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Laser forming of bi-layer Fe/Al sheet by Nd: YAG laser

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ABSTRACT

Laser forming is a modern metal forming method in which no mechanical force is needed. In this paper, numerical and experimental approaches to this phenomenon on were conducted. Numerical method comprised of couple heat-displacement. In it, heat flux distribution of laser beam was applied on the steel layer in Gaussian form and by using subroutine code writing procedure. Experimental tests were conducted by using Nd: YAG laser with maximum power of 300 watts and on a bi-layer Fe/Al work piece. The result of bending angle at different laser power ranges indicated that bending angle increases occur as this parameter is increased.

1. Introduction

Laser Forming (LF) phenomenon is a new technique that has been used since early 1990s. This process is mainly used for sheet metal forming. Its base is on producing heat stress by laser beam radiation on the sheet (Namba, 1985). Many complex parameters of laser beam characteristics, e. g. power, wave length, laser beam diameter, and laser beam velocity are among parameters governing this process. Moreover, other characteristics like thermal and mechanical properties of the work piece such as coefficient of heat absorption and conductivity have effect on the LF process (Scully, 1987; Shen & Vollertsen, 2009).

Perhaps, the greatest advantages of utilizing LF process compared to more traditional techniques are flexibility as well as cost and time reduction in the production of work piece (Frackiewicz, 1993; Geiger, 1994; Walczyk & Vittal, 2000; Watkins, 2001). Since no tool and die are necessary for this process, hence, cost associated with these elements does not exist. On the other hand, through laser forming, locations hard to be accessed by traditional forming methods could also be reached. Forming of geometrically complex parts as well as forming brittle alloys is other positive points of this new method (Vollertsen, 1994; Magee, 1997; Widlaszewski, 1997; Edwardson, 2001)

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Although, most studies conducted on this issue have concentrated on bending the sheet along a straight line, however, this process could be used to produce complex geometrical shapes such as strip form hemisphere, saddle back, conical and spiral (Hennige, 1997; Magee et al., 1999; Hao & Li, 2003 a, b; Safdar, 2007; Peng, 2009; Silve, 2013)

Vollertsen and Geiger for the first time recommended three major mechanisms to express thermal-mechanical behavior of materials in this process. Each mechanism was related to the work piece geometry as well as laser condition. These procedures included Temperature Gradient Mechanism (TGM), Buckling Mechanism (BM), and Upsetting Mechanism (UM) (Shen & Vollertsen, 2009).

Numerical studies are among fields of interest for researchers. Perhaps main reasons for this interest could be flexibility in addition to very wide application range. In this investigation, numerical analysis of Laser Forming of bi-layer Fe/Al sheet is studied. Finite element software ABAQUS version 6.10.1 in particular was used for this purpose. In proceeding, in order to study effect of different parameters on the process and also reducing the number of simulations, Design of Experiment (DOE) with Taguchi method was used. To do this, Minitab software, version 16 was used.

In experimental tests, an Nd: YAG laser with maximum energy of 300 watts was used and laser beam was applied on the steel surface of the bi-layer Fe/Al sheet. Power, velocity and desired laser beam diameter was determined with initial experiments. Then, all parts were laser formed and amount of deflection for each part was measured.

2. Numerical Analysis of the Process

The work piece used in the experiment was a bi-layer Fe/Al sheet. Its dimensions were $105 \times 60 \times 2.105\text{mm}^3$. Thickness of aluminum and steel layers were 0.65 and 1.445 mm consecutively. Fig. 1 depicts the geometrical dimension of the studied bi-layer sheet. In the analysis conducted, it was presumed that initial work piece was completely flat, smooth, homogenous and isotropic.

