of applying the lasers to get the productive material forming. Now here we will be studying how exactly lasers can be used; to enhance the productivity of material forming.

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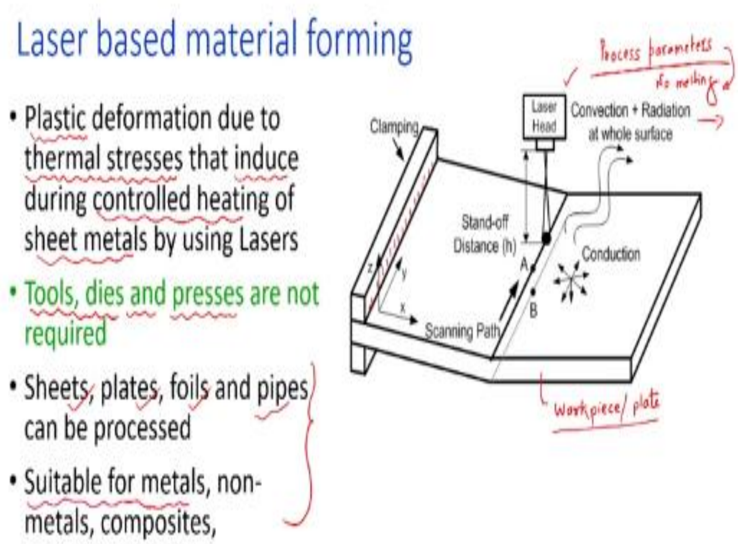

Let us begin the lecture. We have seen in one of the previous classes of this course laser material forming or laser-based material forming. And in that lecture we have seen how the lasers can be used as a non-contact type of manufacturing process so contactless or without tool how can we deform the materials. If you recollect that arrangement we had taken 1 plate or the work piece.

This is the work piece or a plate which was clamped at one location this is the end which was clamped and then we irradiated the work piece by using a laser. Here the process parameters were chosen in such a way that there should not be any melting. So, preferably no melting should be there but in certain cases the melting will occur. The process parameters are applied in such a way that no melting will be there and then there was a deformation of the work piece towards the laser head.

And this deformation was the plastic deformation and it was attributed to the generation of thermal stresses that were induced during controlled heating of the sheet metal. We had seen various mechanisms of that the temperature gradient mechanism, upsetting mechanism and the buckling mechanism. We also seen the advantages of this process that there is no need of any tools, dies and that saved a lot of time the product lead time was very less.

This process was found to be useful for sheets, plate's, foils, even pipes to be processed and the laser based bending process was useful for metals non-metals and for the composites as well.

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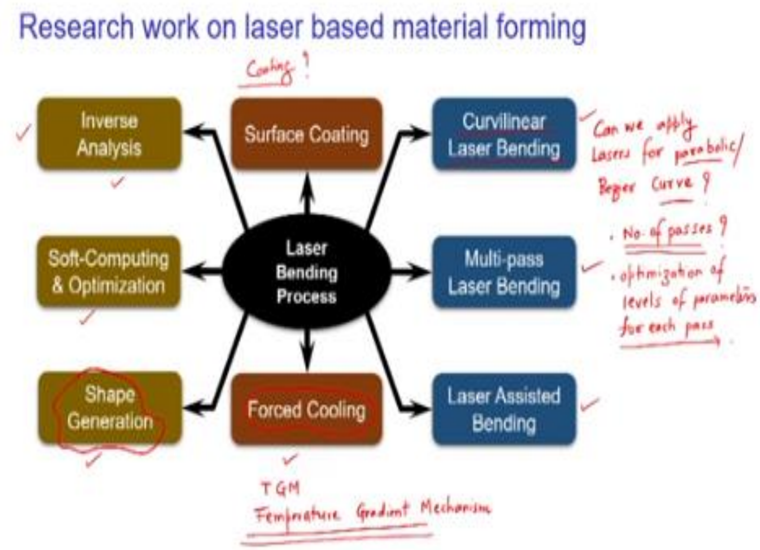

Well when we look into the literature which is available on the research which is going on in the laser-based farming. See this laser-based forming can be classified or can be divided into a number of groups. And these groups are there in front of you. Here the research on laser-based bending or laser-based forming can be divided into curvilinear laser bending, multi-pass laser bending, laser assisted bending than application of forced cooling generation of complex shapes, application of soft computing techniques for optimization of the process, and use of inverse analysis.

Further some research was also noted on use of some coatings which were to be applied on the work surface to improve its productivity. Let us see what is the meaning of curvilinear laser bending. in our previous slide we have seen that the laser was applied in a linear fashion in a linear way. What happens when we apply the laser in a curvilinear fashion? It may be a parabolic shape or it may be any free curve or any plane curve or it may be a space curve.

When we apply the laser in this curvilinear fashion what would be the deformation and can we use this deformation for our purpose. This is the one primary area of research that can we apply lasers for parabolic irradiations? Or we can use Bezier curves any curve which may be a plane curve or space curve what would be the deformation when we apply parabolic or the Bezier curve?

Here when we apply the curve in a linear fashion we have seen that there is non-uniform bend angle was produced along the line of heating. We have seen that at the end or at the end of the pass the bend angle was low while the bend angle was more at the middle of the pass at the middle of the scan line. That non-uniformity can be reduced by using some non-linear type of laser bending.

This is one good area of working and lots of people are working to see what would be the effect of curvilinear laser bending. Moreover the curvilinear laser bending can also be used to deform the metal sheets for 3d shape generations. Then the next area people tried like multi-pass, here multi-pass means number of passes to be find out the optical number of passes so how many numbers of passes are required to get a melt free or the deformation without melting and it should be the maximum.

For this purpose we have to optimize the number of passes. Not only optimization of number of passes we can even optimize the process parameters for each pass. optimizations of levels of parameters for each pass. This is one another area where people are working then the coating we have seen that the laser bending or laser forming is not suitable for reflective surfaces. Suppose we are using aluminum which surface is very clean and most of the energy is getting reflected there is very less absorptivity or in certain cases there may not be any absorptivity of laser beam.

Can some coatings be applied to improve the absorptivity so what would be the coatings and what should be their thickness so this is another area where we can work effect of surface coatings in the improvement of laser forming process. Then the next area is forced cooling. we have seen that TGM that is a temperature gradient mechanism. In temperature gradient mechanism, it is very essential to achieve the temperature gradient the effective temperature gradient or significant temperature gradient.

How to achieve this? So here the effective temperature gradient can be achieved by cooling the bottom surface. When we are applying the laser on the top surface if the material is conductive we may not get the significant temperature gradient across the thickness. In that case can we apply some cooling mechanism at bottom of the sheet it may be the forced convection by using air or by using any fluid say water or we can even use some sort of solid material such as ice or even people can try to apply the nitrogen as well.

