Scientific Research and Essays Vol. 7(3), pp. 279-287, 23 January, 2012
Available online at http://www.academicjournals.org/SRE
DOI: 10.5897/SRE10.389
ISSN 1992-2248 ©2012 Academic Journals

Full Length Research Paper

Experimental analyses of bending angle by a pulsed Nd:YAG laser in sheet metal forming process

M. Hoseinpour Gollo[1]*, H. Moslemi Naeini[2], G. H. Payganeh[3], S. Ding[4] and S. M. Mahdavian[4]

[1]Department of Mechanical Engineering, Faculty of Engineering, University of Mohaghegh Ardabili P. O. Box 179, Ardabil, Iran.
[2]Department of Mechanical Engineering, Faculty of Engineering, Tarbiat Modares University, P. O. Box 14115/143, Tehran, Iran.
[3]Department of Material Engineering, Shahid Rajaaee Teacher Training University, 16785-163, Tehran, Iran.
[4]School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Bundoora, Victoria, Australia.

Accepted 29 August, 2011

The 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.

Key words: Design of experiments, laser, analysis of variance, laser bending.

INTRODUCTION

In the laser beam bending process sheet metal surfaces which are irradiated by a laser beam normally generate a thermal gradient between the upper and lower surfaces. While the heated zone is under compressive stress in this process, a plastic strain is generated by the restriction in the elastic part. Once the laser irradiating is completed, the heated zone will cool off and shrink, and consequently cause a bending angle which may be toward or away from the laser source. Numerical and experimental investigations have been carried out by numerous researchers for a better understanding of the mechanism and effects of control parameters in this process. For example, the study of bending angle and its relation to mechanical behaviour have been conducted by Thomson et al. (2008), Hennige (2000) and Chen et al. (2004). Kyrasanidi et al. (2000) introduced an analytical model for the prediction of distortions caused by the laser forming process through parametric investigation and process optimization. Zhang et al. (2004) have compared Eulerian approach with Lagrangian approach because both approaches can be applied in the modelling of laser forming processes, while Cheng et al. (2001) were focusing on simplified analytical solutions. Different thermo-mechanical simulations have been presented by Hu et al. (2002), Shichun et al. (2002), Zhang et al. (2004) and Hsieh et al. (2004). Zhang et al. (2004) have focused on the definition of minimum discretization requirements of LBF finite element models. The effect of geometric parameters of the sheet metal could be found in Shichun et al. (2002) in which it was concluded that in the laser bending process the counter-bending angle away from the laser source in a narrow sheet is greater than that in a wider sheet. These simulations share some similarities with the presently developed models. However, apart from the difference in the investigated target material which was steel in these researches, other key differences exist as well: the sheet forming mechanism investigated by Hu et al. (2002) is buckling other than bending; while the laser source used by Hsieh et al. (2004) comprises a single pulse other than a continuous heat source scanning the metal sheet.

*Corresponding author. E-mail: mohammad.hoseinpour@gmail.com.

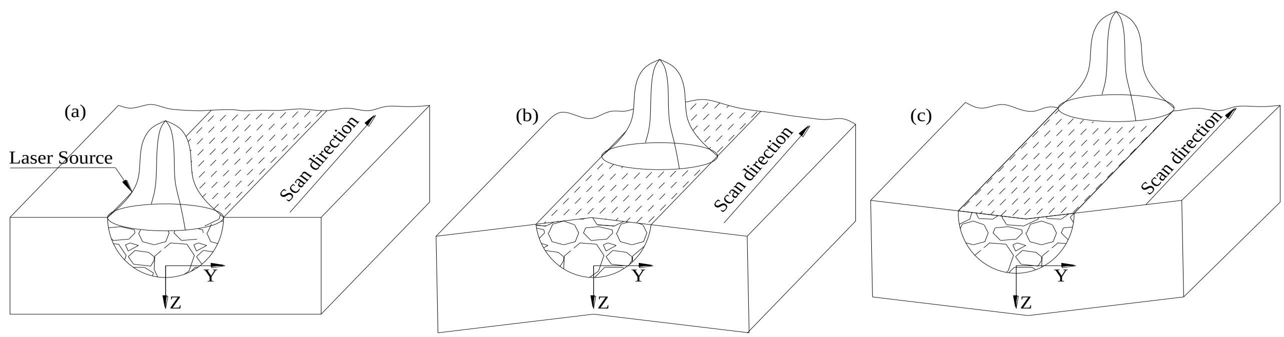

Figure 1. Process step of laser bending. (a) before irradiation, (b) heating process (counter bending) and (c) cooling process (positive bending).

