



Experiment and analysis of Laser forming process through solid state Nd: YAG pulsed laser in AISI 304 Stainless steel

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Abstract: Laser Forming is a non-contact traditional process which uses laser beam as the forming tool. The process offers the industrial promise of controlled shaping of metallic components. This yields the process with strong potential application in heavy manufacturing industries like aerospace, automobile, marine etc., where precision is given more importance. The vast capability of laser bending demands studies on the parameters that influence the bending angle of sheet metal. In this work, laser heat source is applied through straight path in a rectangular sheet metal. Material property of AISI 304 Stainless Steel is used in FE model and experiments. The aim of this study is to determine the parameters (factors) which affect the bending angle the most. This is done by means of Analysis of Variance (ANOVA). The parameters selected for this study are power, feed rate and number of scans, keeping all other parameters a constant. An experimental setup with an Nd: YAG pulsed laser machine having maximum mean laser power of 400 W is used for the experiments. A Finite element (FE) simulation is also performed with the ANSYS 12 (Mechanical APDL) standard software package as an aid to improve the knowledge in this process. A comparison of experimental and analysis result is also done to check the reliability of the simulation procedure.

Keywords: laser forming; DOE; ANOVA; thermo-structural analysis

I. Introduction

Laser bending is an advanced process in sheet metal forming in which a laser heat source is used to shape the metal sheet. Laser forming can produce metallic, predetermined shapes with minimal distortion. The process is similar to the well-established torch flame bending used on large sheet material in the ship building industry but a great deal more control of the final product can be achieved by the use of laser beam. In convectional forming techniques such as bending, drawing, pressing and stamping special heavy tools (i.e., die and punch) and application of the external forces are required to bend flat sheet metal into a component, where the process is changed through retooling or rebuilding the forming machines. Thus, the greatest advantage of the laser forming technique over the conventional methods for small batch production can be placed on process flexibility and reduction of manufacturing cost and time. The principle of the process is thermal deformation that occurs as the laser beam is guided across the sheet surface, where the path of the laser is dependent on the desired result.

Vollertsen et al.[5] introduced the first model for laser forming process using FDM and FEM. Vollertsen suggested a semi empirical model to predict bending angle as a function of material and laser parameters. S.L.Edwardson et al.[7] has done investigation on 2D and 3D laser forming of metallic parts. 2D laser forming comprises of laser forming operations that utilise 2D out-of-plane bends to produce 3D results (e.g. fold). Whereas in the case of 3D laser forming it comprises of laser forming operations that utilise combinations of multi-axis 2D out-of-plane bends and in-plane localised shortening to produce 3D spatially formed parts (e.g. dome). M. Hoseinpour Gollo et al.[8] made a statistical study on the effect of parameters (both laser and material) on bending angle. It is found that pass numbers, material parameters, sheet thickness, beam diameter and scan velocity are factors that can affect the bend angle the most. Laser power and pulse duration are the least affecting factors. A correlation between the parameters and the bend angle is derived, as regression equation, by conducting a Taguchi experiment using ANOVA method. G. Dearden et al.[4] made an experimental study on the asymmetric nature of LF of sheet material along continuous irradiation lines. This is found mainly due to non-uniform distribution of input energy across the work-piece. Edwardson [9] presents an investigation into the two and three dimensional laser forming of metallic components.

During the laser forming process the sheet metal surface is irradiated by laser beam that leads to a thermal gradient between the upper and lower surface with the thermal expansion that causes a small counter-bending away from the laser source. The heated zone of the underneath surface which is not directly in contact with the

laser beam is under compressive stress and plastic strain being caused due to restriction on the elastic part. Once the laser irradiation moves away, the heated zone exposes both to cooling and shrinkage, which induces a bending angle in the direction of the laser beam [14]. In the laser forming process, materials with good deformation at ambient temperature like stainless steel, mild steel, light alloys of aluminum, magnesium, titanium etc., are used. As there is only localised heating involved below the melting temperature the bulk properties are not altered and good metallurgical properties are retained in the irradiated area. Because of the vast potential of this non-convectonal manufacturing method, researches are made to in different industrial sectors, like aerospace, marine and automobile, where the implementation of laser bending can be replaced with some existing convectonal forming processes is under investigation.

II. Objectives

The main objective of this work is to study the parameters that affect the bend angle obtained from laser forming process by means of Analysis of Variance (ANOVA) through conducting experiments. In addition to that a simulation of laser forming process is done using ANSYS software package as an aid to improve the knowledge in this process. A finite element model is developed for the experimental laser forming process conducted and its reliability is checked with the experimental results.

III. Experimental Setup

Work Piece details

Twenty seven rectangular sheet metal of AISI 304 Stainless steel with length 50 mm and width 18 mm is used for the experiment. The work piece is prepared on the same laser machine with a drill head in cutting mode. The chemical composition, mechanical and thermal properties are shown in the tables I and II.

