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Alternative Method of Forming Hard To Form Metal by using LASER: A Review

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Abstract
This paper gives a review for a new technique to give shape to metal by laser source is presented. Typically metal forming by Laser is contactless method in which laser beam is used as energy source and by inducing temperature induced stress in material, we can form material in various shapes. The main benefit of laser forming lies in its capability to form low ductility metal and with high accuracy of forming which normally not possible in conventional forming process which uses mechanical tool and die. In this paper various experimental result and observation of laser forming technique is presented so that one can easily analyze the laser forming technique and its capability and limitations. The important parameters which affect process results are laser beam diameter, sheet thickness, laser input power, scan velocity and material properties. By suitably choosing above parameters two dimensional and three dimensional geometry had been formed from sheet metal.

Key words- **Laser forming, temperature induced stress, Scanning velocity.**

I. INTRODUCTION
Forming metal by Laser is novel technique for sheet metal part which has advantage of higher accuracies and no hard mechanical tool required. In typical laser bending of sheet metal, as shown in fig.1 workpiece is clamped and a beam of laser scanned along a predetermined path and because of that the surface temperature at that location increases very rapidly. This will result in steep temperature difference between the irradiated area and surrounding area that not directly heated. This uneven heating produce thermal stress within the workpiece. When this stresses become higher than the temperature dependent yield strength of the material, due to plastic deformation, metal sheet bend along the scanned laser beam path as shown in fig.1. Because of small laser spot diameter and laser energy input can be controlled accurately, this process gives higher accuracy. Also this process can be automated and controlled very easily. This process is very suitable for metals like titanium which has very low ductility at room temperature and normally difficult to form using conventional forming methods. In laser bending process there is no springback effect and process is gradual in nature so we can achieve very high positional accuracy.

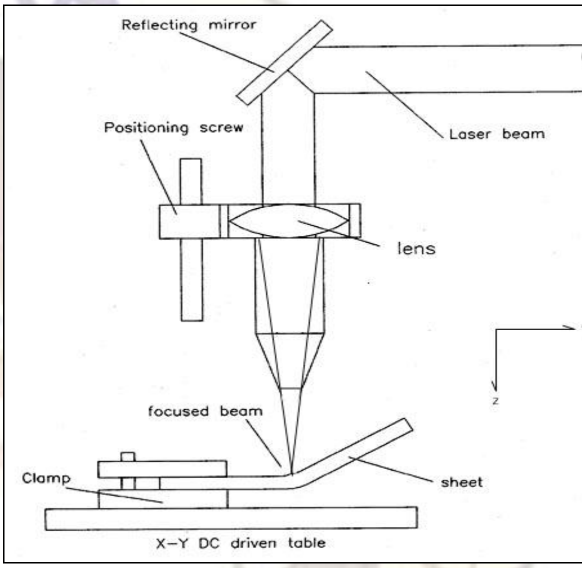


FIGURE 1: Simple Line diagram of Laser bending set up

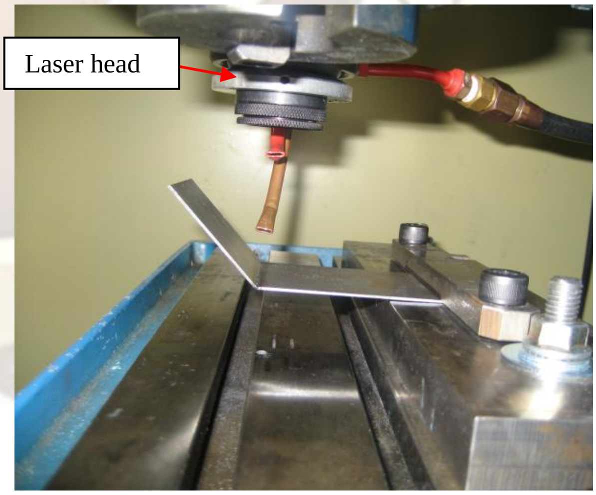


Fig. 2.Typical experimental setup of laser bending of metal sheet.[9]

Direction and amount of bending can be controlled by altering process parameters such as laser input power, scan speed, laser beam diameter and sheet thickness. These changes in process parameters can be grouped to define three important laser bending mechanisms that are discussed in detail in following sections.