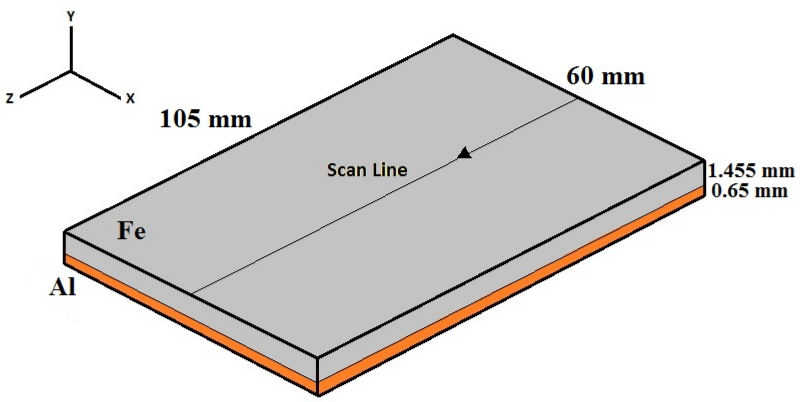


Fig. 1. Schematic of the piece under study

The mechanical model for both steel and aluminum layers were presumed to be perfectly elastic-plastic without presence of any work hardening. In the laser forming of sheet metals, there is no mechanical force present. Thus, all bending force is derived from the heat gradient through laser radiation. Therefore, the surface heat flux of laser is the only source of forming. In order to the analysis, the Gaussian heat flux has been used in accordance with Eq. (1).

$$I(x,y) = \frac{2P}{\pi r_0^2}\, exp\left(\frac{-2[(x-x_0)^2 + (y-y_0)^2]}{r_0^2}\right) \tag{1}$$

In which P is the laser's power, r_0 is the radius of laser beam, and (x_0, y_0) is coordinate of the laser beam center.

In the all conducted simulations, 3-D hexagonal linear element with eight nods (C3D8T) was used. In order to increase the precision of analysis, meshing of the area affected by the heat flux were smaller and other elements were deliberately selected larger to reduce the time of analysis. Fig. 2, depicts the meshing of the work piece.

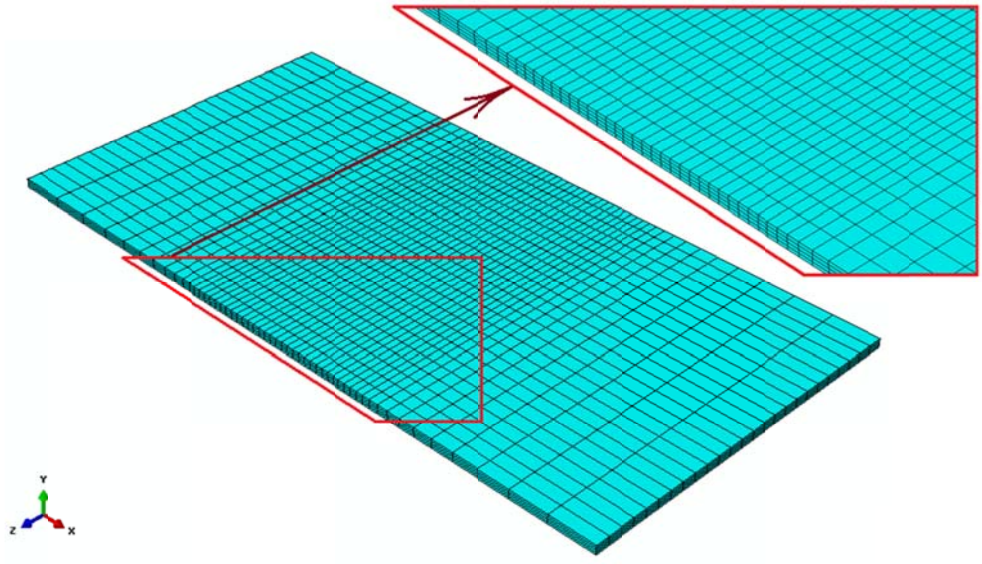


Fig. 2. Meshing of the work piece

Solving of this problem was with regarded to the heat- displacement coupling and in transient shape. In order to provide more precision, the non-linear solution was used. Cooling time of the sheet was 20 seconds immediately after crossing of laser beam over the work piece.

3. Statistical Analysis of the Process

Design of experiment (DOE) is defined as: providing a combination of objective oriented changes in the inlet or characteristics of a process leading to study of their effects on the outlet. Taguchi method is a common DOE method having its own principles. Through utilizing this method, it would become possible to obtain effects of different parameters on the final outcome. This causes the number of experiments to get reduced, which resulted in saving of both time and money (Montgomery, 2000).

Important parameters considered here were: power, scanning velocity as well as laser beam diameter. Each one of these parameters was defined in three levels. Table 1, provides list of parameters in three different levels.