Can we apply a cooling at the bottom to get the significant temperature gradient? And how to; develop the experimental setups? How to come up with the viable setup for the industrial production? All these are the research questions where one can pitch in and can solve the problems. Then shape generation in our previous class we have seen that the simple TGM or we have seen a very simple example of linear heating consider we want to manufacture a very complex shape a saddle shape and what would be the irradiation patterns?

What could be the optimal parameters for generation of 3d complex shapes? This is another area. Then optimization so optimization of laser process because the laser-based manufacturing is very expensive its efficiency is less. We have to pump a lot of energy to get the required laser beam at the workplace at the application. Therefore, it is very essential for us to apply the optimal levels of process parameters. here not only the hard-computing processes the soft computing processes also helping us to solve the optimization problem.

Such as genetic algorithm or the simulated annealing type of optimization methods. Then inverse analysis we have seen in our experimental study of the laser based forming that can we correlate the laser based bend angle which is generated with the process parameters. Consider problem in which we want to achieve a specific bend angle of 15 degrees. , can there be a system which will derive or which will suggest the optimal level of process parameters in the inverse way?

Or the laser based bending has many unknown parameters that are absorptivity during the process of application the material properties or the surface properties are getting changed and the absorptivity values are also getting changed. What could be the effect or what could be the effect of bend angle or what could be the relation of the bend angle with the absorptivity? Because the entire success or the success of laser forming is dependent upon; the surface property that is absorptivity.

During numerical analysis as well the surface absorptivity or the laser beam absorptivity is a crucial parameter. So, can we have some sort of mechanism which will predict the absorptivity during the process of the study itself and that can be applied for the computation of bend angle in an inverse way? Is it possible to have such mechanism that would be a very good tool for the process engineers the process planners or the process simulators?

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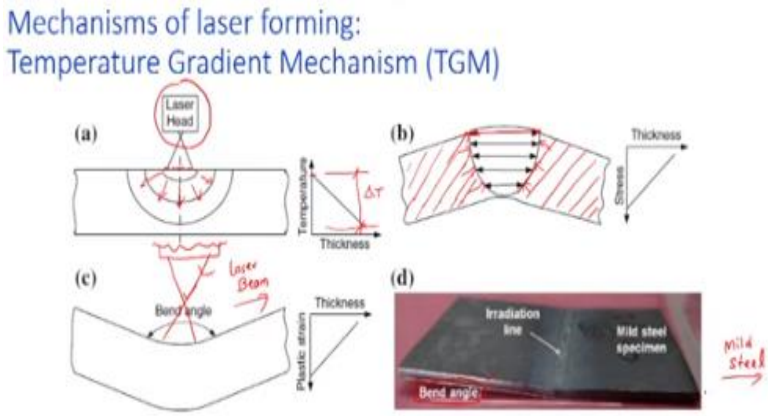

Process steps of temperature gradient mechanism (process condition for figure (**d**): laser power = 400 W, scanning speed = 400 mm/min, beam diameter = 6.77 mm and total number of laser beam irradiations = 3). **a** Temperature distribution due to laser irradiation. **b** Thermal expansion and stress distribution due to laser heating. **c** Final bending towards laser source and plastic strain distribution. **d** Laser bent mild steel specimen with TGM

Now let us quickly revise the TGM that we have seen. So, in TGM we have seen that a laser we are applying on the surface and when we apply the laser there is conduction of heat in the surface due to laser material interaction at the surface. So, there is a heat generation and that heat is getting dissipated it is getting conducted inside the work material so naturally the temperature at the top surface is high and as we move along the thickness direction it is getting reduced.

This gradient has to be significant this difference has to be significant to achieve the deformation. Now what is happening when there is an enhancement in temperature at the top fibers. This top fiber are trying to expand. However, the surrounding material this is the surrounding material which is at normal temperature at ambient temperature and that is going to restrict the expansion of top fibers. And due to this restriction they are applying the compressive stresses on the top fibers.

Now this expansion is occurring when there is application of laser beam as the laser beam is pass over the material then the surrounding cooler medium which has generated the compressive stresses. That stresses will overcome the expansion of the fibers and there we will get the bend angle towards the laser beam. , this is the bend angle that we got towards the laser beam here was the laser beam and we got the bend angle towards the laser beam.

In our previous lecture we have seen some experimental setup as well to get the bend angle for the mild steel specimen this is the mild steel specimen which was used to carry out certain preliminary studies.

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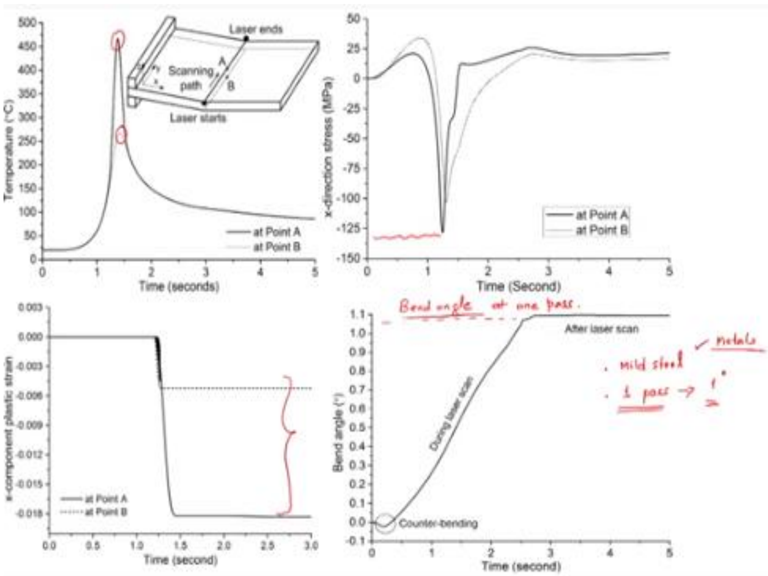

We have also studied the temperature which is generated at the top surface and at the bottom surface. Due to this difference in temperature at top and bottom surfaces there is a generation of compressive stresses compressive strain and that strain is leading to the bend angle. This is the bend angle that we got at the end of 1 pass. Well it is quite known that now laser can used for deformation of mild steel which is a ductile material and commonly used material.

And second point is that in 1 pass the bend angle was about 1 degree fine. metals can easily be deformed and a one degree per pass is normal we can achieve the bend angle. Fine, now the question is that can we apply lasers for difficult to deform materials or difficult to form materials. One such material is magnesium alloy or magnesium material which is widely used in aerospace applications which is widely used in the automotive applications as well.

Can we apply the laser to such material which is very difficult to deform by using mechanical bending? So, in this way let us see whether it is possible to use the lasers for such application.

