Aero2015P142

Numerical Simulation of Power, Movement Speed and Laser Beam Diameter in Forming Process of FGM Plates According to the Exponential Law

H. MADANI NASAB [1], S. GOLABI [2]
1- PhD Candidate, School of Mechanical Engineering, Kashan University, Kashan, Iran
2- Associate Professor, School of Mechanical Engineering, Kashan University, Kashan, Iran

Abstract:
Functionally graded materials (FGMs) are made of advanced composites in which the material properties vary continuously and smoothly in a structure. Laser bending is an advanced process in sheet forming in which a laser heat source is used to shape FGM plate. Laser forming of functionally graded metal –metal plates offers the advantages of requiring no external forces and thus reduces cost and increases flexibility. FGM plate forming by using a modern laser technique is taken into consideration in this paper. It is assumed that the material property of each plate varies exponentially through the thickness. This paper presents a numerical model to estimate the angle bent during the laser forming of a FGM plate. Finite element (FE) simulation is performed with the ABAQUS/CAE standard software package. Three dimensional nonlinear coupled thermo-mechanical solid elements with eight nodes C3D8T are used for thermal and structure analysis. For the analysis, the same mesh model is used. According to the law of the change in the properties of FGM material in line with the sheet thickness, the subroutine for the application of matter specifications (VUMAT) is used to define matter. By using finite element simulation, the effects of movement speed, laser diameter and laser power on the value of the FGM plate transverse bending angle are investigated. By comparing the simulation with analytical formulas, it is observed that the FE results are in good agreement with the analytical results. Plastic deformation is considered during both heating and cooling and is calculated based on a history-dependent incremental stress–strain relationship. On the basis of the proposed model with known temperature distributions, the bending angle induced by laser can be calculated. Comparison of the present model with analytical data is provided to demonstrate the accuracy of the present model under TGM.

Keywords: *Laser forming, Functionally graded materials (FGM), Transverse bending, Finite element simulation.*

Introduction

The process of laser forming is considered a novel method in forming plates. Since the early 1980s, a novel application has been discovered for using laser beam in forming complex pieces. In the early 1990s, computerized one-dimensional simulation of metal forming by laser beam was conducted at Earlangen University in Germany for the first time. Effects such as heat transfer and bending angle were studied in this research [1]. Plenty of pieces with unique specifications in the area of electricity, light, magnetism, and biochemical materials are made of functionally graded materials (FGM). Scientists have analyzed the behavior of the panels and the shells made of the FGM [2]. By producing variable coatings by some methods including laser and/or plasma, some conditions are created so that the piece can resist thermal stresses. It is worth mentioning that the FGM matter can be formed by combining two metals. Aluminum/steel electric transition joints are used in aluminum reduction cell for the aim of welding steel bracket and aluminum rod components. Researchers have recently been able to make FGM matter by combining steel 304 and aluminum 2024. The method employed for the manufacture of this combination is powder metallurgy [3]. With regard to the importance of laser forming process in forming FGM steel made of steel 304 and aluminum 2024 and its application in different industries such as aerospace, the effects of laser movement speed, laser diameter and laser power on the plate bending angle are studied. By comparing the simulation with the analysis formulas, it becomes clear that the simulations performed are very close to the formulation.

Principles of forming by laser beam

Fig. 1 shows the general view of laser forming process along with the bending angle produced [4]. The applied energy is also a function of the laser beam scanning speed and heat flux. The thermal load generated by the laser radiation is applied in the form of a Gaussian heat flux on the surface of the FGM plate [5]:

$$\mathrm{I}=\frac{2\mathrm{AP}}{\pi \mathrm{r}_{\mathrm{b}}^{2}}\exp\left(-\frac{2\mathrm{r}^{2}}{\mathrm{R}^{2}}\right) \qquad (1)$$

where A is the laser absorption coefficient, R the effective laser beam radius, r the distance from the center of the heat source, and P the laser power. Free convection and radiation boundary conditions occur on all surfaces. In this process, the major allotment of the cooling phase was done via convection. Convection boundary conditions are given by Eq. (2) [6].

$$\mathrm{q}_{\mathrm{c}}=\mathrm{h}_{\mathrm{c}}(\mathrm{T}-\mathrm{T}_{\circ}) \qquad (2)$$

where h_c is the heat transfer coefficient, which is equal to $10\ w/m^2\,k$, the surrounding temperature $T_{\circ}=20℃$, and T is the sheet surface temperature.

Also, heat transfer ‘‘q_r’’ via radiation was obtained by Eq. (3) [6].

$$q_r = \sigma \varepsilon_r (T^4 - T_\circ^4), \tag{3}$$

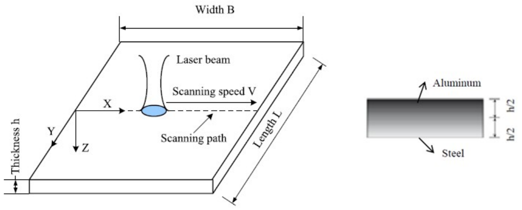

Fig. 1.FGM plate forming process by the laser beam.

where $\varepsilon_r = 0.4$ is the surface emissivity coefficient and $\sigma = 5.68 * 10^8\, W/m^2K^4$ is the Stefan Boltzman constant.