Table 1. Parameters and different levels of DOE

Factors	Level 1	Level 2	Level 3
P (W)	150	225	300
V (mm/s)	5	7	10
D (mm)	1.6	2.1	2.6

4. Experimentations

Water jet cutting process was used for preparing samples in desired dimensions to provide minimal amount of residual stress. Next, in order to de-grease and clean the minute amount of oxidation residues on the surface, initially, work pieces were placed in the bath tub containing sodium hydroxide (NaOH) of 5% intensity for a period of 30 minutes. Then, surfaces were cleaned by Ethanol and Acetone.

The Nd: YAG laser used herein was 300 watts with brand of HAN*S LASER. Frequency spectrum of this laser was between 1-1000Hz with pulse duration of 0.02-20ms and pulse energy of 0-30 J. Since this machine contains a suitable fixture, there was no need for re-design. Fig. 3 shows the laser machine used in this process.

Fig. 3. Nd: YAG laser machine used in the process

The laser beam diameter in TGM mechanism should be within the range of work piece thickness. Therefore, initially, the nuzzle of laser were placed at a determined distance from a wooden sheet and moved a short distance. By measuring the affected surface, suitable distance from work piece was realized.

By applying the appropriate parameters, designed experiments were conducted, and obtained results will be explained later. Fig. 4 depicts sample of the work pieces formed by laser.

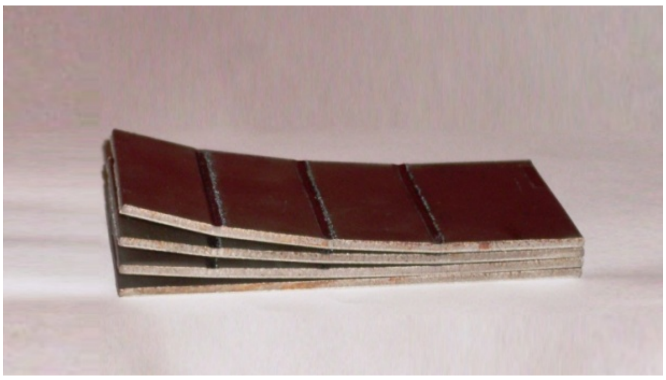


Fig. 4. A sample of formed work pieces via using Nd: YAG laser

5. Discussions

Since a key factor in the process of laser forming is heat transfer and its distribution, as a result, studying it has the utmost importance. In Fig. 5A, temperature distribution on the surface of the bi-layer Al/Fe sheet is presented. As shown, maximum temperature of the work piece is in the center of laser beam. Figs. 5B and 5C show temperature distribution of work piece's thickness along laser movement and in vertical position with respect to it.