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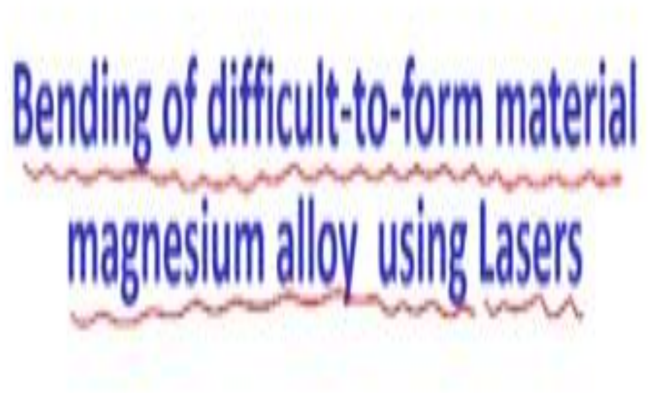

This is the topic of the lecture that is the bending of difficult to form material that is magnesium using lasers.

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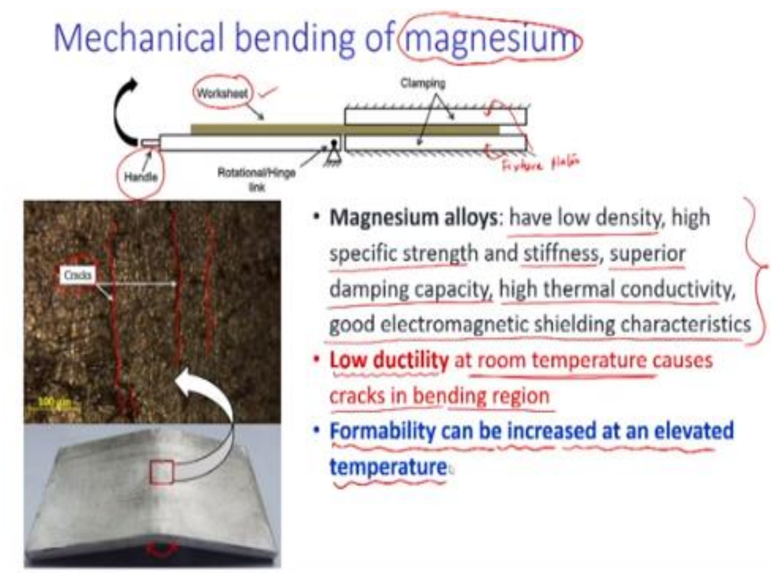

Let us see the magnesium material. Magnesium is having a low density It is having very high specific strength and stiffness. It is also having superior damping capacity. It is also having high thermal conductivity good electromagnetic shielding characteristics. All these are the positive characteristics or positive points or advantages of the magnesium alloys and that is why the magnesium alloys are widely used in aerospace applications.

However the magnesium alloys are having low ductility at room temperature. And therefore there is a formation of cracks during normal bending operation that has been observed with variety of literature that when we try to deform the magnesium at room temperature there will be cracks during the deformation process. To verify this fact, it was tried to deform the magnesium sheet by mechanical bending.

That experimental setup is in front of you we got a sheet here this is the worksheet and the worksheet is clamped. , these are the fixture plates and now by using a handle and plate arrangement we will try to deform these magnesium worksheets let us see what happens. , when we deform this worksheet to get certain plastic deformation there is a formation of cracks on this surface here you can see we could successfully deform this worksheet here.

However, on the rear surface of that bend we got lot of cracks these are the cracks which were occurred at the rear surface. And such cracked material or such correct work piece or products are very dangerous we cannot accept that particular product for the intended purpose. Now the question comes how to tackle this problem? It has been noticed that the formability of magnesium can be increased at an elevated temperature.

If we increase the temperature of magnesium we can easily deform the magnesium material at elevated temperature. To verify this or to study the feasibility of applying lasers for magnesium deformation the experiments were carried out.

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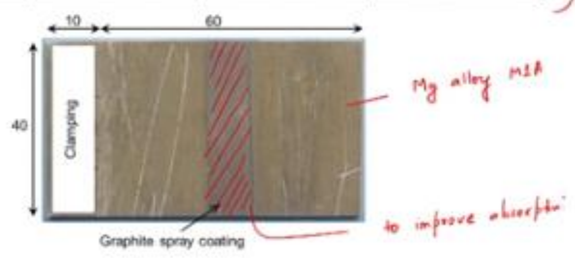
Experimental Study of Laser Bending of Mg Alloys

Material: Mg alloy M1A sheet of 1.9 mm thickness: Mg 98.07% and Mn 1.93%

Level of process parameters

S. No.	Laser Power, *P* (W)	Scan Speed, *V* (mm/min)	Stand-off Distance (mm)	Beam Diameter, *D* (mm)
1.	300	1000	20	3.87
2.	400	2000	30	5.81
3.	500	3000	40	7.74



Specimen details

Here you can see these are the results of laser bending of magnesium alloys. We have taken a magnesium alloy M1A. The sheet thickness was about 1.9 mm and the composition of that alloy was magnesium 98.07 percentages and manganese of 1.93 percentages. The initial investigations were carried out by varying 4 parameters that is laser power, scan speed, standoff distance, and beam diameter.

, these levels are there in front of you. The laser power was varied from 300 to 500, speed was varied from 1000 to 3000 mm per minute, standoff distance was 20, 30, and 40 and the beam diameter was 3.87, 5.81, and 7.74. Here you can see this is the magnesium alloy sheet and a coating were applied on its surface this is the graphite coating to improve the absorptivity.

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Fine, now the experimental setup was developed on a CO_2 laser machine and that CO_2 laser machine is there in front of you. it is 2.5-kilowatt CO_2 laser machine with the CO_2 gas that is the lasing medium, nitrogen gas, and helium gas.

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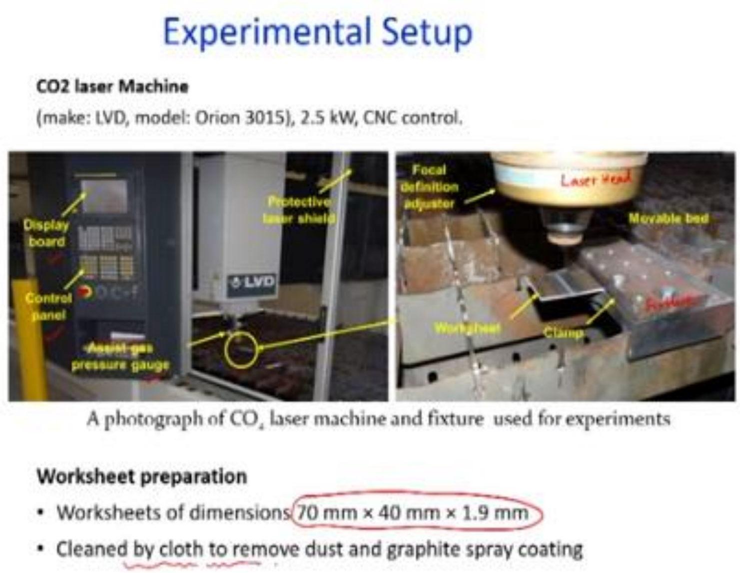

Well the experimental setup is there in front of you. here you can see the worksheet which is clamped in a fixture. And this is the laser head through which we are applying the laser beam. The other parts of the machines are there such as the display board, control panel, and the pressure gauge to control the assist gas. the worksheet was about a dimension of 70 mm in length, 40 mm in width, and the thickness was around 1.9 mm. And as I mentioned the worksheet was cleaned by cloth the dust was removed and then the graphite was applied to improve the absorptivity.