Based on the researches mentioned earlier, several general comments can be made regarding current laser forming methods. In almost all cases, CO_2 or ND:YAG lasers were used for bending; small bending angles were obtained for all the materials tested. Although experimental polynomial regression equation is able to predict bending angles; unfortunately, no research has been performed in this area. These works deal with the investigation of bending angles of mild steel AISI1010 (St12) and stainless steel 304. The selection of this material was based on a wide range of applications in manufacturing industry. This research is to determine the process parameters (factors) that affect bending angles. And this identification is done by means of analysis of variance (ANOVA). Regression analysis is used to establish the correlation between factors and responses (bending angles). The appropriate degree of the found polynomial regression equation is considered to be a useful evaluation of the predictive equation (Montgomery, 2000; Raymond, 1978). Optimal factor levels are obtained at the final stage of these calculations.

PROCESS DESCRIPTION

In laser beam bending process, the sheet metal surface is irradiated by a laser beam in which a thermal gradient is generated between the upper and lower surfaces. As shown in Figure 1, the thermal expansion causes a small counter-bending away from the laser source while the heated zone is being under the compressive stress. This produces a plastic strain which is caused by the restriction on the elastic part. After the completion of laser irradiating, the heated zone shrinks and cools off and this will cause a bending angle toward or away from the laser source. A long pulsed Nd:YAG laser with a standard square shape pulse is chosen as the heating laser source for theoretical model and also to carry out the experiments. The pulse energy of the laser beam, duration and process speed may be changed. The pulse repetition rates (20 Hz) were kept invariant during the experiment.

MATERIALS AND METHODS

Experimental equipment and setup

A pulsed Nd:YAG laser, Model IQL-10 with maximum average laser power of 400 W was used for the experiments as shown in Figure 2. Square shape pulse is the standard output of this laser. The pulse frequency, pulse duration and pulse energy of laser system are 1 to 1000 Hz, 0.2 to 20 ms and 0 to 40 J respectively. 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 overlapping of laser pulses in conjunction with the process travel speed and absolute irradiated energy per unit length of the workpiece was required. Secondly, technical limitations of laser source would confine 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 75 mm focal length and 250 μm minimum spot size. For each combination of pulse energy and duration, the laser beam was defocused to different extents in order 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 the average power and pulse energy. Pure argon gas with a coaxial nozzle and flow rate of 5 to 10 L/min was used as shielding gas. Coaxial shielding assists the protection of optical elements when operating in an industrial environment. The shorter wave length Nd:YAG laser light (1.06 μm) is more effective on heating sheet metal because more energy is absorbed by metal surface at this wave length. The experimental studies were conducted for the laser bending of 1 mm thick square shape with 100 mm side length samples cut from cold rolled low carbon steel (mild steel) and stainless steel with standard designation of mild steel AISI1010 and stainless steel S304. The thermal and mechanical properties of these materials are given in Table 1. The samples were cleaned using ethyl alcohol.

The bending of the samples was measured by using a coordinate measuring machine (CMM) at 3 to 5 locations along the scanning path and their average was calculated. In this process the leading edge of the metal sheet is being located and clamped and the trailing edge is free to move. As explained earlier as the laser beam is scanned as the result of temperature gradient stress, the workpiece is bended. Figure 3 shows the formed parts from two