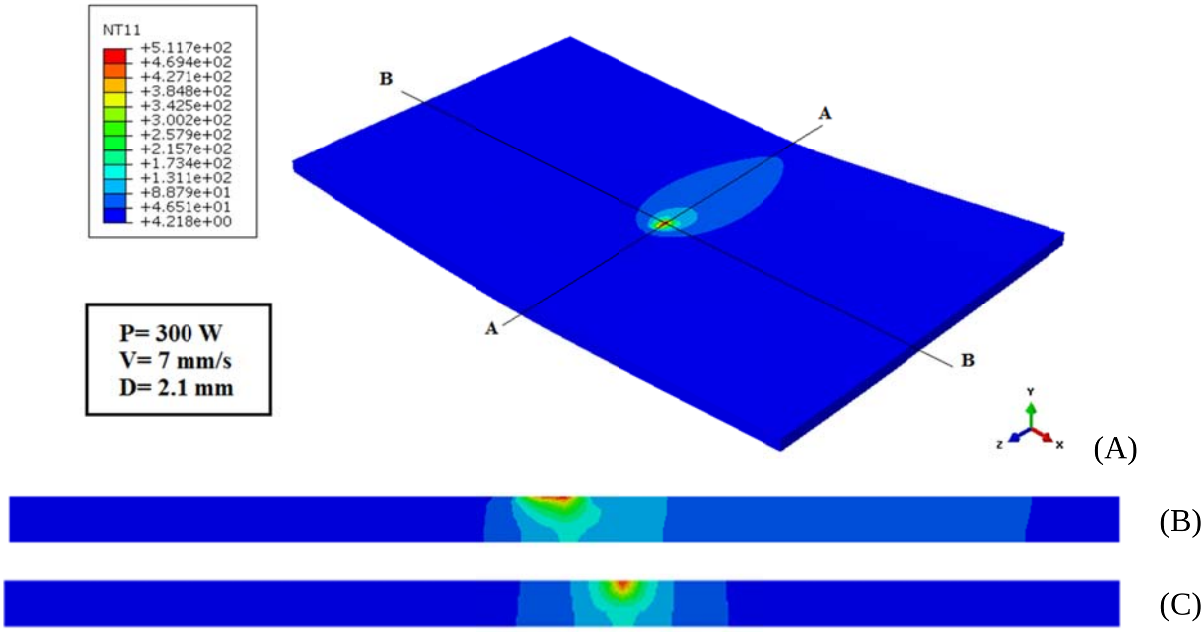


Fig. 5. Temperature distribution of the work piece A. on the surface, B. Along A-A, and C. along B-B

In order to study the work piece temperature in the middle of process, 9 distinct paths on three surfaces of the bi-layer Al/Fe sheet were defined as shown in Fig. 6. Figure 7 depicts the obtained results.