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Fine! this is the graphite spray coated specimen before the application of laser. And after the application of laser this photograph is shown over here. here you can see there was certain melting at the scan line. When we apply the laser, some melting was noted and there is a damage of coating along the scan line which is very natural when we apply the intense laser heating the coating was damaged and some melting was noted.

Now it is interesting to note a bend angle a deformation here you can notice the material was successfully deformed for a laser power of 500 watts, scanning velocity of 3000 mm per minute, and a beam diameter of 3.87 mm. thus the difficult to deform material was also deformed by using laser.

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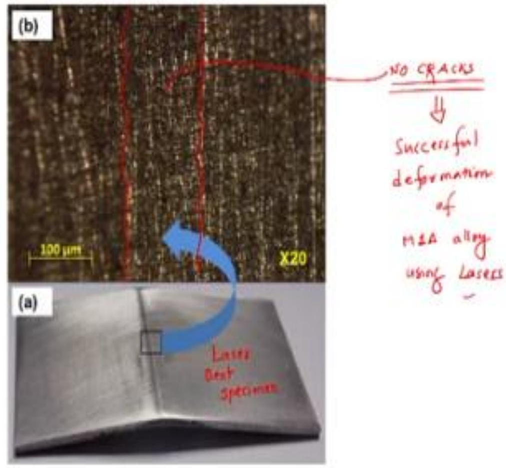
Microscopic examination of laser bent metal sheet



Now let us see the rear surface of that laser bent specimen. We have seen that during mechanical bending, at the rear surface there were some cracks which may get propagated and there is a chance of the breakage of the material. Here we observed in the optical microscope the rear surface of laser bend specimen. this is the laser bent specimen. And at the rear surface here you can notice that there is no crack produced. Certainly, there were no cracks on the rear surface and that led to the successful deformation of M1A alloy using lasers.

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Bend angle obtained in single scan and multi-scan laser bending of Mg alloy sheets

S. No.	P (W)	V (mm/min)	D (mm)	Single scan Average bend angle	Single scan CV (%)	Multi-scan (10 scans) Average bend angle	Multi-scan (10 scans) CV (%)
1	300	1000	3.87	1.069	4.11	13.58	7.01
2	300	1000	5.81	0.731	3.14	11.49	4.22
3	300	1000	7.74	0.49	4.6	9.07	0.81
4	300	2000	3.87	0.836	3.96	10.89	1.94
5	300	2000	5.81	0.312	3.77	7.06	11.28
6	300	2000	7.74	0.119	18.09	3.54	9.69
7	300	3000	3.87	0.604	19.31	7.73	7.47
8	300	3000	5.81	0.139	18.62	3.01	3.19
9	300	3000	7.74	-	-	0.86	6.56
10	400	1000	3.87	1.281	6.37	11.9	2.37
11	400	1000	5.81	0.836	13.4	10.49	1.99
12	400	1000	7.74	0.771	7.1	9.33	0.99
13	400	2000	3.87	1.305	9.69	14.49	0.37
14	400	2000	5.81	0.766	3.91	11.96	3.22
15	400	2000	7.74	0.437	22.17	8.33	13.33
16	400	3000	3.87	1.113	10.99	12.81	4.44
17	400	3000	5.81	0.418	11.78	7.69	15.17
18	400	3000	7.74	0.107	28.65	3.5	17.28
19	500	1000	3.87	0.993	7.31	7.79	2.49
20	500	1000	5.81	0.94	1.44	8.86	0.65
21	500	1000	7.74	0.753	18.69	8.83	3.38
22	500	2000	3.87	1.425	15.45	15.39	1.11
23	500	2000	5.81	1.003	7.58	13.42	0.47
24	500	2000	7.74	0.721	13.98	11.45	4.66
25	500	3000	3.87	1.268	6.63	15.25	1.53
26	500	3000	5.81	0.838	15.93	12.2	7.12
27	500	3000	7.74	0.345	12.29	8.3	13.53

P=Laser power, V=Scan speed, D=Beam diameter, CV=Coefficient of variation

1.425 → 15.39
12 - 13 times

With this successful deformation then the experimental study was carried out in full-fledged manner. Here you notice the experimental matrix and corresponding results: power, velocity, diameter, and if you just look at the bend angle variations. You can just notice that the maximum bend angle achieved was about 1.425 degrees and the minimum it was around 0.107 degrees at certain process parameters there was no bend angle noticed.

There was insignificant bend angle. It is due to very low power that is applied. Now, instead of applying a single scan we applied multiple numbers of scans. after 10 numbers of scans it was noticed that a maximum bend angle achieved was around 15.39 degrees and the minimum bend angle was around 0.86 degrees. in this case for a single bend angle there was no bending no deformation. when we apply multiple number of times the same process parameters then there was very minor change in the deformation was noticed.

However, it is very interesting and encouraging to note that there is a multi-fold enhancement in the bend angle for the process parameters 500 watt of power, 2000 mm per minute of the velocity, and 3.87 mm of the laser beam diameter. You just notice that there is enhancement of the bend angle from 1.425 degrees to 15.39 degrees. It is around 12 to 13 times the bend angle is improved.

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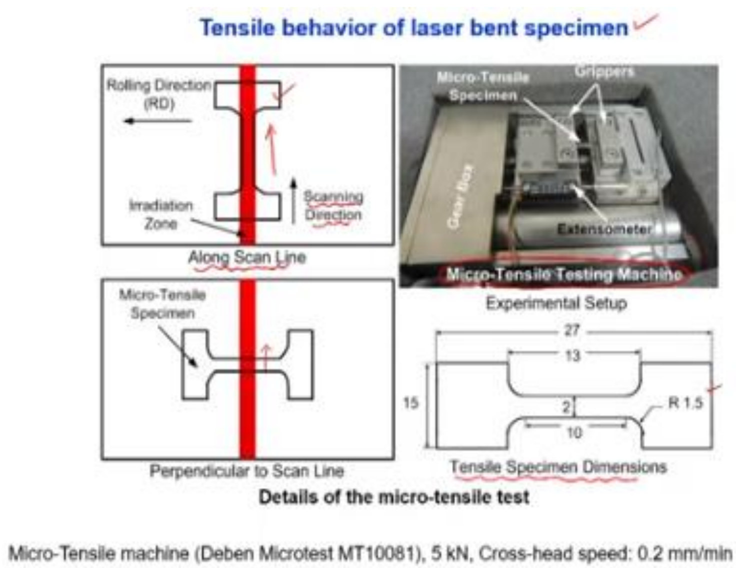

We have seen that the lasers can be applied to deform the work material now it is also important to study what is the effect of the application of laser on the mechanical properties of the specimen. , to analyze this or to study this, the tensile behavior of laser bend specimen was studied. , that is arrangement is there in front of you. , here we have taken the specimen and we irradiated the specimen along its length.