Laser Bending Mechanisms

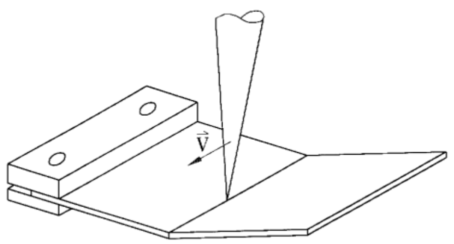
Laser bending can be classified by mechanisms used for achieving deformation. These mechanisms are differentiated from each other by parameters used; such as, Laser beam diameter, sheet thickness, laser input power and scan speed. These mechanisms are classified as,

A. Temperature Gradient Mechanism
B. Buckling Mechanism
C. Upsetting Mechanism

These mechanisms are discussed in detail in following sub-sections

A. Temperature Gradient Mechanism (TGM)

In Temperature Gradient Mechanism, laser and material parameters are chosen in such a manner that a steep temperature gradient can be formed across the thickness of the sheet material. Temperature Gradient Mechanism (TGM) dominates when the beam diameter is much smaller than the sheet thickness. The beam travels along a line often called as the bending line. As the beam is irradiated on the work piece surface, the surface temperature begins to rise at a very rapid rate. A sharp temperature gradient is established across the thickness that produces differential thermal expansion at the top surface and compressive stresses at the bottom surface. Expansion of the material at the top surface causes the sheet to bend away from the laser beam as seen from Figure 3.(a). After the laser scan is complete, temperature of the top surface begins to drop rapidly.The material expanded at the upper surface layer begins to contract and the plate starts bending towards the laser beam as shown in Figure 2.



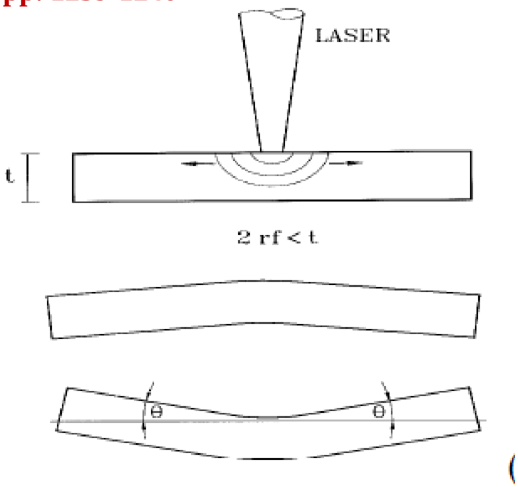


Fig. 3 Sequence of Temperature Gradient Mechanism[9]

This mechanism dominates under the conditions corresponding to a small (≤ 1) modified Fourier number which is expressed as,

$F = \lambda \cdot d / (h^2 \cdot u)$,where, λ is Thermal diffusivity (m2/sec), d is the laser beam diameter at the sheet surface (m), h is the sheet thickness (m) and u is scan velocity (m/sec).

Along with bending in *y*-axis direction, the material along the *x*-axis also produces thermal expansion during heating bending the workpiece in three dimensions.

B. Buckling Mechanism (BM)

Buckling Mechanism (BM) as bending/distortion that occurs in thin sheets or in a situation where ratio of thermal conductivity to sheet thickness is large [see Figure 1.4]. In buckling mechanism, the temperature gradient across the thickness is much smaller. This is usually achieved by reducing the scan velocity and the sheet thickness. A local elastic buckling and plastic deformation takes place when the speed of the laser scan is maintained low in order to provide more energy input. The beam diameter is also maintained much higher than the sheet thickness. The ratio of the diameter of the heated area to the sheet thickness is in the order of 10 in BM while for TGM it is in the order of unity. The use of large beam diameter results in larger heated area and the small thickness results in small temperature gradient. BM dominates for a large value of the Fourier number.