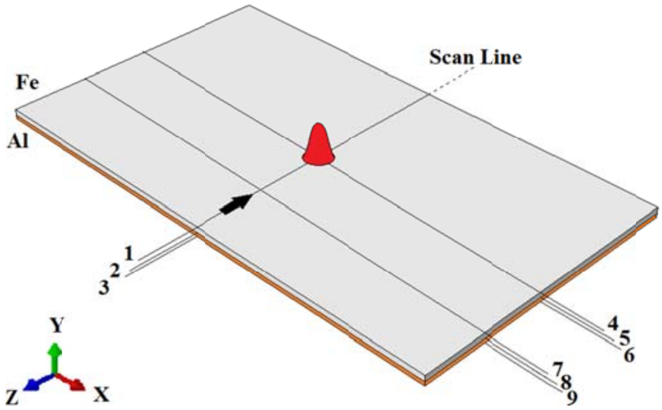


Fig. 6. Intended paths for surveying temperature distribution

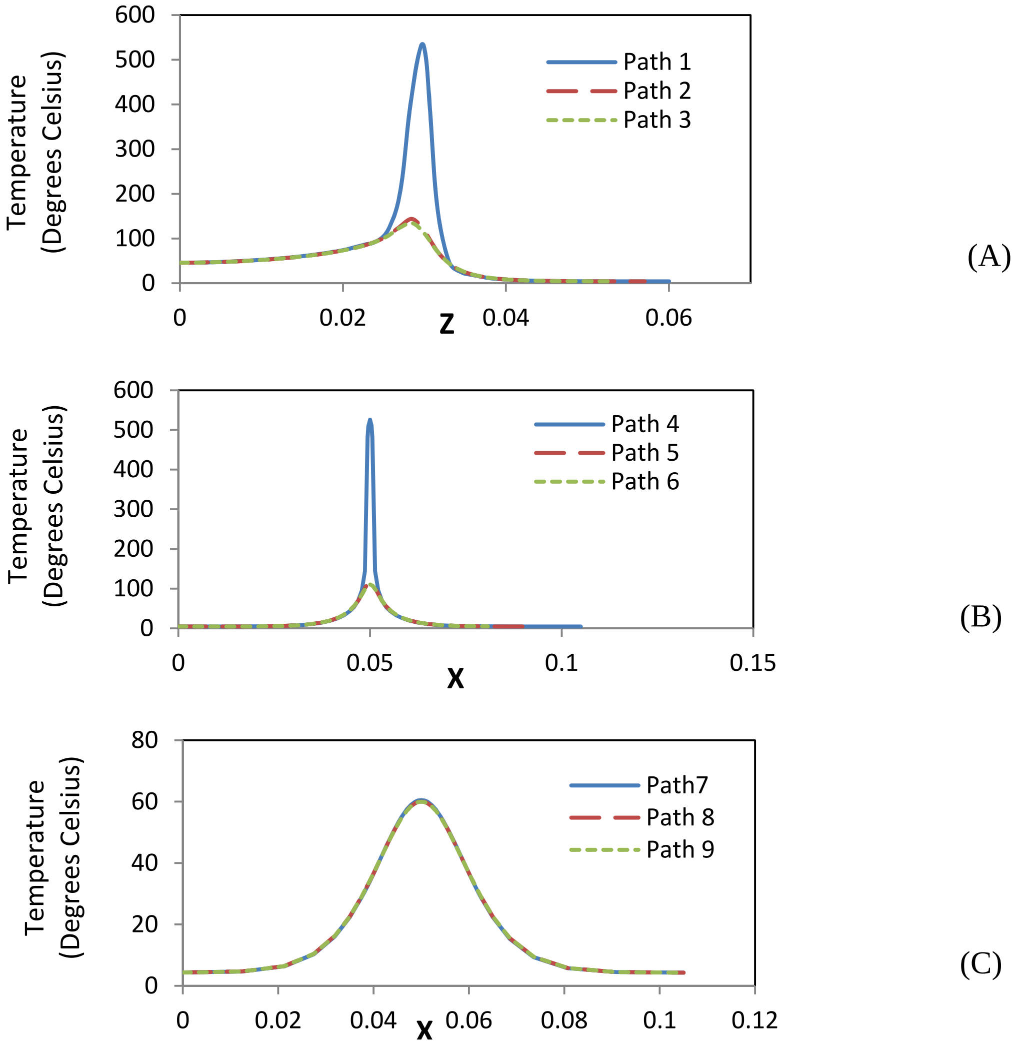


Fig. 7. Temperature distribution of the work piece at mid-process. **A.** Along laser path, **B.** Along vertical path on laser, and **C.** Along vertical path on laser and after passage of heat flux

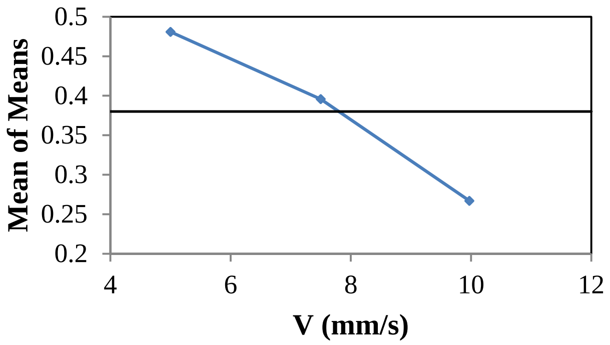
As for the three paths 1, 2 and 3, as expected, maximum temperature was along path 1. Afterwards, temperature was drastically reduced along paths 2 and 3. Due to low thickness of aluminum layer and having higher conductivity and specific heat, there is almost no difference along these two paths. About paths 4 through 9, due to axisymmetric nature of the problem, diagrams have also turned out to be symmetric. As explained about the previous three paths, maximum temperature was in path 4. Paths 5 and 6had almost equal conditions. Regarding paths 7, 8 and 9, it is obvious that in light of sufficient time allowed coupled with high conductivity of both aluminum and iron, temperature distribution occurs to a great extent.

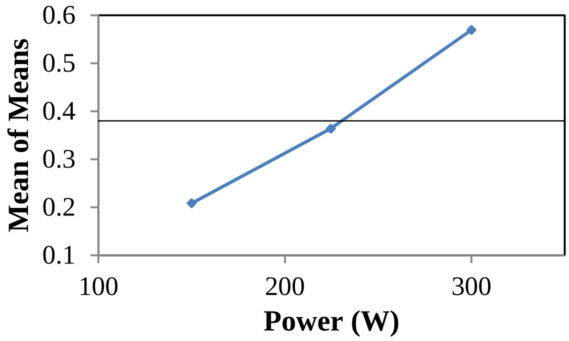
Table 2 depicts arrays obtained from the design of experiment as well as results from numerical solution and statistical analysis of the process. In order to analyze these results, main effect plots for means were extracted according to Fig. 8. As depicted in Fig. 8A, increasing in laser power causes increase in the bending angle. Also, according to Figs. 8B and 8C, this amount reduces as scanning velocity and laser beam diameter increase.