Here you can see the scanning direction is along the length of the specimen. And we have taken another specimen and we irradiated that specimen along the transverse direction, not along the longitudinal direction. Here you notice that in transfer direction the laser is applied with respect to the specimen length. This is the tensile specimen dimensions which are there in front of you and we have carried out micro tensile testing to find out the effect of laser beam energy on the mechanical properties.

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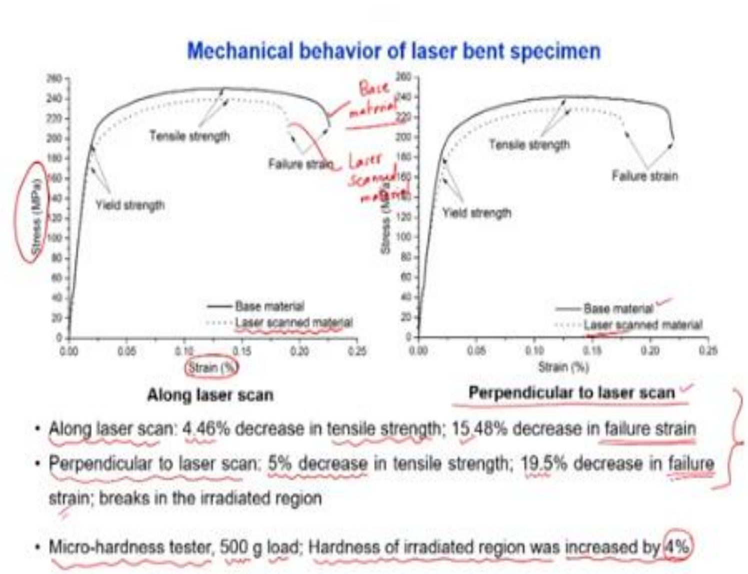

When we plotted the stress with respect to the strain we notice that there is little deterioration in the stress or the strength of the material when we apply the laser for processing. This is the base material and this is the laser scan material. On x-axis we have got the strain and on y axis we got the stress. Similarly, when we use a specimen where the laser scanning was perpendicular in that case as well we notice that there is a deterioration in the strength of the material when the laser was applied with respect to the material which was normal the base material.

In case of the tensile behavior along the laser scan it was noticed that there is 4.46 percentage decrease in the tensile strength and when we studied the tensile properties perpendicular to the laser scan. , in that case decrease is about 5 percentage in the tensile strength. Regarding the failure strain along the laser scan case it was around 15.48 percentage reduction. And in case of perpendicular to laser scan there is a reduction of about 19.5 for the failure strength.

These reductions is attributed to the thermal degradation of the material. Moreover the hardness was also tested by using 500 gram load and it was noticed that the hardness of irradiated region was increased by 4 percentage. It is very interesting to note here that the strength of the material got reduced however the hardness was improved by 4 percentage. Here we can notice or here we can conclude that of course there is a degradation of material properties, but it is marginal. It is not that significant by 4 to 5% the mechanical property or the strength is getting reduced. However, there is enhancement in the hardness that is the advantage of laser-based processing of the difficult to form materials. The mechanical processing of the difficult to form material was producing cracks but with lasers we got the crackles deformation with little reduction in the strength and improvement in the hardness.

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However during this processing it was noticed that there is a severe surface melting. Here you can notice that there is a severe surface melting and that is affecting the formation of bend angle. When we are expecting the bend angle should be 15 degrees or 20 degrees we could achieve around 8 degrees of bend angle with severe surface melting. Now what could be the solutions to this? here there could be 3 solutions:

First is we can use lasers and then we apply the mechanical power. We can take the assistance of laser to improve the formability to preheat the material and then we apply the mechanical power. Then the next is improvement in surface absorptivity and working at low power. You improve the surface absorptivity by certain coatings and you apply the low power. by applying the low power the chances of surface melting would be reduced. And you can get the efficient bending done.

But in this case to get the higher bend angles we have to apply the low power laser for multiple numbers of times. And when we apply the laser for multiple numbers of times there is a damage of the coating. we have to apply the coating number of times that may hinder the operation that may obstruct the laser beam operation. The second solution have certain limitation is that application of frequent coating on the surface will intervene or interrupt the laser-based bending operation.

Then the next solution is forced cooling. Can we enhance the temperature gradient by applying some sort of force cooling say nitrogen as I mentioned previously or by using ice or by using some cold gases at the rear surface? But making such kind of arrangement and executing the experiments or making such kind of arrangement and applying it at the industrial level on the shop floor it is tedious it is a cumbersome.

The first solution could be a feasible solution let us try the laser assisted farming can we use lasers for preheating and then you apply the mechanical loading to get the required bending done.

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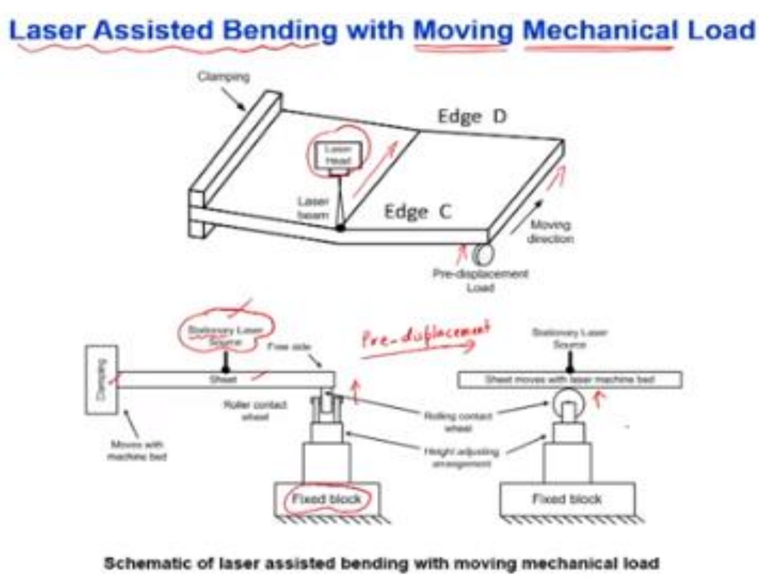

Schematic of laser assisted bending with moving mechanical load

Now how can we use laser to assist the bending operation that is a mechanical bending operation? Typical solution is there in front of you. This is laser assisted bending with moving mechanical load. laser is assisting here we have taken the laser for the preheating of the worksheet and simultaneously we are also applying the mechanical loading at the free end here we are applying the mechanical loading at the free end.