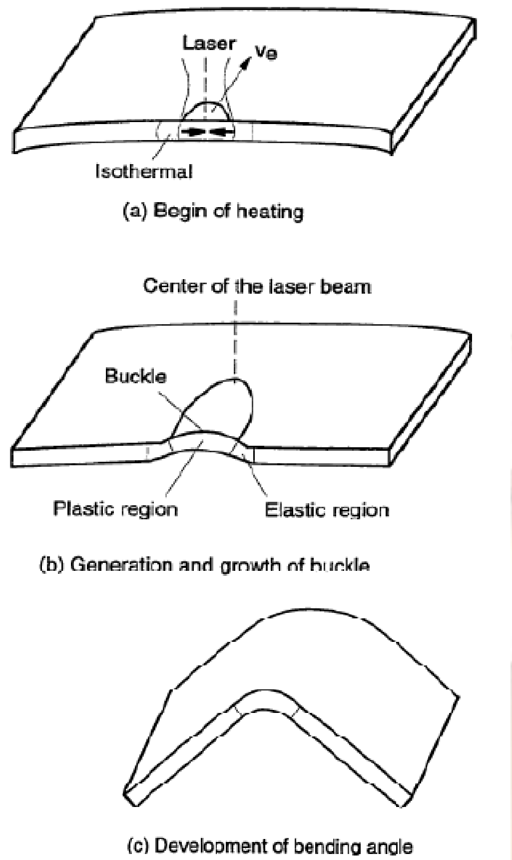


Fig 4. - The Buckling Mechanism[9]

The sheet may bend towards or away from the laser beam. direction of bending can be manipulated by following methods;

1. Elastic prebending by external forces
2. Plastic prebending
3. Relaxation of residual stresses
4. Counter bending due to temperature gradient

Bending can be achieved at a higher rate (10º / step) using buckling mechanism, as compared to TGM (1º- 5º / step).

C. Upsetting Mechanism (UM)

In this mechanism, parameters are chosen in such a way that the heat penetration is as homogenous as possible. The process parameters are similar to that of BM except the heat zone is much smaller. Due to nearly homogenous heating of the sheet and restrictions in thermal expansion from the surrounding material, the sheet is compressed with a nearly constant strain across the thickness. This leads to shortening of the material across its length and increase in the thickness if the material does not buckle. UM is more difficult to achieve as compared to TGM and BM. Fig. 5. shows the working principle of the UM.

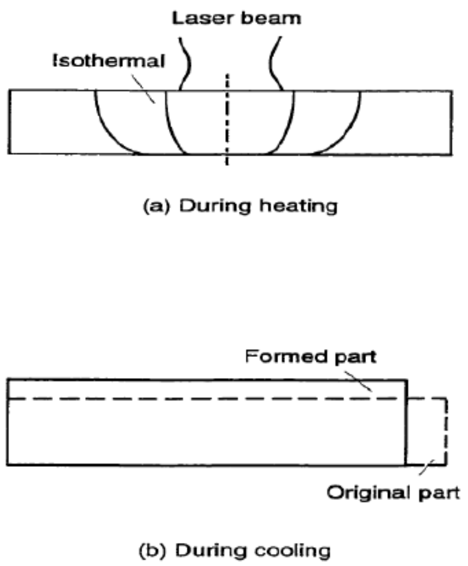


Fig.5 The upsetting mechanism[9]

Factors Affecting Laser Bending Process

In order to optimize the results of the laser forming process i.e. the bending angle, factors that affect its magnitude must be studied. A significant amount of research has been conducted on the factors that affect the bending angle and overall performance of the process . Following are the important process parameters and material properties that significantly affect the laser bending process.