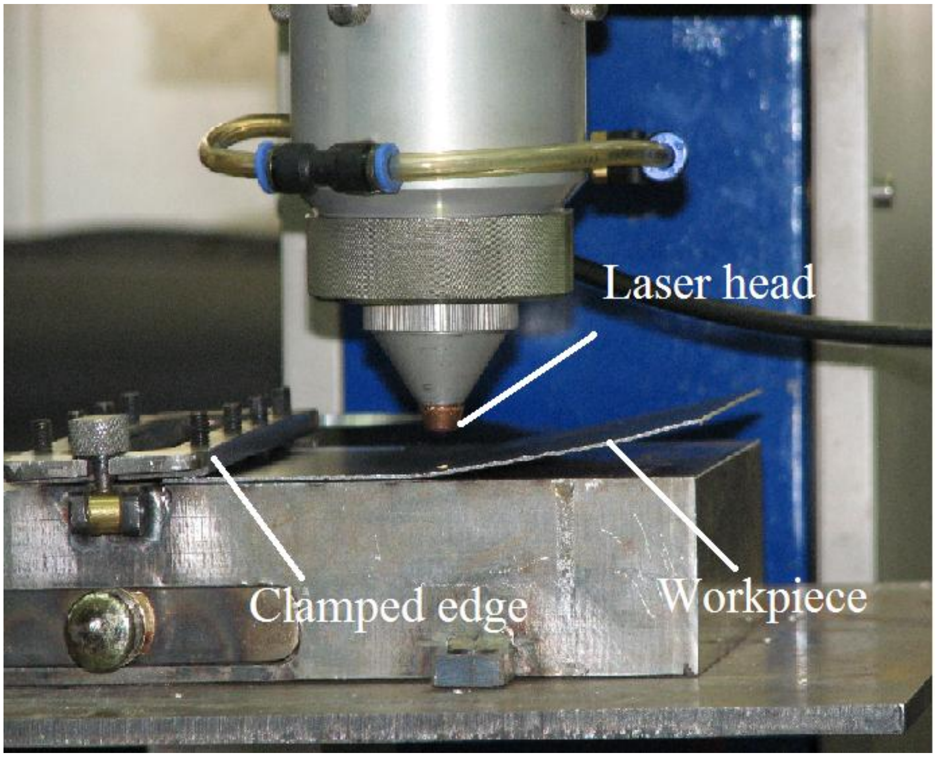

Figure 2. Experimental setup for laser forming.

Table 1. Mechanical and thermal properties of AISI1010 (Brown, 1992; ASM metals handbook, 1990).

Parameter	Unit	AISI1010	S304
Density	kg/m^3	7870	8000
Young's modulus	GPa)	205	193
Tensile strength	MPa	365	515
Yield strength	MPa	305	205
Thermal conductivity	W/mK	49.8	16.2
Argon conductivity gas as shielding gas	mW/mK	6.36587	6.36587
Coefficient of thermal expansion at 20, 250 and 500°C	10^{-6}/K	12.2, 13.5, 14.2	17.2,17.8,18.4
Specific heat capacity at 100, 300, 450 and 700°C	J/kg.K	448	500

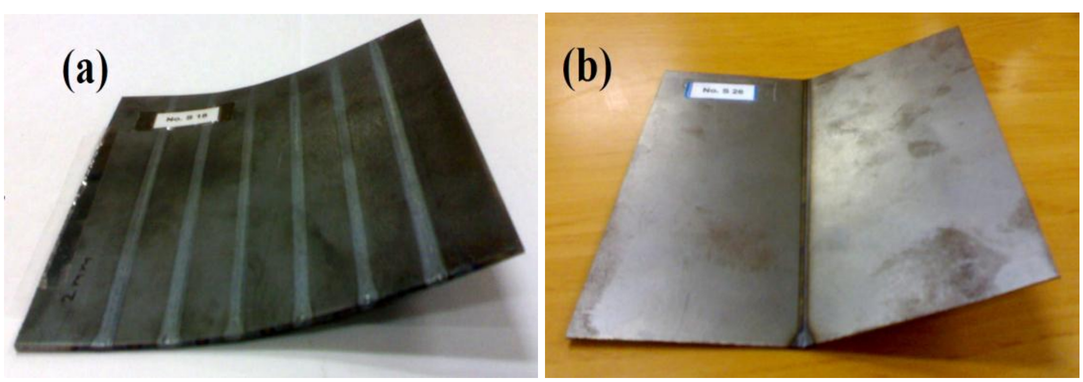

Figure 3. Formed work pieces by laser. (a) parallel scan path and (b) multi scan in the same path.

