An experimental study of sheet metal bending by pulsed Nd:YAG laser with DOE method

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ABSTRACT: The laser forming process can be most useful in the automation of sheet metal forming. Three-dimensional transient temperature and stress fields complicate the simulation of the process. The aim of this experimental study is to identify the response related to deformation and characterize the effects of process parameters such as laser power, beam diameter, scans velocity and pulse duration, in terms of bending angle for a square sheet part. Extensive experimentation, including a design of experiments, is performed to address the above-mentioned aims. From these experiments it has been determined that laser forming using Nd:YAG laser is a flexible manufacturing process for steel sheet bending.

Key words: Laser Forming, Laser Bending, DOE, Taguchi Method.

1 INTRODUCTION

Laser forming is a process of gradually adding plastic strain to a metal component to generate desired shape. Laser forming can be used for forming straight bends in high strength metal such as titanium instead of hot brake forming. The laser forming process involves scanning a focused or partially defocused laser beam over the surface of a workpiece to cause localized heating along the bend line. The sharp thermal gradients in the material cause the sheet to bend either toward or away from the laser source. The resulting deformation of the material, which is, bending toward the laser beam, is permanent. By repeating the laser forming process, either with over lapping or parallel scans, bend of desired angle and radius can be obtained. Some of the earliest works on laser forming of sheet metal into Two-dimensional shape are attributed to Namba [1, 2] in 1985. The laser forming process was first modelled by Vollertsen, Geiger, and Li using both of the FDM and FEM [3]. Vollertsen has suggested a semi empirical model to predict bending angle as a function of material and laser parameters [4, 5]. Kyrsanidi has developed a numerical model of the laser forming process for steel by using a coupled transient thermal-structural finite element analysis [6]. Edwardson presents an investigation into the 2D and 3D laser forming of metallic component [7].

2 EXPERIMENTAL EQUIPMENT AND SETUP

A pulsed Nd:Yag laser, Model IQL-10,with maximum mean laser power of 400 W was used for the experiments. Square shape pulse is the standard output of this laser. The available ranges for the laser parameters were 1-1000 Hz for pulse frequency, 0.2-20 ms for pulse duration, and 0-40 J for pulse energy. The experiments were conducted with frequency 20 Hz and workpiece velocities from 2 to 4 mm/s. Two major factors were important for selecting the 20 Hz frequency; firstly the required overlapping of alternative laser pulses, regarding process travel speed and absolute irradiated energy per unit length of the workpiece and secondly technical limitations of laser source that confines our choices about each combinations of laser pulse energy, pulse duration and frequency for each value of average output power. The focusing optical system was composed of three lenses with 75mm focal length and 250μm minimum spot size. For each combination of pulse energy and duration, the laser beam was defocused to different extents to obtain various spot diameters and power densities on the workpiece surface. A 5000 W-Lp Ophir power meter and LA3000 W-Lp joule meter were used to measure average power and pulse energy. Pure argon gas with a coaxial nozzle, and flow rate 5-10 liter/min was used as shielding gas. Coaxial shielding supports the safety of optical elements when operating in an industrial environment.

The shorter wave length Nd:YAG laser light(1.06μm) is more effective on heating sheet metal because more energy is absorbed by metal surface. The investigation presented is the laser bending of 1mm thick mild steel St12 (AISI1010), a cold rolled low carbon steel sheet. The size of the samples is 100x100 mm. The samples were cleaned using ethyl alcohol. The bending of the samples was measured using a coordinate measuring machine (CMM) at 3 to 5 locations along the scanning path and their average was calculated. Material data is given in table (1).