A. Laser Power

As shown in Figure 1.6., bending angle increases with an increase in the laser input power as the energy density increases, while other parameters remain unchanged

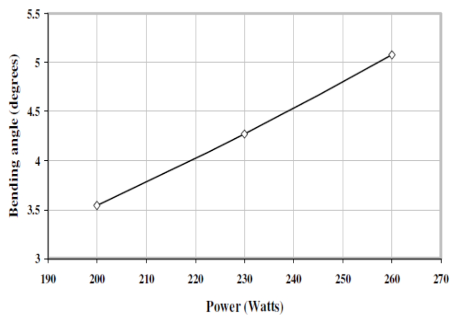


Fig.6. - Effect of laser power on the bending angle . Material: AISI1010, laser input power =200 – 260W, laser beam diameter = 2 – 3 mm,scan velocity = 2 – 4 mm/s, pulse duration = 7 – 11 ms [9]

B. Beam Diameter

Laser beam diameter or spot size is another parameter used to regulate the bending angle. As the laser beam diameter increases, energy density will decrease given that the laser input power and scan velocity are unchanged. Decrease in energy density will result in decreasing the bending angle. Figure .7 shows the relationship between beam diameter and bending angle obtained via experiment results.

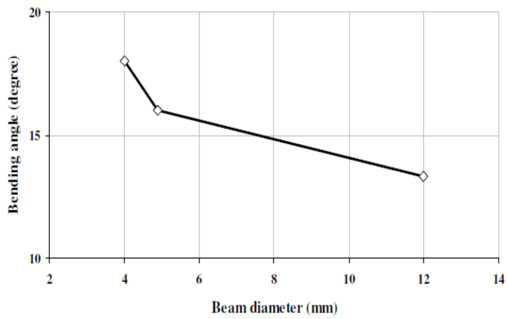


Fig.7- Effect of beam diameter on the bending angle . Process parameters; Material: AISI1010, laser input power =200 – 260W, scan velocity = 2 – 4 mm/s, pulse duration = 7 – 11 ms[9]

C. Scan Velocity

bending angle is inversely proportional to the scan velocity. As scan speed increases, incident heat flux absorbed by the workpiece surface per unit time will decrease for constant laser input power and beam diameter. Thus, lowering attainable surface temperature and reducing the bending angle.

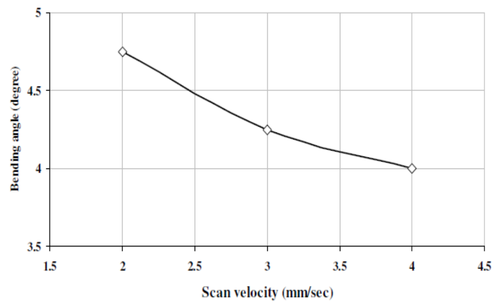


Fig.8 - Effect of scan velocity on the bending angle . Process parameters; Material: AISI1010, laser input power =200 – 260W, laser beam diameter = 2 – 3 mm, scan velocity = 2 – 4 mm/s, pulse duration = 7 – 11 ms[9]

D. Number of Scans

In laser bending process, the value of bending angle achieved per laser scan (pass) ranges from 0.1° to 5° depending on the process parameters. When steeper angles are required, the multi-scan system (up to 20-30 scans for 55° angle for low carbon steel) is used. Figure 1.8 shows the relationship between the number of scans and the bending angle .

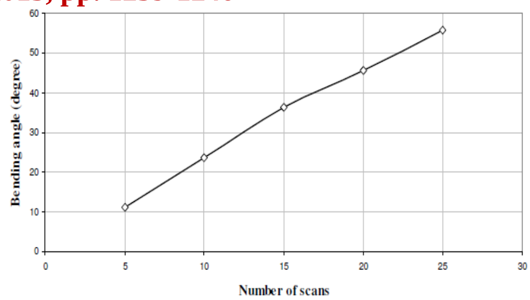


Fig .9 - Relationship between bending angle and number of scans. Process parameters: Material = Low carbon steel, laser input power = 170 W, laser beam diameter = 1.2 mm, scan velocity = 3 mm/sec, workpiece thickness = 1.2 mm[9]

According to Figure 8, bending angle varies linearly as the workpiece is scanned multiple times. Linear variation of bending angle over multiple scans is usually observed for the materials whose properties do not vary significantly after However, for the materials that are sensitive to the laser radiation, bending angle may show non-linear variation.