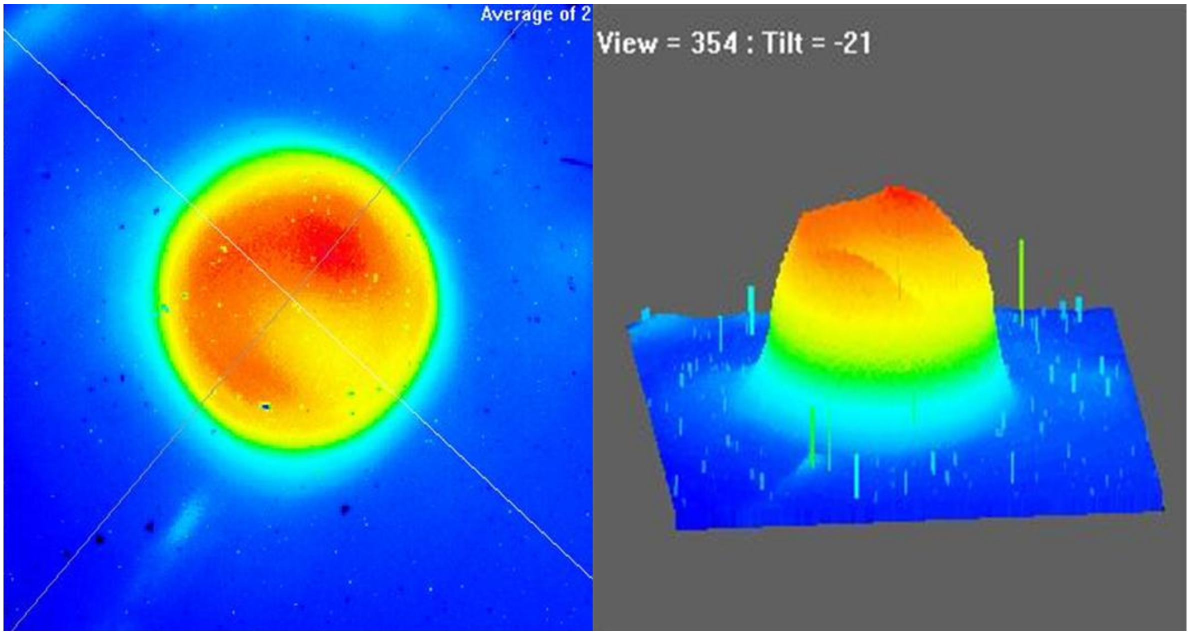

Figure 4. Laser beam profile.

separate experiments. Multi scan and parallel scan with the laser beam profile shown in Figure 4 were used in the experiments.

DESIGN OF EXPERIMENT

Design of experiments (DOE) is a structured method that is used to determine the relationship between different factors affecting a process and the output of that process by running tests at various levels of the 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.

Taguchi experiments

Taguchi approach is a form of DOE with special application principles. DOE using Taguchi approach is a standardized form of experimental design technique (Phadkeh, 1989). In this research a set of experiments was performed to determine the bending angle of sheet components formed by laser. The effects of laser power, scan velocity, beam diameter, sheet thickness, pass number, pulse duration and material parameter on the bending angle were investigated experimentally. The following non dimensional material parameter is defined in order to quantify the mechanical and thermal characteristics of the materials.

$$M = K_{METAL}.\alpha \cdot A \cdot \sigma_Y / K_{SHG} \rho c \qquad (1)$$

The symbols in this equation are defined as follows: *M:* non dimensional material parameter; ρ: density; *c:* specific heat; K: the conduction coefficient; *A*: the absorption coefficient; σ_Y : the yield stress of the material; K_{SHG}: the conduction coefficient of the shielding gas that is used as material protector from oxidation.

Taguchi experimental design (Phadkeh, 1989) is used to identify variables which mostly influence the results. This will limit the number of experiments and consequently reduce the cost. An L-18 Taguchi array with seven factors is given in column 2 of Table 2. The levels of experiment given in the rows in Table 2 represent variation in experimental parameters. For example, in the 2nd row there are 3 levels of laser powers 120, 135 and 150 W. According to Taguchi procedure the experimental repeatability is considered to be three times. Therefore, the total number of experiments conducted was 3 × 18 = 54. The objective of these experiments is to determine the bending angle which is a function of the process parameters mentioned earlier.

RESULTS AND DISCUSSION

Effects of factors on bending angle

In order to clarify the variation of bending angle with variables, the data in Table 3 are plotted in Figures 5 and 6. Figure 5 (a, b, c) shows the variation of bending angle with the defined material property parameter in Equation 1. This data was obtained by using the software program Minitab (Minitab release 15, 1997). The averages of bending angles for two different types of materials were calculated. It can be seen in Figure 5 that the bending angle is decreased by increasing parameter M, scan velocity and sheet thickness factors. Figures 5 and 6 were obtained in the same way. From Figures 6 (a, b, c, d), it can be found that the increases in laser power, beam diameter, pass number and pulse duration lead to the increase in the value of bending angles. Figures 5 and 6 can not be used to reach quantitive conclusions because the plots are not accurate enough. They can only be used for comparison purpose. To address the issue more accurately, analysis of variance (ANOVA) which

Table 2. Factors and their corresponding levels.

Factor	Factor description	Level 1	Level 2	Level 3
M	Material parameter	St12	304	
P	Laser power(W) 90 90	120	135	150
V	Scan velocity (mm/s)	2	3	4
S	Beam diameter (mm)	1	1.25	1.5
T	Sheet thickness (mm)	1	1.25	1.5
N	Pass number	1	2	3
D	Pulse duration (ms)	70	90	110
e	Error	N/A	N/A	N/A

Table 3. Orthogonal array or Taguchi design.