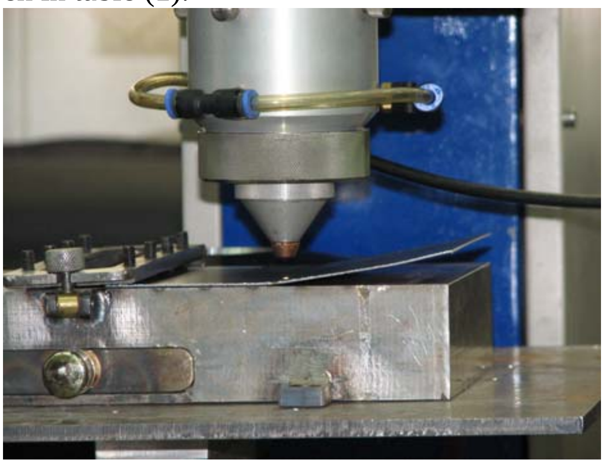

Fig. 1 Experimental setup for 2D laser forming

Table 1- Mechanical and Thermal properties ofAISI1010 [8]

Parameter	Unit	Value
Density	[kg/m3]	7870
Young's Modulus	[GPa]	205
Tensile Strength	[MPa]	365
Yield Strength	[MPa]	305
Thermal conductivity	[W/mK]	49.8
Coefficient of Thermal Expansion at 20°C,250°C,500°C	[10-6/K]	12.2, 13.5, 14.2
Specific Heat Capacity at 100°C,300°C,450°C,700°C	[J/kg.K]	448, 536, 649, 825

3 DESIGN OF EXPERIMENT

3.1 Taguchi Experiments

A set of experiments was performed to determine the bending angle of sheet components formed by laser. The effects of laser power, beam diameter, scan velocity and pulse duration on the bending angle are investigated experimentally.

To limit the experimental costs a Taguchi experimental design is used. A L-9 Taguchi array with four factors (power, beam diameter, scan velocity and pulse duration) and three levels for each factor is given in tables (2) and (3). Because replication is used, the total number of experiments is (3x9=27). The objective of these experiments is to determine bending angle as function of the process parameter mentioned above.

Table2- Factors and their corresponding levels

Factors	Level 1	Level 2	Level 3
P -Laser-Power (W)	200	230	260
S -Beam Diameter (mm)	2	2.5	3
V -Scan Velocity(mm/s)	2	3	4
D -Pulse Duration(ms)	7	9	11

Table3-Orthogonal array or Taguchi design

Exp.	P	S	V	D	P (W)	S (mm)	V (mm/s)	D (ms)	Bending Angle(θ)
1	1	1	1	1	200	2	2	7	3.285667
2	1	2	2	2	200	2.5	3	9	3.712
3	1	3	3	3	200	3	4	11	3.642667
4	2	1	2	3	230	2	3	11	4.226
5	2	2	3	1	230	2.5	4	7	3.730333
6	2	3	1	2	230	3	2	9	5.464667
7	3	1	3	2	260	2	4	9	2.179333
8	3	2	1	3	260	2.5	2	11	4.634667
9	3	3	2	1	260	3	3	7	4.351333

A Taguchi design of experiments has the advantage of allowing the effect of each process variable (called "Main Effect") as well as any suspected interactions between them (called "Interaction effect") to be statistically evaluated. In this case, a popular statistical technique called ANOVA or Analysis of Variance has been used. The software MINITAB is used to perform the ANOVA.

3.2 Data analysis

The ANOVA indicates that the bending angle is influenced by beam diameter, pulse duration, scan velocity and laser power. There does not appear to have any significant interactions between the beam diameter and other process parameters, such as scan velocity and pulse duration [9].

3.2.a Effect of factors on bending angle

Main effects plot of factors can be used to draw a draft conclusion about effects of factors. These plots are shown in Fig.2 for the sake of quick reference. Fig.2a shows that laser power factor has a significant effect on bending angle. It can also be seen from this figure that the effect of this factor is directly proportional to bending angle. In addition, it can be stated that by increasing the laser power factor, bending angle increases significantly.