We are applying the mechanical loading in vertical direction at the free end and that load is getting applied along the free edge as the laser beam is moving. , here we should notice that the laser is moving and the mechanical loading is also applied in a synchronized way with the laser head. , you keep on applying the laser beam and there is a application of the moving load along this direction simultaneously with the laser beam energy.

This could be 1 solution and let us see how the solution is working. To implement this solution, we can have a fixed block to implement this solution we can have a clamping a sheet is clamped in the clamping arrangement there is a laser beam source. Here you notice that laser beam source is stationary. Because this is the usual arrangement in the commercial laser machines. The laser is stationary and we are moving the sheet. We are moving the sheet in x y direction by using the stage.

As the laser is stationary we have to use the mechanical loading in a fixed block only thing we have to increase the height of this roller which is getting touched at the free end by using some screw arrangement. , as we move the roller in vertical direction so that moment of the roller in vertical direction is applying the mechanical loading. , this is called as the pre-displacement we are applying the pre-displacement at the free end.

Fine!

This roller is having the line contact to minimize the friction. As we know that rolling friction is less than the sliding friction. That is why we are applying the mechanical loading in the form of rollers.

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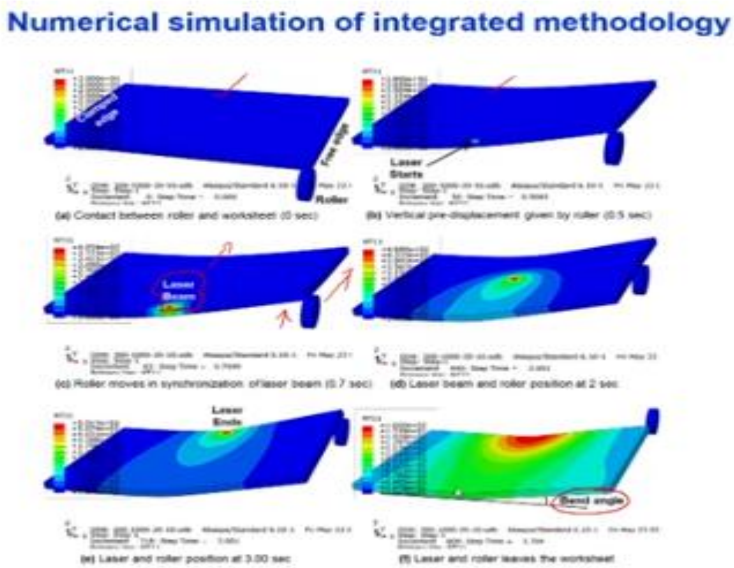

Now before development of the actual experimental setup let us have the numerical simulation of this integrated methodology. The numerical simulation was carried out and that screenshots are there in front of you. Here you can see that model is created this is the sheet and this is the free edge of the sheet and then we are applying the roller the laser beam is applied simultaneously.

We are applying the loading in a vertical direction and moment of roller along the free edge with respect to the laser beam as well. As the laser is moving the roller will also move and at the end we will try to see how much is the bend angle that we got. Is any deformation? after numerical simulation it was noticed that there is a significant bend angle was reduced?

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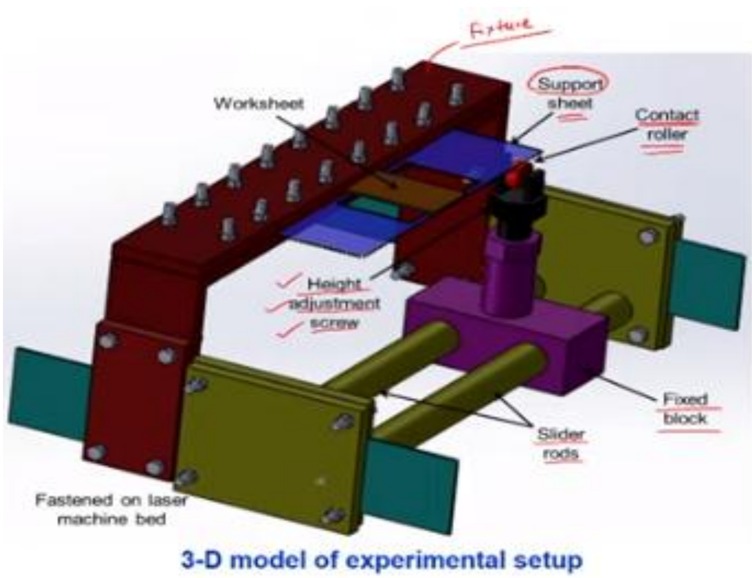

With this feasibility study then the experimental setup was developed this is the experimental setup in front of you. This is the worksheet and the fixture arrangement and we have also got a support sheet this is the support sheet and this is the contact roller. The worksheet is moving and the contact roller is fixed it is a in a fixed block and these are certain the machine arrangements which I have done to have the roller contact with the work part.

There is a height adjustment screw. by using this height adjustment screw we are deciding the pre-displacement. By what amount the roller has to move in a vertical direction with respect to the worksheet. It may be 5 mm or a 10 mm or 15 mm. After the development of the 3d model of the experimental setup, the actual experimental setup was fabricated.

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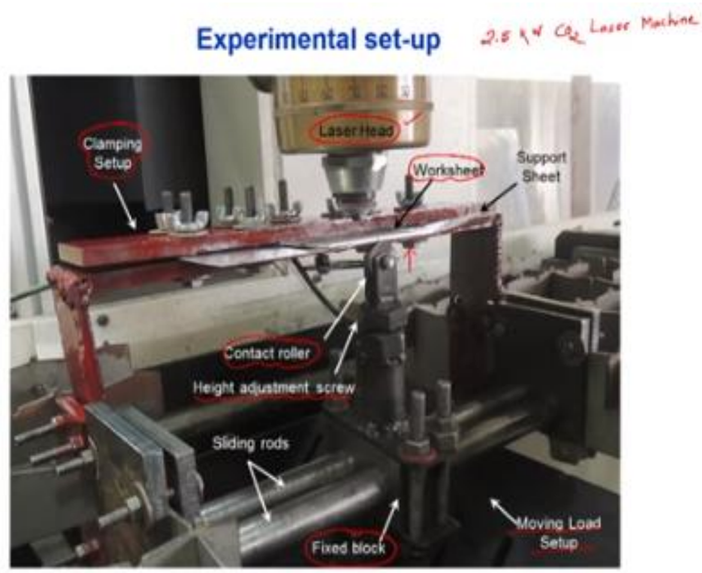

Here you can see this is the clamping setup which was developed this is the contact ruler this is the worksheet, this is the laser head and this entire setup was developed on 2.5-kilowatt CO_2 laser machine which we have seen earlier it is a 2.5-kilowatt laser machine. The laser head was fixed therefore the moving load was also fixed. The relative motion of the roller with respect to the work piece was carried out by moving the worksheet with respect to the laser heat and the fixed block.