Run #	Factors							Bending angle		
	M	***P***	***V***	***S***	***T***	***N***	***D***	**a**	**b**	**c**
1	1	1	1	1	1	1	1	2.582	2.503	2.794
2	1	1	2	2	2	2	2	3.829	3.686	3.877
3	1	1	3	3	3	3	3	5.155	5.063	5.278
4	1	2	1	1	2	2	3	4.255	4.012	4.267
5	1	2	2	2	3	3	1	5.396	5.349	5.466
6	1	2	3	3	1	1	2	2.057	2.043	2.262
7	1	3	1	2	1	3	2	6.652	6.685	6.943
8	1	3	2	3	2	1	3	2.026	1.8	1.863
9	1	3	3	1	3	2	1	3.553	3.449	3.530
10	2	1	1	3	3	2	2	3.062	3.060	3.230
11	2	1	2	1	1	3	3	4.258	4.322	4.727
12	2	1	3	2	2	1	1	1.036	1.019	1.045
13	2	2	1	2	3	1	3	1.189	1.245	1.265
14	2	2	2	3	1	2	1	4.935	4.908	5.049
15	2	2	3	1	2	3	2	3.228	3.195	3.318
16	2	3	1	3	2	3	1	5.754	5.744	5.929
17	2	3	2	1	3	1	2	.001	.0015	.001
18	2	3	3	2	1	2	3	3.319	3.356	3.69

is now widely used in industry can be applied. ANOVA is a statistic tool which is used for evaluating the effects of individual parameters in the process. Through calculations the factor which has the most significant influence in the process can be found based on the prescribed confidence level. In ANOVA it is assumed that:

i) Residuals are normally distributed,
ii) Error is independent,

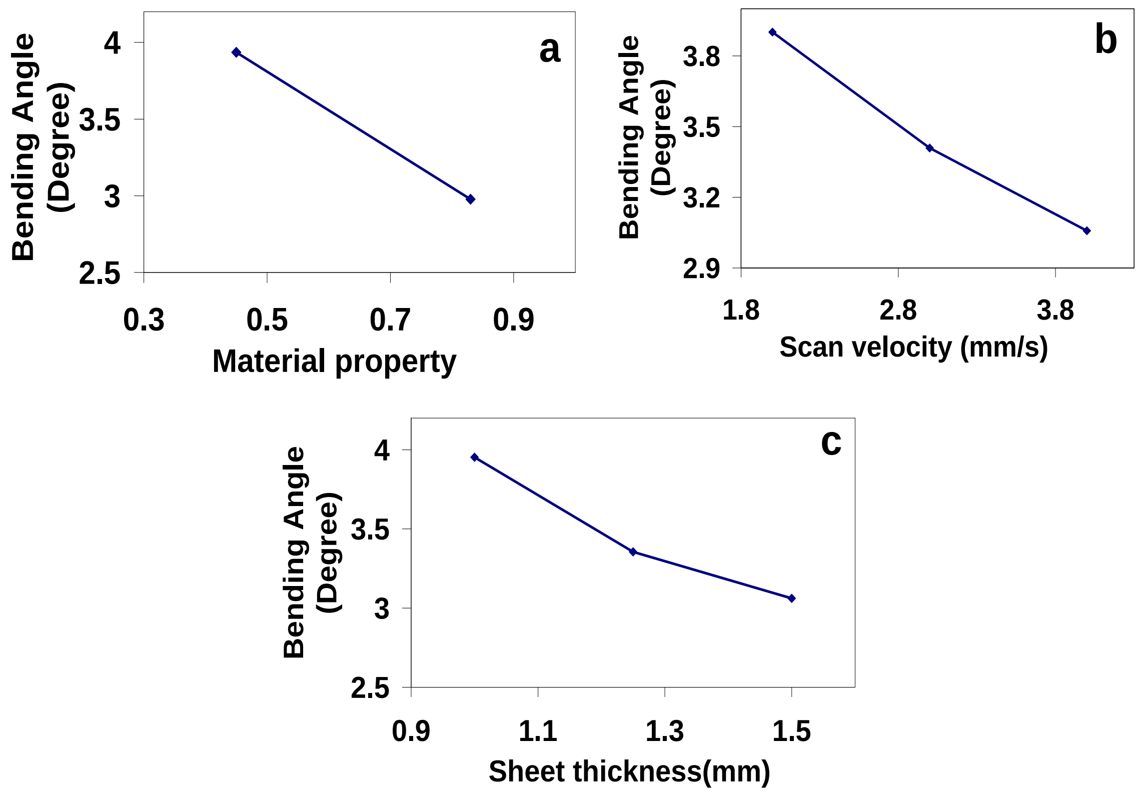

Figure 5. Plot of main effects on bending angle (a, b and c).