Another useful outcome of the statistical analysis capable of providing much information is the contours of the work piece bending angle based on main effect parameters, shown in Fig. 9. Figure 9A, shows the bending contour of the work piece on the basis of two parameters: power and laser scanning velocity. As shown, increasing in power as well as reduction in the scanning velocity, cause a higher bending angle in the work piece. The reason for this occurrence is in increasing of temperature gradient in work piece thickness and as a result, intensifying the TGM mechanism. Fig. 9B is also indicative of the same finding equally. It is clear that highest bending angle was made when laser power was maximum and laser beam diameter was minimum. This is due to the intensification of temperature gradient in the work piece thickness. The contour of bending angle on the basis of velocity and laser beam diameter is shown in Fig. 9C. Since, increasing in both these parameters cause reduction in the bending angle, it is clear that most bending angle occurred when both were minimal.

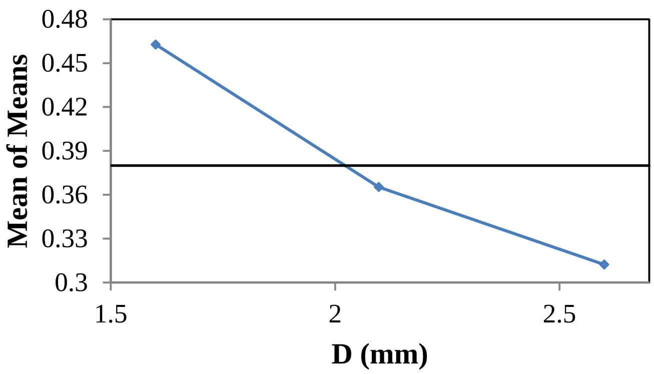
Table 2. Arrays obtained from the DOE, numerical results and its difference

Number of experiments	Power (W)	Scan Velocity (mm/s)	Beam Diameter (mm)	Bending Angle of Simulation (℃)	**Relative difference** of Simulation and DOE
1	300	7	2.1	0.5676	**1.40%**
2	300	5	1.6	0.7788	**5.48%**
3	300	10	2.6	0.3581	**3.76%**
4	225	7	1.6	0.4351	**7.82%**
5	225	5	2.6	0.3971	**2.32%**
6	225	10	2.1	0.2646	**0.28%**
7	150	7	2.6	0.1846	**24.48%**
8	150	5	2.1	0.2645	**13.45%**
9	150	10	1.6	0.1719	**7.44%**





(B) (A)



(C)