Table I Chemical composition

Element	Percentage
Cr	18
Ni	8
C	0.08
Mn	2
Si	0.75
P	0.045
S	0.03
N	0.1

Table II Shows Mechanical and Thermal Properties

Properties	Value
Thermal Expansion Coefficient	17.8e-6/K
Poisson's ratio	0.3
Modulus of Elasticity	193 GPa
Density	8000 kg/m ³
Melting Point	1440-1455 °C
Heat Capacity	500 J/kg K
Thermal Conductivity	16.2 W/m K

Statistical Analysis

In this work an L9 orthogonal array is selected for three parameters (cutting speed, feed rate and number of scans), each at three levels (Table III). The values of the parameter levels are selected according to the data available from the previous literatures, experienced personals, from the tool manufacturer's information, etc. [1]

Table III Parameter variations considered for experiment

FACTORS	LEVEL 1	LEVEL 2	LEVEL 3
Power (W)	20	35	50
Feed rate (mm/min)	100	150	200
No. of Passes	2	4	6

The power is adjusted using the equation: **Energy × repetition rate = Power**. The energy is kept constant at 2 Joule and the repetition rate of the laser beam is varied so as to get the required power as mentioned in table IV.

Table IV Power input method and other machine parameters

Power (W)	20	35	50
Energy(J)	2	2	2
Focal Length (mm)	80	80	80
Depth Of Focus (mm)	20	20	20
Repetition Rate (Hz)	10	17.5	25

Design of Experiment (DOE) is a structured method that is used to determine the relationship between different factors that affect a process. The output of the process is determined by running tests at various levels of these factors. A factor is a variable that has direct influence on the output. The level is the description that defines the condition of the factor while running the experiments. DOE includes Formation of experimental array and Analysis of Variance [19].

Experimental Procedure

The sheet metal is clamped at one side on a CNC (Computer Numerical Control) machine. The heating on the material surface by a laser beam occurs on one side along a selected line while the CNC table is moving. The surface melting of the material is avoided by adjusting the laser parameters such as laser power, feed rate and beam diameter.

Figure 1 JK704 pulsed laser machine



Figure 2 Laser Formed workpiece



Fig. 7.1 shows the 27 specimens of Stainless steel (SS 304) sheet metal laser formed into various degrees of bend. Maximum bend angle of 34.7 degree is obtained in specimen 21 and a minimum bend angle of 3.5 degree is obtained in specimen 7.

IV. Laser Forming Simulation

A. Simulation Procedure

A sequential thermo-structural analysis is conducted to simulate the laser forming process. For this, initially a heat transfer analysis is done to develop a moving heat source along a straight line as done in the experiment. The result from the thermal analysis is the nodal temperatures generated throughout the process. In the second stage, a structural analysis is done on the same FEM model on which the thermal analysis is done. Here the nodal temperatures from the thermal analysis are set as the thermal loads for the structural analysis. Thus finally a bend is developed at the irradiated portion lifting the free end upwards by a small length.

B. Finite Element Model

Assumptions

The assumptions made for the numerical modelling are as follows: work piece material is isotropic; the laser works in a continuous wave mode; no melting occurs in the laser forming process and no external forces are applied to the sheet metal.

Element and mesh

A rectangular plate of 0.018 x 0.050mm is modelled in ANSYS. Different elements are assigned for both thermal and structural analysis. SHELL 57 is used for thermal analysis and SHELL 181 is used for structural analysis.

For thermal and structural analyses, the same mesh model is used. To achieve a good accuracy near the heat source fine mesh is necessary. To reduce the run time, coarse meshes are used far from the heat source.

Figure 3 Meshed view

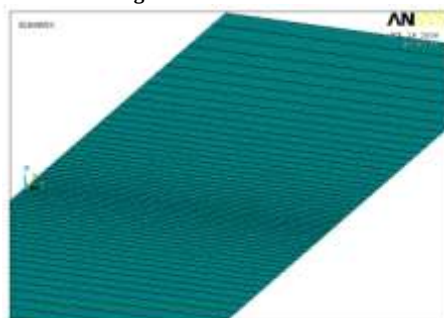
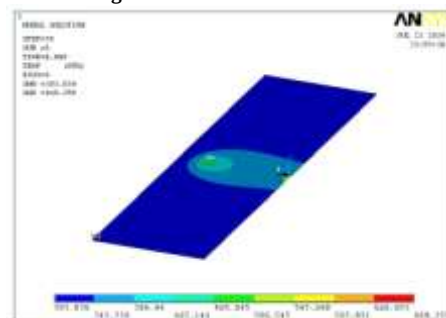


Figure 4 Laser heat source



Thermal Boundary Conditions

The thermal load is given in the form of heat flow. The heat flux generated by the laser beam is applied only on the top surface of the sheet metal. Room temperature is set to 30°C.

$$\text{Heat Input, } q = \frac{\text{power}}{\text{velocity}}$$

Material Properties

Thermal properties (thermal conductivity, specific heat and coefficient of thermal expansion) and mechanical properties (Density and Poisson's ratio) are assigned as per the values from the ASM data handbook.