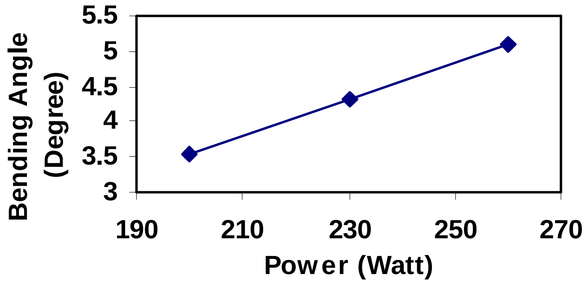

Fig. 2a Effect of laser power on bending angle

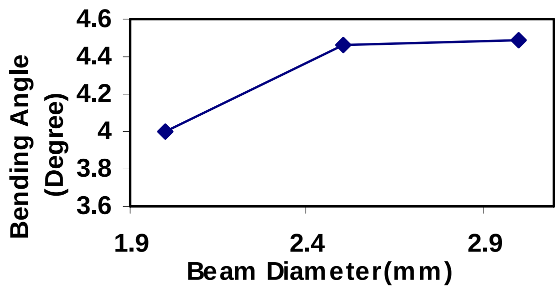

Fig. 2b Effect of beam diameter on bending angle

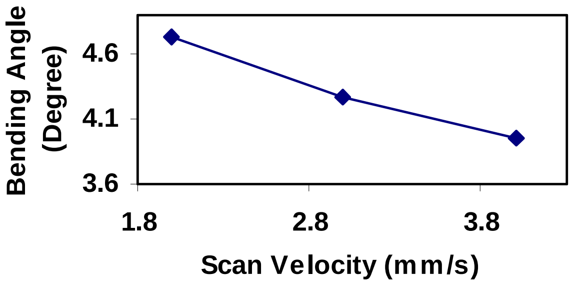

Fig. 2c Effect of scan velocity on bending angle

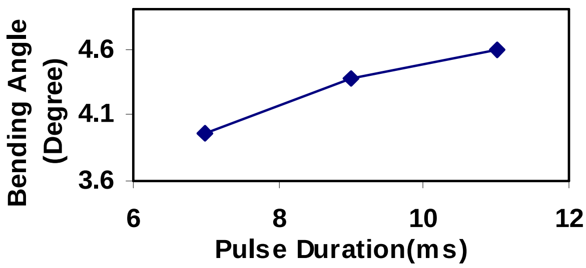

Fig. 2d Effect of pulse duration on bending angle

Fig.2b illustrates the effect of Beam diameter on bending angle. It can be seen that the increasing rate of the bending angle is reduced by increasing beam diameter. The relationship between the scan velocity and the bending angle is shown in Fig.2c.It is clear that the bending angle is decreased by increasing scan velocity. The relationship also appears to be quasi-linear. Eventually Fig.2d shows the effect of pulse duration on bending angle. The bending angle increases with increasing of the pulse duration.

3.2.b Effect of laser power and beam diameter on bending angle

Fig. 3 shows the interaction between laser power and beam diameter. It can be seen that the maximum bending angle is obtained by higher laser powers at beam diameter of 2.5 mm approximately.

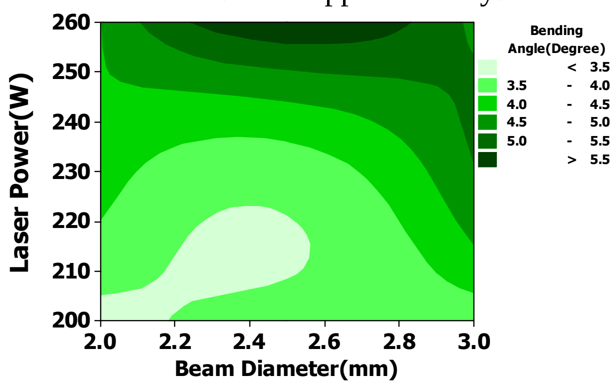

Fig. 3 Contour Plot of Laser Power and Beam Diameter on the Bending Angle

3.2.c Effect of laser power and scan velocity on bending angle

Fig. 4 indicates the effects of laser power and scan velocity on the bending angle. The results show that using lower scan velocity and higher laser power leads to higher bending angle.