E. Material Properties.

Different materials respond differently to the laser treatment. *Yield strength* is an important property that decides the material's response to laser bending. Larger bending angles could be achieved with materials having low yield strength. Figure 2.11 illustrates the effect of yield strength on the bending angle. Materials with low yield strength will require less heat to deform plastically. Hence, more bending angle is achieved for given set of parameters, while Materials with high yield strength need to be formed at a higher temperature by increasing the laser input power or decreasing the scan velocity.

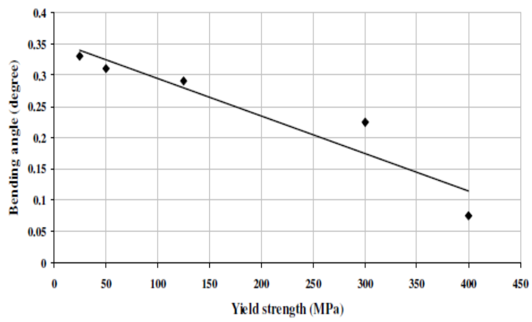


Fig.10 - Relationship between material yield strength and bending angle in degrees.[9]

As the temperature gradient in a material is a function of its thermal conductivity, for materials having high thermal conductivity, heat input by the laser will be rapidly dispersed throughout the material, hence, producing smaller temperature gradient. This results in reduction of the bending angle.

F. Absorption of the Laser Beam

Any light, including the laser radiation, striking on the surface of a material is either absorbed, reflected, transmitted or re-radiated . *'Absorption Coefficient'* is a measure of the radiant energy absorbed into a material and '*Absorptivity*' is a material property that characterises how easily a material can absorb a radiation.

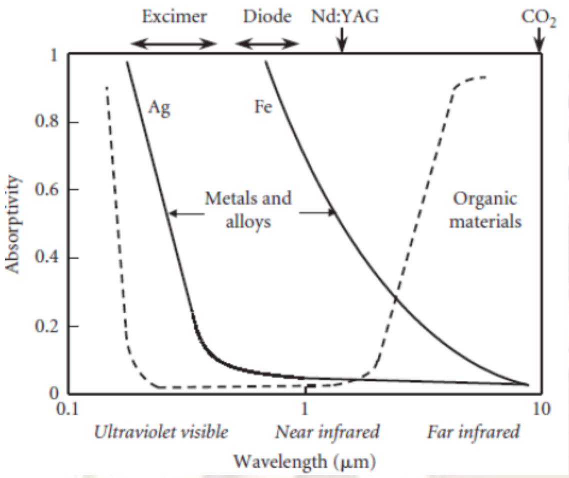


Fig.10 – Schematic of variation of absorptivity with wavelength for metals, alloys and organic materials .[9]

As evident from Fig.10, absorption of the laser beam by the workpiece surface depends on two important parameters, i.e. wavelength of the laser beam and type of the material in use. Metals mostly reflect the laser beams having high wavelength. Hence, the Nd: YAG laser (wavelength of 1.06 μm) is more suitable for processing metals as compared to the CO2 laser, which has a wavelength of 10.6 μm. To minimise reflection of the laser beam, coatings such as graphite are used to improve the absorption. A number of researchers have studied the effect of absorptive coatings . Depending on the base material, efficiency of the process can be improved up to 80% with the use of absorptive coatings.However, it is suggested in previous research that coatings such as graphite will be damaged after few scans because of high temperature and laser beam shock waves. Ablation of coating will result in reduction of the bending angle over multiple scans; however, it can be improved again by respraying.

II. REVIEW

To get better result of laser forming process, here different model and experimental results of laser forming are analyzed, so we can select optimum parameters for better control over process. Therefore this paper concentrate on the review of laser forming parameters.