Mechanical Boundary Conditions

In mechanical analysis, necessary constraints are added to eliminate rigid body movement according to the fixture used in real experiments. The boundary conditions are zero displacement at one side of the sheet metal, which is fully constraint.

Figure 5 Bend obtained on the plate

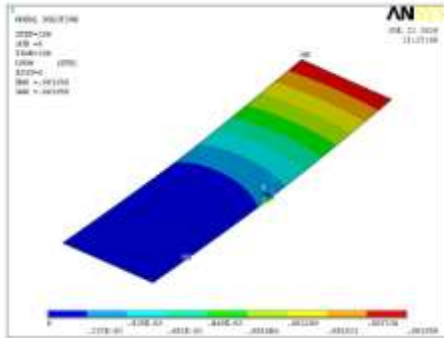
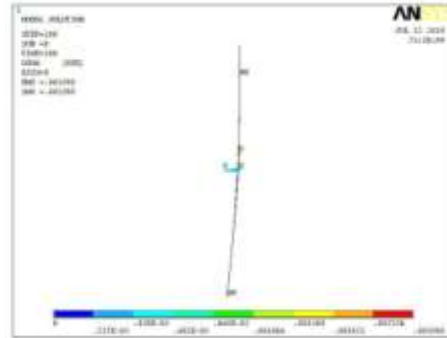


Figure 6 Side view of the plate



Time step

The time step must be small enough as in this case the heat flow is applied from node to node on the basis of the ratio of total time period to the total number of nodes in the irradiated path.

V. Results and Discussion

Twenty seven experiments were conducted and the work piece after laser forming is measured for bend angle using a bevel protractor. The resulted bend angles with the experimental array are shown in table 5.

Table V Experiment array with Results

Sl. No.	Power (W)	Speed (mm/min)	No. of scans	Bend Angle (deg)
1	20	100	2	5.5
2	20	100	4	9.7
3	20	100	6	13.25
4	20	150	2	4.08
5	20	150	4	7.7
6	20	150	6	10
7	20	200	2	3.5
8	20	200	4	6.5
9	20	200	6	7.08
10	35	100	2	12.9
11	35	100	4	24.5
12	35	100	6	32.4
13	35	150	2	8.9
14	35	150	4	13.5
15	35	150	6	17
16	35	200	2	8.4
17	35	200	4	8.3
18	35	200	6	17.2
19	50	100	2	16.3
20	50	100	4	27
21	50	100	6	34.7
22	50	150	2	12
23	50	150	4	24.3
24	50	150	6	34
25	50	200	2	7.7
26	50	200	4	21
27	50	200	6	29.5

From the figure 7, it can be inferred that at higher feed rates, there is an exponential increase in the bend angle as the power is increased from 20 to 50W. This can be seen from the lines representing feed rates at 150 and 200 mm/min. At lower feed rates, as power slightly increases from 20 to 35 W, there is an exponential increase in the bend angle. This is because at lower feed rates, a small increase in power is sufficient to heat the sheet metal so as to cause the bend easily. But, as the power goes on increasing, the rate of increase of the bend angle

decreases finally reaching a stage where further increase of power causing melting of the metal and not bending as desired.

Table VI ANOVA Results

SOURCE	SS	DOF	Variance (V)	F
A (Power)	1079.2	2	539.6	86.61
B (Feed rate)	259.31	2	129.65	20.81
C (No. of passes)	747.75	2	373.87	60.01
AxB	78.13	4	19.53	3.13
AxC	175.55	4	43.88	7.04
BxC	15.1	4	3.77	0.605
Error (e)	49.86	8	6.23	1
TOTAL	2404.9	26		

Figure 7 Variation of bend angle with power

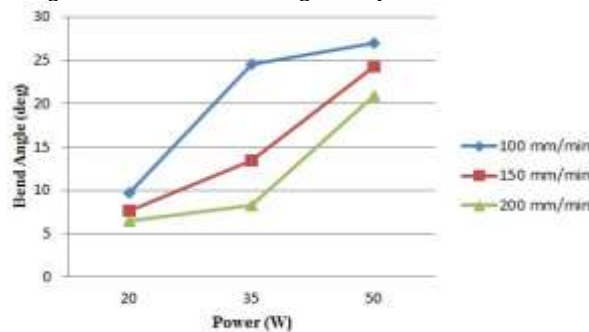
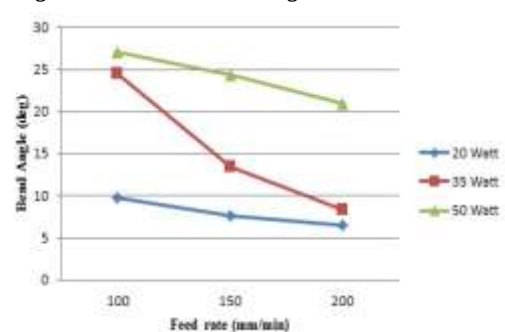