This is the moving load setup this is the height adjustment screw. this is the height adjustment screw by using we can increase the distance that is a pre-displacement.

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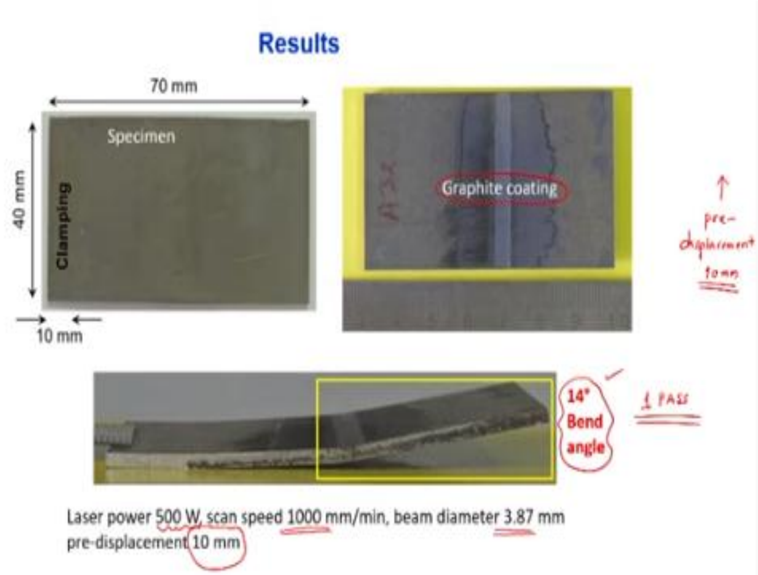

Now after development of the experimental setup the graphite coating was applied on the work part. And then we carried out the experiments and it was noticed that a very high bend angle was produced. We just noticed around 14 degree of bend angle for 1 pass. Within a pass a 14-degree bend angle was possible for a laser power of 500-watt, scan speed of 1000 mm per minute and beam diameter of 3.87 and the pre-displacement here you notice is 10 mm.

When we apply a 10 mm of pre-displacement a very significant bend angle was achieved which was earlier possible on with multiple number of passes say 10 or 15 number of passes. You imagine for many numbers of passes you have to input or you have to apply huge amount of electrical energy.

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Results

S. No.	P (W)	V (mm/min)	D (mm)	Bend angle (°) without pre-displacement load: Num	Exp	CV (%)	Abs. Error (%)	Bend angle (°) with 5 mm pre-displacement load: Num	Exp	CV (%)	Abs. Error (%)
1	300	1000	3.87	1.10	1.07	4.11	2.39	4.09	3.63	5.44	12.45
2	300	1000	5.81	0.72	0.73	3.14	1.77	3.40	3.31	5.83	2.78
3	300	1000	7.74	0.40	0.49	4.60	19.41	2.80	2.90	13.65	3.41
4	300	2000	3.87	0.93	0.84	3.96	10.72	2.75	2.39	9.36	14.99
5	300	2000	5.81	0.33	0.31	3.77	7.07	1.88	1.71	6.88	10.17
6	300	2000	7.74	0.08	0.12	18.09	30.44	1.24	0.99	3.99	25.36
7	300	3000	3.87	0.55	0.60	19.31	8.59	1.99	1.60	17.45	24.11
8	300	3000	5.81	0.11	0.14	18.62	25.26	1.20	1.20	9.60	0.05
9	300	3000	7.74	0.01	*	*	*	0.56	0.58	20.15	3.12
10	400	1000	3.87	1.25	1.23	6.54	1.67	5.69	4.78	5.08	19.14
11	400	1000	5.81	0.97	0.90	9.57	8.66	5.26	5.02	0.98	4.83
12	400	1000	7.74	0.74	0.76	3.87	3.17	4.79	4.56	6.55	5.01
13	400	2000	3.87	1.46	1.28	10.82	14.35	4.07	3.49	4.30	16.69
14	400	2000	5.81	0.86	0.79	12.84	9.42	3.18	2.82	12.26	12.62
15	400	2000	7.74	0.40	0.35	16.97	15.52	2.40	1.88	2.53	27.35
16	400	3000	3.87	1.16	1.26	5.38	7.91	2.97	2.38	2.29	24.77
17	400	3000	5.81	0.40	0.33	13.14	19.26	2.63	2.13	2.49	23.95
18	400	3000	7.74	0.10	0.09	25.15	11.47	1.20	1.04	4.48	15.79
19	500	1000	3.87	1.11	0.99	7.31	12.77	6.63	5.28	0.62	25.61
20	500	1000	5.81	1.05	0.94	1.44	12.67	6.58	5.55	2.64	18.46
21	500	1000	7.74	0.87	0.75	18.69	15.84	6.21	5.13	4.89	21.09
22	500	2000	3.87	1.59	1.42	15.45	12.28	4.96	4.18	1.91	18.76
23	500	2000	5.81	1.16	1.00	7.56	15.78	4.24	4.20	17.42	1.02
24	500	2000	7.74	0.71	0.72	13.98	0.85	3.45	2.81	4.07	23.00
25	500	3000	3.87	1.57	1.27	6.63	23.90	3.76	3.28	4.32	14.54
26	500	3000	5.81	0.77	0.84	15.93	7.81	3.92	2.96	0.93	32.86
27	500	3000	7.74	0.27	0.34	12.29	20.03	1.86	1.63	10.27	13.87
					Average error =		12.26	Average error =			15.40

CV=Coefficient of variation, Abs. Error=Absolute error, P=Laser power, V=Scan speed, D=Beam diameter, Num=Numerical bend angle, Exp=Experimental bend angle, *=insignificant bend angle in experiments

Here you notice a lot of experiments were carried out. Without pre-displacement this particular table will give you the idea how much is the improvement in the bend angle and the second section is the bend angle with 5 mm of pre-displacement and the bend angle without any pre-displacement that is a 0 mm of pre-displacement. , you just notice that 1.07 was improved to 3.63 in a similar way you just note here in all the process conditions there is improvement in the bend angle for multiple number of times.

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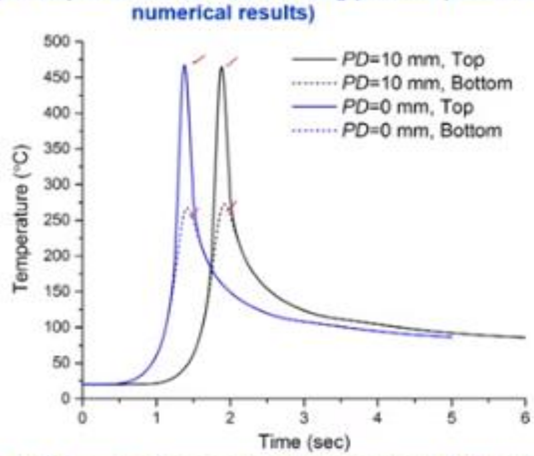
Effect of pre-displacement on laser bending process (based on numerical results)



Effect of pre-displacement on temperature distribution (Power 300 W, scan speed 1000 mm/min, beam diameter 3.87 mm)

Now let us see what is the temperature versus time history for the pre-displacement type of bending and without pre-displacement type of bending. Here you can see temperature wise, in both the cases is the same the top surface temperature was about 450 in both the cases and the bottom surface temperature was around little more than 250 degree Celsius in both the cases. Temperature wise there is no difference only there is an offset and this is offset due to the application of the mechanical loading.