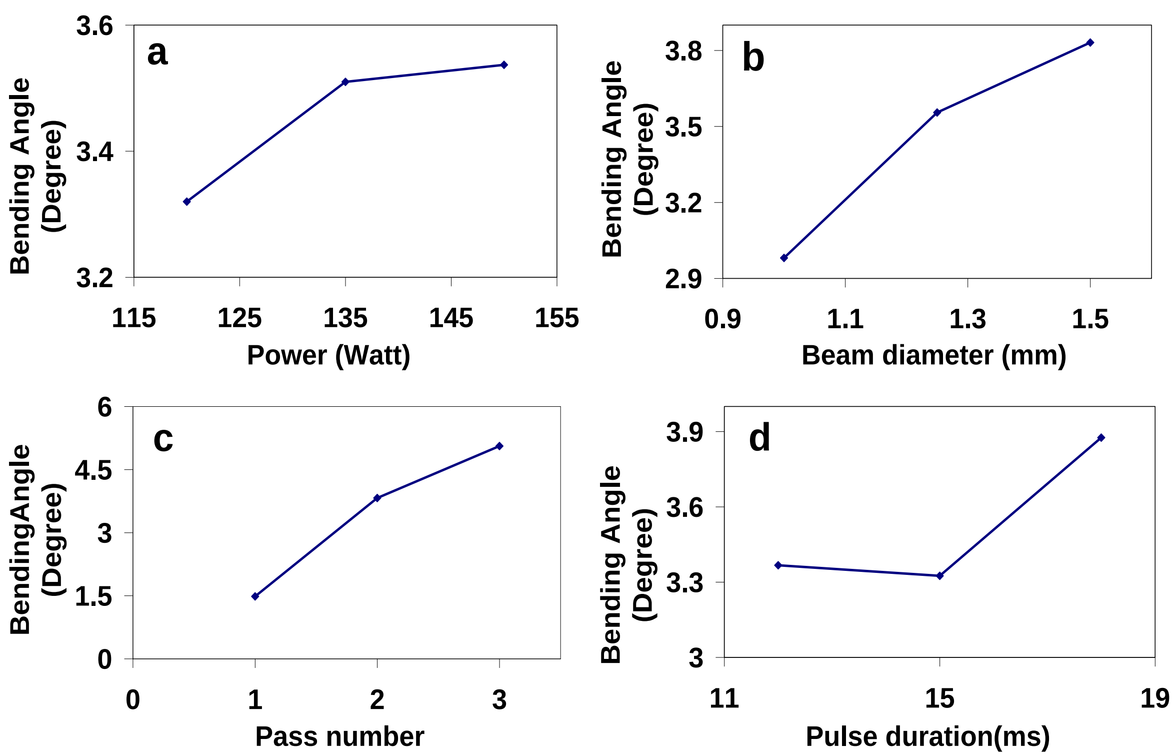

Figure 6. Plot of main effects on bending angle (a, b, c, d).

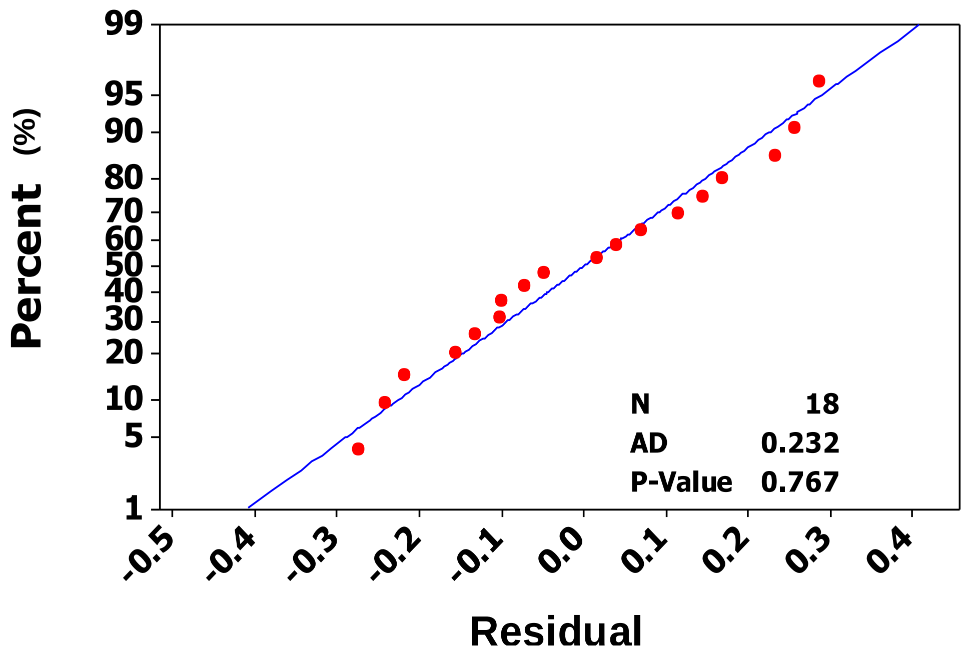

Figure 7. Normal plot of residuals.

iii) Variance is constant.