Figure 8 Variation of bend angle with Feed rate



From figure 8, at moderate power, the heating of the metal is not uniform which shows the exponential decrease in the bend angle. At lower feed rates, bend angle does not vary significantly by varying the power from 35 to 50 W, whereas, at higher feed rates, the bend angle variation is almost constant at different powers.

From figure 9, the lines are plotted by noting the bend angles at different number of passes namely 2, 4 and 6. The figure shows the behaviour of the bend angle as a linear increase with increasing number of passes or scans. This is quite predictable as with each increasing pass, the metal is heated to a higher temperature causing the metal to bend more and more. But, this behaviour cannot go on infinitely. After a threshold value of number of passes, the effect on bend angle decreases and the surface of the metal starts to melt due to very high temperature.

Figure 9 Variation of bend angle with no. of scans

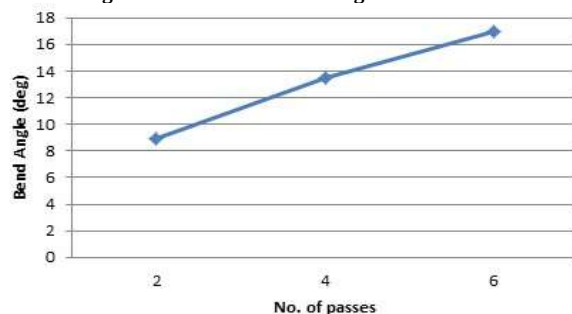


Figure 10 Variation of bend angle due to line energy

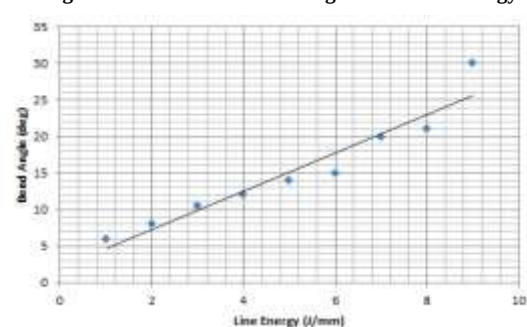


Figure 10 illustrates the variation in bend angles due to variation in line energy (power to speed ratio). The energy absorption into the material is mainly determined by the laser power and the scanning speed. In general, the bend angle increases with the increase of the laser power due to high absorbed energy.

Table VII shows the comparison of results shows a difference in the bend angle values, i.e., the analysis values are found lower than the experimental values. The FEM model developed is of shell element that captures bending. Thus the thickness of the shell is given as the thickness of the plate.

Table VII Comparison of experimental and analysis results

Sl. No.	Power (W)	Speed (mm/min)	Bend Angle		Difference (deg)
			Experiment	Analysis	
1	20	100	5.5	4.06	1.45
2	20	150	4.08	2.71	1.37
3	20	200	3.5	2.03	1.47
4	35	100	12.9	7.10	5.79

5	35	150	8.9	4.74	4.16
6	35	200	8.4	4.26	4.04
7	50	100	16.3	10.13	6.17
8	50	150	13.4	6.76	5.23
9	50	200	12.9	5.08	2.63

The basic acting of laser forming is due to the generation of thermal gradients. The different layers, developed due to thermal gradient, on contraction results in the bending. The reason for difference in bend angle can be the due to the selection of element type or due to nodal thermal loading.

VI. Conclusion

This paper discussed an experimental study of laser forming operation on AISI 304 Stainless steel. From experiment, at higher feed rates, there is an increase in the bend angle as the power is increased. At higher and lower powers, the bend angle variation is almost linear embossing the fact that the thermal gradient formed at these feed rates cause uniform heating to occur throughout the metal. At moderate power, the heating of the metal is not uniform which shows the exponential decrease in the bend angle.

The comparison of results shows a difference in the bend angle values, i.e., the analysis values are found lower than the experimental values. The reason can be because, the element selected is a shell element which has a single thickness as a whole. The effect of thermal loading acting on a single layer restricted the effect thermal gradient. As a future scope of work, an FEM model can be developed for Laser forming process by considering a 3D layered element with stacked mesh in the thickness direction which can take into account the effect of thermal gradients and can provide a more accurate deformation range.

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