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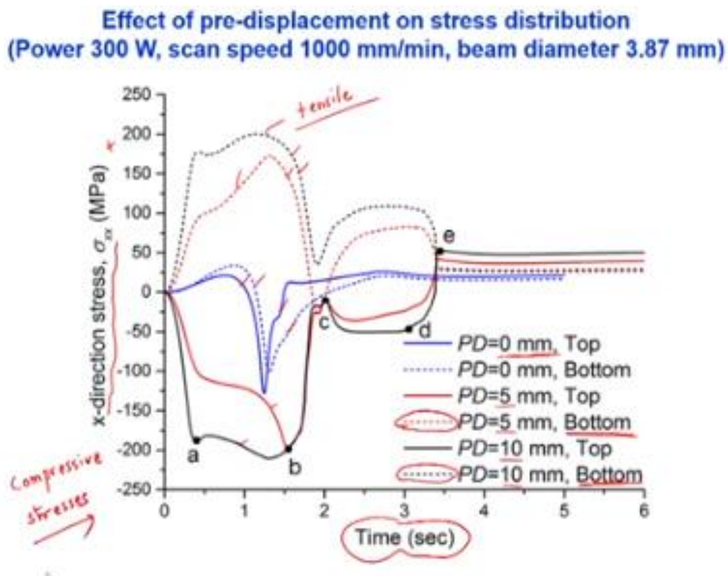

However when we look at the x direction stress during the laser beam based deformation with preloading of 5 mm and 10 mm and without preloading that is 0 mm fine. Here you notice that the blue color graphs are without preloading that we have already seen in our previous class but with preloading now you just imagine that on the top surface you know there is a compressive stress being applied.

All these solid lines are related to the compressive stresses at the top surface and these dotted lines are designating the tensile stresses and this tensile stresses are occurring at the bottom surface. , dotted lines are with respect to the bottom surface and these are the tensile stress positive and on the top surface there are compressive stresses.

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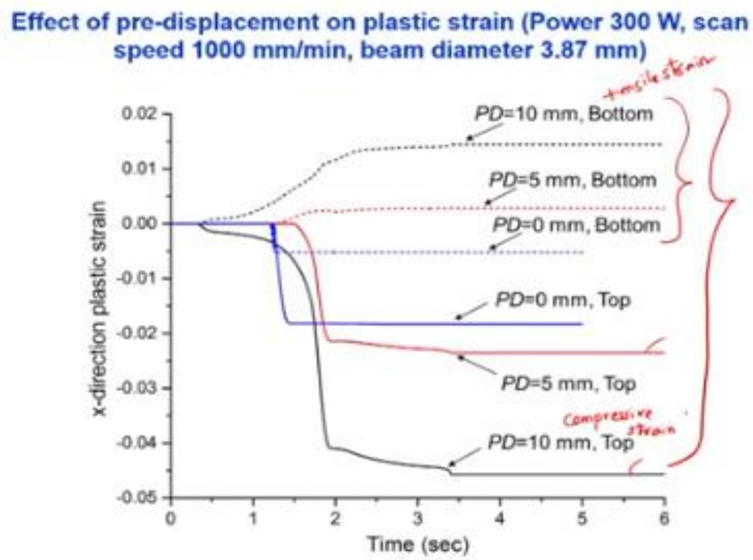

Similarly we can also notice that on the top surface there is a compressive strain and at the bottom surface we got the tensile strength. This is the tensile strain and this is the compressive strain.

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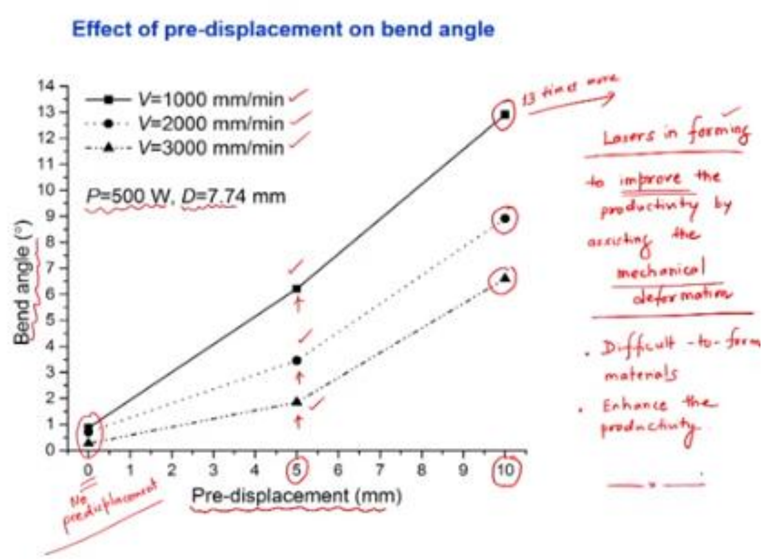

Now let us see how much is the increase in bend angle with pre-displacement. On your screen you can see a pre-displacement on x axis and the bend angle on the y axis. here we have plotted 3-line graphs. The one is for velocity of 1000 mm per minute, second is velocity of 2000 mm per minute, and third one is 3000 mm per minute. The power was constant of 500 watt and the diameter of the laser beam was 7.74 mm.

You can notice over here that the bend angle which is produced for pre-displacement of 0 mm that is no pre-displacement. , the bend angle was very marginal very low and as we enhanced or as we apply the pre-displacement of 5 mm, there is huge impact on the laser forming. , you just imagine the bend angle is improved about 5 times in this case 5 times in this case about 2 to 3 times and in this case about 2 times.

Further we increase the pre-displacement and then there is an again huge jump in the bend angle here you just notice that bend angle is around 13 times more. This signifies the application of lasers in forming to improve the productivity by assisting the mechanical deformation process. Lasers can be used in forming, not in a direct way. We can also use the lasers in indirect way as well. The primary deformation is a mechanical deformation only, but to improve the productivity we can preheat the material by using laser. And in this way, we can deal with difficult to form materials easily and we can enhance the productivity, both the things can be possible.

Thank you well with this I would like to stop for today's lecture. In this lecture we have seen how the lasers can be used to improve the mechanical forming we will continue our discussion on application of lasers for some other manufacturing operations as well. Till then goodbye, thank you.