Fig. 8. A-C. Diagram of main effect plots for means

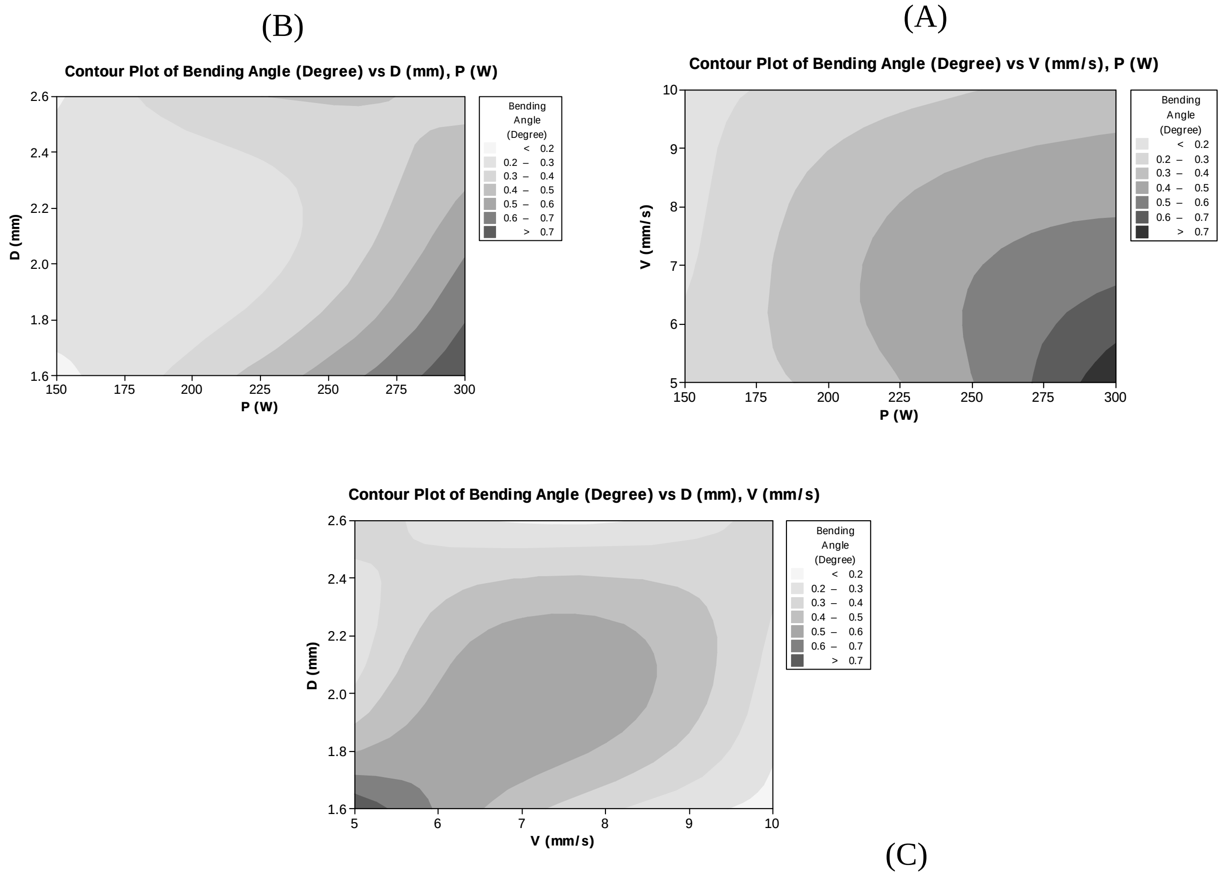


Fig. 9. A-C. Bending angle contours based on main parameters

In experimental studies, in order to bend the work piece, an Nd: YAG laser, with the maximum power of 300 watts was used. The characteristics of this laser were demonstrated previously. Used parameters in this experiment are depicted in Table 3. These values were selected in light of laser forming mechanism and conducted experiments. Full details of which were presented in the previous section.

Obtained results from conducted experiments based on the above mentioned parameters are presented in Fig. 10. Also, obtained results of the numerical analyses are provided herein. As shown, increase in laser power has had to increase in the bending angle of the work piece. This trend was also realized through numerical analyses of the laser forming process. However, it is obvious that real value of bending is always slightly higher than the value obtained by finite element method. Reason for this lies within the assumptions made when applying the materials’ properties and definition of the problem condition.

As an example, in simulation of this process, initial stresses of the work piece as well as presence of inhomogeneities and non-axisymetric of locations were not considered.

Table 3. Used parameters for conducting laser forming experiments

Power (W)	Velocity (mm/s)	Frequency (Hz)	Pulse Duration (ms)	Beam Diameter (mm)
130~300	7	29	11	2.1

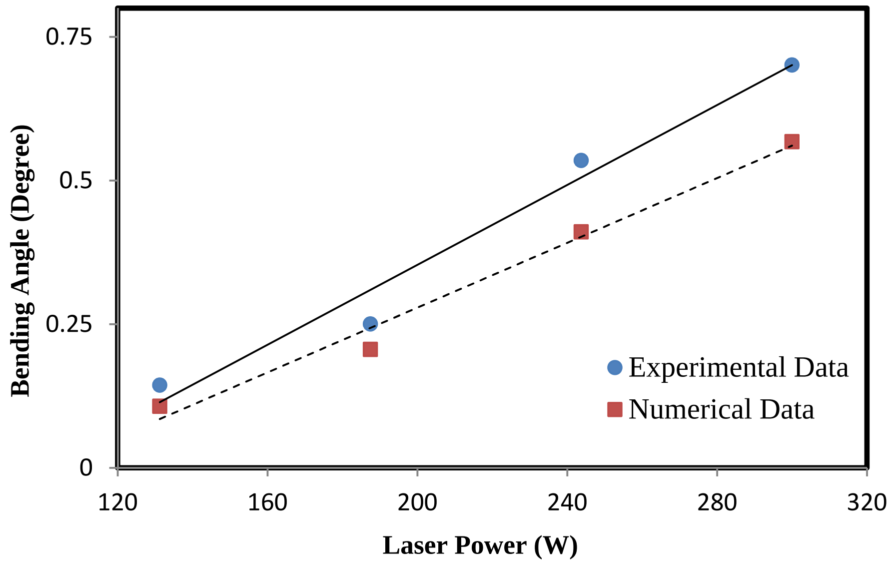


Fig. 10. Experimental results and its comparison with numerical solution of the process