K.C. Chan and J.Liang et al.[1] had formed low ductility Ti_3Al based intermetallic alloy with CO_2 laser. They reveled that bending take place because of differential thermal expansion of the the intermetallic alloy across the thickness. The final bending angle found to be strongly related to laser power, the scanning velocity and number of irradiations. But linear relationship found between laser bending angle and input line energy found only when line energy found between minimum and maximum limit. when line energy is below minimum value, called threshold value, bending angle is zero. But when line energy above maximum value, excessive melting occurs and which is not suitable for laser forming. So we conclude that for better control of the process, the process must be operated within certain line energy limit based on process parameters.

Lubiano and Jorge et al[2], studied laser bending of thin metal sheets by means of a low power CO_2 laser, for three different materials 304 stainless steel, 1100 Aluminium and 1010 Carbon steel. They had scanned sheets for several times and results were plotted as bending angle Vs.number of scansin fig 1.11. they observed that as the optical power of the laser beam increases, keeping the scanning speed and number of scans constant, the bending angle also increases in all three materials. But 1100 aluminium apperars to be more sensitive to laser power relative to 1010 steel,while 304 stainless steel is less sensitive to both laser power and scan speed.

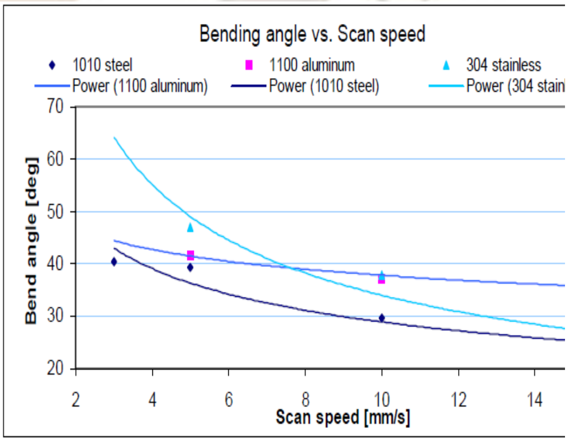


Fig.12 2θ-scan speed results for three different materials at 80 W after 15 scans[2].

1100 aluminum and 1010 steel both show a decreasing-increments behavior of the bending angle (i.e. 2θ) evolution as the number of laser scans increase beyond the initial scans. The strain due to the as-received rolled condition of the sheets and in-situ strain-hardening during bending are not annealed by the laser heat flux due to its short lived thermal cycles and high thermal diffusivity of 1100 aluminum and 1010 steel. On the other hand, 304 stainless steel, shows an increasing-increments behavior of the bending angle instead. Strain-hardening is prone to occur in the latter material, however, stress relief and partial annealing may occur due to higher magnitude and longer time-scale thermal cycles. This is thought to be caused by 304 stainless steel low thermal diffusivity and possibly faster nucleation kinetics, due to a high density of stacking faults and twins, which may facilitate partial recrystalization.

Watkins, J.Magee et al [3] present study of aluminium and titanium alloys, mainly used in aerospace industry, for non contact forming using thermal source with laser. They reviews the mechanisms involved in laser forming of 2-D sheet materials and material of particular interest include high strength alloys like titanium and aluminium alloys. Also they present forming of 3-D geometry from flat sheet. They demonstrated method of to develop large primitive 2-D shape. By using data from parametric and metallurgical study they formed flat rectangular sheet of 450*225*0.8 mm dimension made from $AA2024T_3$ into a part-cylinder of radius 900mm as shown in fig.12 Important to note that the shallow radius of curvature is almost at the spring back limit of conventional forming operations. The system uses CO_2 laser, CNC tables and pneumatic clamping system.

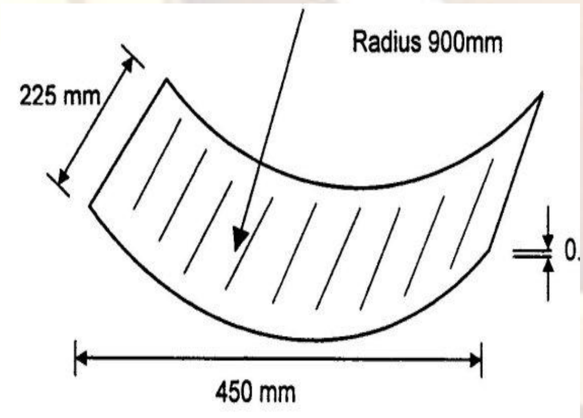


Fig. 13 Demonstrator Part [3].