It is necessary to check the aforementioned three assumptions before performing ANOVA. The normal probability plot of residuals for bending angle, Anderson-Darling (AD) statistic and p-value is displayed in Figure 7. A normal probability plot is a graph of the cumulative distribution of the residuals on, that is graph paper with the ordinate scaled so that the cumulative normal distribution is plotted as a straight line. In this figure:

$$P_k = (k - 1/2)/N \qquad 2$$

In which P_k is calculated for the kth point, while there are N data points in total. Straight line in Figure 7 is the bell like normal distribution which is plotted on normal probability paper. The P-value and AD statistic are used to examine the conformity of experimental data to the normal distribution. The P-value is the probability of obtaining a test statistic that is at least as extreme as the actual calculated value, assuming that the null hypothesis is true. It is used in hypothesis tests to determine whether a null hypothesis should be rejected or accepted. The commonly used cut-off value for the P-value is 0.05. If the calculated P-value of a statistic test is less than 0.05, the null hypothesis will be rejected (Mason et al., 2003). In Figure 7 the P-value is higher than α-level of confidence (0.05), it can be concluded that the residual (error) is normally distributed. The distribution shown in Figure 7 demonstrates that the error normality assumption is valid. The other two assumptions are shown to be valid by means of plot of residuals versus fitted values. This plot is illustrated in Figure 8. The structureless distribution of dots above and below the abscissa (fitted values) in Figure 8 illustrates both the error independency and variance constancy (Montgomery, 2000). Now that the assumptions are proved not to be violated through this experimentation, ANOVA results listed in Table 4 can be trusted.

The symbols in this table are defined as follows (Montgomery, 2000): DF: degrees of freedom; Seq SS: sequential sum of squares; Adj SS: adjusted sum of squares; Adj MS: adjusted mean squares; F: f-value); P: p-value. Confidence level is chosen to be 95% in this study. So the P-value which is less than 0.05 indicates that the effect of the respective factor is significant.

Regression analysis

Regression analysis was performed to find out the relationship between factors and the bending angle. A second order polynomial equation may predict the result satisfactorily. The regression equation in terms of factors (Table 2) is obtained as follows:

$$\theta = 15.1 - 0.477\,M + 0.0012\,P - 0.84\,V + 7.66\,S - 7.86\,T + 4.01\,N - 1.74\,D + 0.000002\,P^2 + 0.070\,V^2 - 2.38\,S^2 + 2.43\,T^2 - 0.554\,N^2 + 0.0552\,D^2 \qquad (3)$$

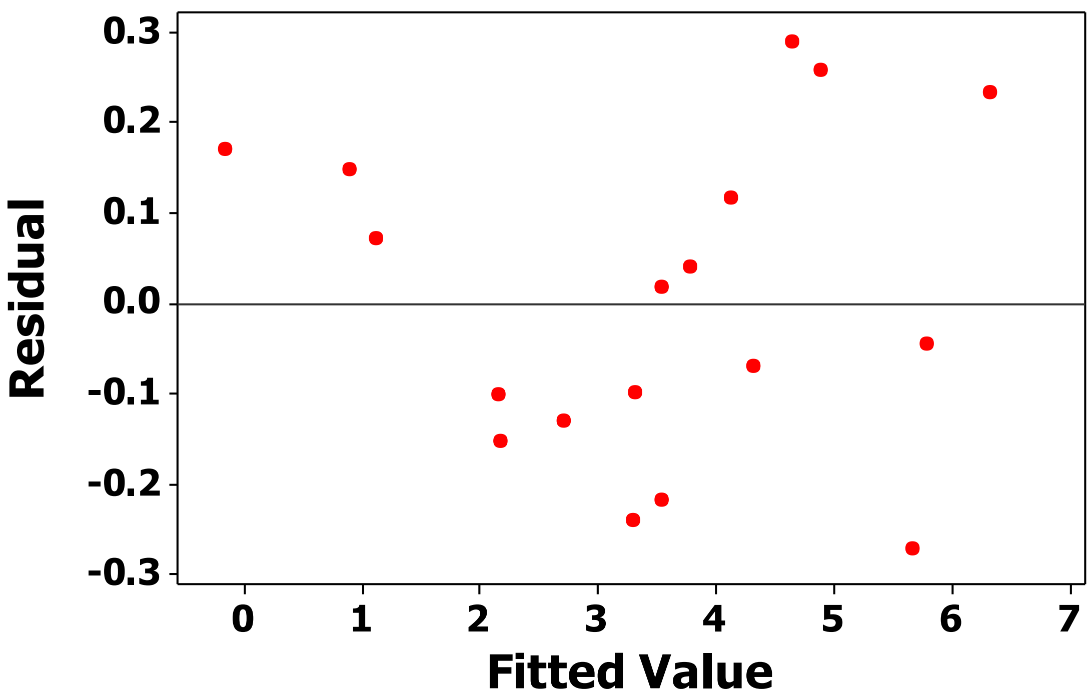

Figure 8. Residuals versus the fitted value.