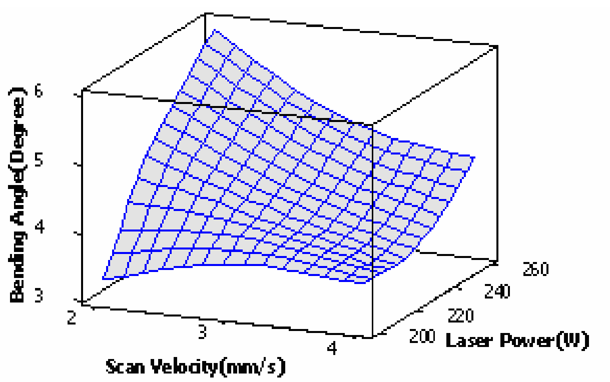

Fig. 4 3-D effect plot of Laser Power and Scan velocity on the Bending Angle

3.2.d Effect of laser power and pulse duration on bending angle

Fig. 5 shows the interaction between laser power and pulse duration. The maximum bending angle is obtained using the highest values of laser power and pulse duration.

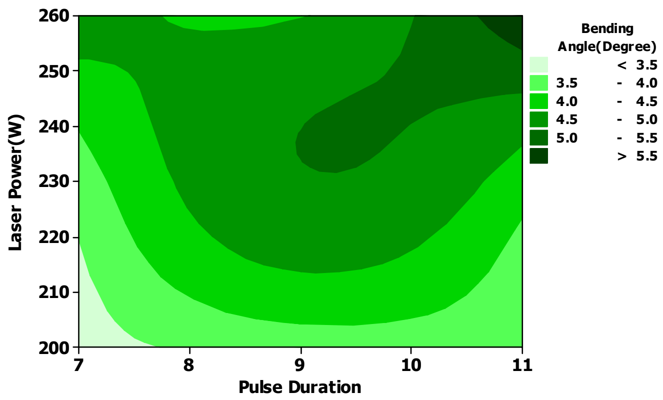

Fig. 5 Contour Plot of Laser Power and Pulse Duration on the Bending Angle

3.3 *Regression analysis*

Regression analysis is performed to find out the relationship between factors and bending angle. Accordingly, a first order polynomial best predicts the observation. The regression equation in terms of factors (table 2) is obtained and presented as below:

Bending Angle-θ(Degree) = *- 3.10 + 0.0257P(W) + 0.489 S(mm)- 0.389 V(mm/s) + 0.161 D(ms)* (1)

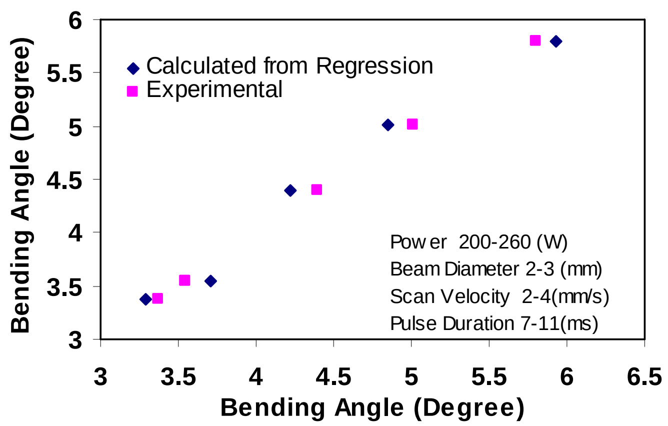

Fig. 6 Comparison between experimental results and calculated data from regression analysis

The R^2 value for equation (1) is 97.7%, indicating that this model can be used with sufficient accuracy. Fig.6 shows the differences between experimental results and calculated data using regression equation for bending angle. It demonstrates that the regression equation gives the bending angle for specific conditions with good accuracy.

4 CONCLUSION

In this paper laser bending of sheet metals has been studied experimentally. Influences of main process parameters including laser power, beam diameter, scan velocity and pulse duration on bending angle were investigated.

- Bending angle is most strongly affected by beam diameter, followed by pulse duration, scan velocity and laser power.
- Increasing laser power, beam diameter, pulse duration and decreasing scan velocity increased the bending angle.
- A formula is obtained using a regression analysis to predict bending angle.

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