They also formed saddle shape from rectangular sheet to demonstrate 3D forming. In fig 13 scan strategy and in fig 14 formed 3-D saddle shape is shown.

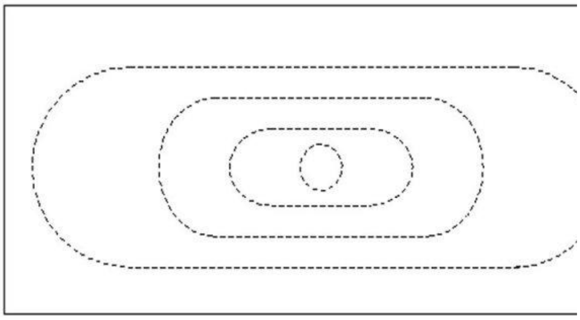


Fig. 14: Scan strategy to laser form the saddle shape, 800W , 20mm/s [3]

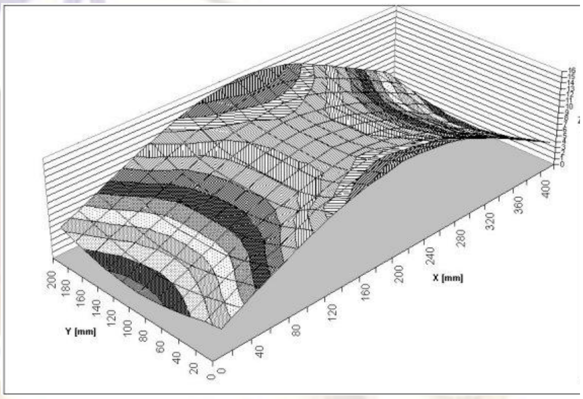


Fig. 15 3-D Contour plot of laser formed saddle shape[3].

Laser forming has emerged as a process with strong potential for application in aerospace, rapid prototyping and adjustment of misaligned components. This process advantage has arise due to progressive nature of laser forming process that can be used to achieve adjustment of misaligned part.

A.R. Majed and F.Ahmadi et al [4] present study of bending of needle having 0.63 mm outer diameter and 0.19 mm thickness with pulsed Nd-YAG laser. Laser bending of tubes haing following advantages over mechanical bending of tubes. Neither hard bending tool nor external force required, wall thickness reduction seems to be avoided and lesser ovalization results. It can be seen that the material in the intrados moves outward in the radial direction and shortned in the longitudinal direction as indicated by distorded mesh in finite element analysis. Maximum thickening of less than one percent occur at intradoce while there is no appreciable thinning at the extradose. The laser local heating causes large thermal expansion and low yield stress on the upper surface under high temperature subsequently the heated region of the material produces compressive plastic strain. The material of the heated region of the tube becomes shorter than that of the unheated region after cooling and thus the difference in length enables the tube to bend.

Zhang, G.Chen et al[5] present method of numerical simulation of pulsed laser bending. The aim of this work is to develop an efficient method for computing pulsed laser bending. During pulsed laser bending, thousands of laser pulses are irradiated onto the target. Simulations of the thermomechanical effect and bending resulted from all the laser pulses would exceed the current computational capability. The method developed in this work requires only several laser pulses to be calculated. Therefore, the computation time is greatly reduced. Using the new method, it is also possible to increase the domain size of calculation and to choose dense meshes to obtain more accurate results. The new method is used to calculate pulsed laser bending of a thin stainless-steel plate. Results calculated for a domain with a reduced size are in good agreement with those obtained by computing all the laser pulses. In addition, experiments of pulsed laser bending are performed. It is found that experimental data and computational results are consistent. A new efficient method for computing pulsed laser bending is developed. The total computation time is greatly reduced and results are found to agree with those obtained using a conventional computation method. Experimental studies are also carried out to verify the simulation results. It is found that the calculated results agree with the experimental values. For most pulsed laser bending processes, the newly developed method is the only possible way to compute bending within a reasonable amount of time.