6. Conclusion

In this study, numerical, statistical, and experimental analysis of bi-layer sheet metal laser forming was conducted. Fe/Al sheet was laser formed by utilizing a 300 watts Nd: YAG laser. Dimensions of work piece were $60 \times 105 \times 2.105\ mm^3$in which Fe and Al layers thickness were 1.455 mm and 0.650 mm. In the numerical analysis, laser beam was applied as Gaussian heat flux in the software. Reviewing heat contour indicated that maximum temperature of the work piece is in the middle of the laser beam, on the surface of Fe layer. Also, it was noticed that heat gradient in the lower level made from aluminum was minute. Perhaps, this could be due to the lower conductivity of aluminum compared to that of iron.

In order to design the experiment, Taghuchi method and L9 array was used. Thus, three parameters of power, velocity and diameter of laser beam at three different levels were considered.

Reviewing of main effect plots for means and displacement contours indicated that increasing the laser power causes rise in the bending angle as well as increasing velocity, at the same time, increases in laser diameter causes reduction in the bending angle.

In the end, comparison of obtained results from work pieces bending angle through numerical analysis as well as experimental tests was made. Rate of increase in the bending angle from experimental measurements was on the average equal to 0.0038 degree/ W. This indicated good confirmation with the obtained results from numerical analysis.

References

Edwardson, S. P., Watkins, K. G., Dearden, G., & Magee, J. (2001). 3D laser forming of saddle shapes. *Proceedings of Laser Assisted Net Shaping*, 559-568.

Frackiewicz, H. (1993). Laser metal forming technology. *FABTECH INTERNATIONAL, Illinois, 93,* 723-747.

Geiger, M. (1994). Synergy of laser material processing and metal forming. *CIRP Annals-Manufacturing Technology*, 43(2), 563-570.

Hennige, T. (1997). Laser forming of spatially curved parts. *Proceedings of the LANE*, 409-420.

Hao, N., & Li, L. (2003a). An analytical model for laser tube bending. *Applied Surface Science*, 208, 432-436.

Hao, N., & Li, L. (2003b). Finite element analysis of laser tube bending process. *Applied surface science*, 208, 437-441.

Magee, J. (1997). Laser forming of aerospace alloys. *ICALEO*, 156-165.

Magee, J., Watkins, K. G., & Hennige, T. (1999). Symmetrical laser forming. *Proceedings of ICALEO*, 77-86.

Montgomery, D. C. (2008). Design and analysis of experiments. *John Wiley & Sons*.

Namba, Y. (1985). Laser forming in space. *Proceedings of International Conference on Lasers*, 403-407.

Peng, Z., Jingbo, Y., & Hongwei, Z. (2009). Deformation Behaviour of Laser Forming of Ring Sheet Metals. *Tsinghua Science and Technology*, 132-136.

Safdar, S., Li, L., Sheikh, M. A., & Liu, Z. (2007). Finite element simulation of laser tube bending: Effect of scanning schemes on bending angle, distortions and stress distribution. *Optics & Laser Technology*, 39(6), 1101-1110.

Scully, K. (1987). Laser line heating. *Journal of Ship Production*, 237-246.

Shen, H., & Vollertsen, F. (2009). Modelling of laser forming-An review. *Computational Materials Science*, 46(4), 834-840.

Silve, S. (2013). Laser forming and creative metalwork.

Vollertsen, F. (1994). Mechanisms and models for laser forming. *Proceedings of the LANE*, 345-359.

Walczyk, D. F., & Vittal, S. (2000). Bending of titanium sheet using laser forming. *Journal of Manufacturing Processes*, 2(4), 258-269.

Watkins, K. G., Edwardson, S. P., Magee, J., Dearden, G., French, P., Cooke, R. L., ... & Calder, N. J. (2001). Laser forming of aerospace alloys (No. 2001-01-2610). SAE Technical Paper.

Widlaszewski, J. (1997). Precise laser bending. *Proceedings of the LANE*, 393-398.