Table 4. ANOVA for bending angle.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
M	1	4.1319	4.1319	4.1319	31.32	0.005
P (W)	2	0.1676	0.1676	0.0838	0.64	0.576
S (mm)	2	2.1500	2.1500	1.0750	8.15	0.039
V (mm/s)	2	2.2588	2.2588	1.1294	8.56	0.036
T (mm)	2	2.4756	2.4756	1.2378	9.38	0.031
N	2	39.5821	39.5821	19.7911	150.00	0.000
D (ms)	2	1.7646	1.7646	0.8823	6.69	0.053
Error	4	0.5278	0.5278	0.1319		
Total	17	53.0584				

Table 5. ANOVA regression analysis.

Source	DF	SS	MS	F	P
Regression	13	52.5306	4.0408	30.63	0.002
Residual error	4	0.5278	0.1319		
Total	17	53.0584			

R^2 (= $SS_{Regression}/SS_{Total}$) and $R_{adj}{}^2$ statistics are used to assess the best order of the polynomial. R^2 indicates how well the model fits the data. These values are calculable for different orders of regression equations. Predicted R^2 is between 0 and 1. Larger values of predicted R^2 suggest models of greater predictive ability. Table 5 shows the ANOVA table for regression analysis.

This table indicates that the model estimated by regression procedure is significant at the α-level of 0.05 (Mason et al., 2003).

Determination of the optimal condition

Optimal condition is detected by means of the signal-to-noise (S/N) ratio method. The rationale behind this method is to find a condition under which the effect of signals (controllable factors) is the greatest of all compared with effects of noises (uncontrollable factors). S/N ratio statistic (η) can be obtained by using Equation 4:

$$\eta = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2}\right) \quad (4)$$

Where y_i is the ith observation of a treatment combination and n is the number of replications. The factor level which produces the largest η is detected as the factor level which pertains to the optimal condition. Accordingly, the optimal levels of factors would be equal to 1, 2, 1, 3, 1, 3 and 1, respectively. The corresponding value of each factor level can be found when referring to Table 1.

Conclusions

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.

REFERENCES

ASM Metals Handbook (1990). ASM International, 10th Edition.

Brown S, Song H (1992). Finite element simulation of welding of large structures. J. Eng. Ind., 114(4): 441-451.

Chen DJ, Wu SC, Li MQ (2004). Studies on laser forming of Ti–6Al–4V alloy sheet. J. Mater. Process. Technol., 152: 62-65.

Cheng PJ, Lin SC (2001). An analytical model to estimate angle formed by laser. J. Mater. Process. Technol., 108: 314-319.

Hennige Th (2000). Development of irradiation strategies for 3D-laser forming. J. Mater. Process. Technol., 103:102-108.

Hsieh HS, Lin J (2004). Thermal–mechanical analysis on the transient deformation during pulsed laser forming. Int. J. Mach. Tools Man., 44: 191-199.

Hu Z, Kovacevic R, Labudovic M (2002). Experimental and numerical modeling of buckling instability of laser sheet forming. Int. J. Mach. Tools Man., 42: 1427-1439.

Kyrsanidi AK, Kermanidis TB, SG Pantelakis (2000). An analytical model for the prediction of distortions caused by the laser forming process. J. Mater. Process. Technol., 104: 94-102.

Mason RL, Gunt RF, Hess JL (2003). Statistical design and analysis of experiments. John Wiley & Sons, Hoboken, New Jersey.

Minitab Release 15 (1997). User Guide, Data Analysis and Quality Tools, Minitab Inc.

Montgomery DC (2000). Design and Analysis of Experiments. John Wiley & Sons.

Phadke MS (1989). Quality Engineering Using Robust Design. Prentice-Hall, Englewood Cliffs, New Jersey.

Raymond HM, Ronald EW (1978). Probability and Statistics for Engineers and Scientists. Macmillan Publishing Co. New York.

Shichun W, Zhong J (2002). FEM simulation of the deformation field during the laser forming of sheet metal. J. Mater. Process. Technol., 121: 269-272.

Thomson G, Pridham M (1998). Improvements to laser forming through process control refinements. Opt. Laser Technol., 30: 141-146.

Zhang L, Michaleris P (2004). Investigation of Lagrangian and Eulerian finite element methods for modeling the laser forming process. Finite Elem. Anal. Des., 40: 383-405.

Zhang L, Reutzel EW, Michaleris P (2004). Finite element modeling discretization requirements for the laser forming process. Int. J. Mech. Sci., 46: 623-637.