C.Carry, W.J.Cantwell et al [6] present experimental results of graphite coating on laser sheet bending. Due to the optical nature of laser material processing it is often necessary to reduce the reflectivity of surface to be processed or to protect the surface from irradiation of laser. In many cases graphite is used for coating in spray form, to achieve this. Graphite is normally selected for its high absorptivity qualities, ease of application, availability and for economic reasoans. The method of application greatly varies the resultant graphite layer and therefore level of absorption ad types of interaction. Trying to apply thick layer at once reduces surface roughness, which in turn increase reflectivity reduces the advantages of the graphite coating. Also graphite layer buildup process is nonlinear process with initial layer having sub 10 micron thickness and additional layers being 15-20 micron thick.

M.Gollo, S.Ding et al [7], present that **t**he process of laser bending requires numerous experiments to pinpoint parameters that produce the highest bending angle of sheet metals. The effects of laser power, beam diameter, scan velocity, pass number, pulse duration, sheet metal thickness and proposed parameter for material properties on bending angle were investigated. The Taguchi method and analysis of variance (ANOVA) were applied to find out significant parameters in laser bending. An equation through regression analysis was introduced to predict the bending angle with respect to these parameters. The optimum laser bending angle was also determined by using signal-to-noise (S/N) ratio method**.** The influence of various process parameters on bending angle in the laser bending process has been investigated in this paper. ANOVA was used for the experimentation. Factors which are detected to have most significant effects on bending angle are found to be: i) Pass number, ii) Material parameter, iii) Sheet thickness, iv) Scan velocity, v) Beam diameter. Other factors which have less effect on the bending angle under this condition are as follows: i) Laser power, ii) Pulse duration. The correlation between factors and bending angle was derived by using a regression analysis. An optimized parameter combination for the maximum bending angle has been obtained by using the analysis of S/N ratios.

M-L Chen, J Jeswiet, P J Bates, and G Zak et al[8], Present in this experimental study, the two-dimensional laser bending of the low-carbon steel sheet demonstrated that a 940Nm diode laser is an effective tool for laser forming of carbon steel sheets. No additional surface coating is required. The buckling mechanism may be the main source contributing to the large angle of bend as well as the mixed bending up and bending down for the laser beam width to sheet thickness aspect ratio close to 4; both temperature gradient and buckling mechanisms contributed to the lower bend angles for a laser beam width to sheet thickness aspect ratio less than 2. This laser beam width study showed that the maximum bend angle depends mainly on the material thickness, not the power intensity distribution across the bend line for the given laser beam profile and material thickness range tested here. However, a more evenly distributed laser beam is preferred to a sharp one for obtaining approximately the same bend angle but with less material property and surface appearance changes. For obtaining the same bend angle, less laser line energy is required if a higher laser scan speed is applied, except for the extreme high-line energy level. Laser bending is more effective in the initial number of passes. So, a multi-path bend strategy may be preferred for maximizing the total bend angle as well as reducing the bend surface morphology change.

III. CONCLUSION

To get the better results of force forming process, various models and experiments published by previous authors are critically examined and retrieved to optimize the parametric control over the forming process. The contributions and conclusions are as follow.

Bending angle increased with the laser power and pulse duration, and decreased with the laser scan speed. There was an optimum spot diameter for which bending angle was the maximum. Bending angle increased with the increase in overlap, and decreased with the increase of gap at a constant laser power. However, for the constant line energy, there was an optimum value for both overlap and gap corresponding to the maximum bending angle. Bending angle increased with the increase of pulse width at constant laser power, but it showed a decreasing trend at constant pulse energy. It increased with the increase of pulse energy in both overlapping and discrete spots laser forming. Moreover, for the same pulse energy it was seen to be more in case of overlapping spots.

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