FGM modeling

Fig. (1) shows a FGP that measures $L \times B \times h$. A coordinate system (x,y,z) is established on the middle plane of the plate, and thematerial properties are assumed to alter through the thickness according to the Erdogan law[15]:

$$p_{al} = P_{\circ al} e^{\beta_1 n}$$
$$p_{stl} = P_{\circ st} e^{\beta_2 n}$$
$$p(z) = (p_{al} - p_{st})V_{al} + p_{st} \tag{4}$$
$$V_{al} = \left(\frac{1}{2} + \frac{z}{h}\right)^n \ (n \geq 0)$$

where P represents one of the effective material properties, such as Young’s modulus E, Poisson’s ratio ν, density ρ, thermal conductivity k, or thermal expansion α; the subscripts al and st represent the aluminum and steel metals, respectively; V_{al} is the volume fraction of the aluminum; n is the volume fraction exponent and β_1, β_2 is constant. For temperature-dependent materials, the corresponding properties are given by [7]

$$P = P_\circ (P_{-1} T^{-1} + 1 + P_1 T + P_2 T^2 + P_3 T^3) \tag{5}$$

Where $P_\circ, P_{-1}, P_1, P_2$ and P_3 are the temperature coefficients. With regard to the importance of application, performance accuracy, and production of FGM materials by using Reddy distribution, we modeled the plate in this paper. On the other hand, the mechanical and thermal problems are both solved in our model. Mechanical properties are also dependent on the coordinates and temperature.

Simulation of the process

Fig. (2) shows the volume fraction function of the FGM components in terms of dimensionless thickness for different powers. To simulate the laser forming process, the mechanical-thermal analysis is employed by using ABAQUS software. The element of thermal-displacement coupling was used for thermal analysis and plate element was used for mechanical analysis. In this paper, FGM with a combination of steel 304 and aluminum 2024 was used for modeling. We combine the mechanical-thermal properties of these two materials with regard to the structure of FGM material [8]. According to the law of the change in the properties of FGM material in line with the plate thickness, the subroutine for the application of matter specifications (VUMAT) is used to define matter.

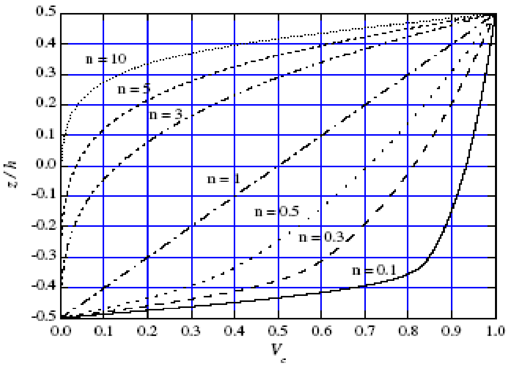

Fig. 2. Volume fraction versus thickness.

Fig. (3) shows the plate meshed model of FGM material in ABAQUS software. Of course, simultaneous changes of temperature and thickness should be taken into consideration in this program. Some assumptions, which we refer to later, are applied for laser forming process simulation. In addition, the heat generated due to plastic deformation is negligible compared to the laser focused energy. Additionally, the maximum temperature of the workpiece is below the melting temperature. As a presupposition, the external force is not applied to the workpiece. As mentioned earlier, the rectangular plate is of the FGM material. It is assumed that the workpiece is free of any residual stress. Also, the opaqueness of matter is due to the necessity for the absorption of laser energy, which is necessary and assumed. To define thermal flux generated along the laser heating and cooling, the subroutine program of thermal flux (DFLUX) is used. To better model the effect of heat, efforts were made to make the sections under the effect of heat have smaller elements compared to other sections during meshing. Selection of the other coarser sections is also done to accelerate the convergence and the solution of the problem. The resolution algorithm used in ABAQUS software for this process is the

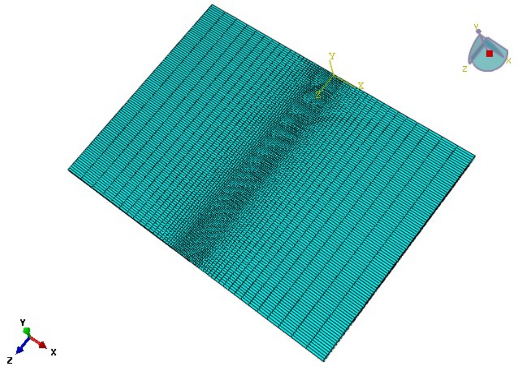

Fig. 3. 3-D model meshing of FGM plate.

thermal-displacement coupling algorithm. Bending angle contour over the FGM plate is shown in Fig. (4). As pointed out earlier, if the steel volume percentage parameter in Reddy formula is equal to zero, the thermal-mechanical properties related to pure aluminum is obtained. Specifications related to the numerical solution employed as the independent factor for the comparison of the results are presented in Table (1). Researchers have proposed theoretical models for the calculation of bending angle [9]. The related analyses are performed on steel304 and aluminum2024 samples sequentially. The bending angle obtained from simulation is compared with the formulas presented. After proving the correctness of simulation, the study of the parameters effective in the bending angel of the FGM material with a combination of steel 304-aluminum 2024 is carried out. The dimensions of the two models compared are 40*20*2 millimeters, simulation conditions with a 500-Watt laser, and laser movement speed of 50 mil/sec. The material of models 1 and 2 are steel 304 and aluminum 2024, respectively. By comparing the simulation with analytical formulas, it is specified that the finite element results are in good conformity with the analytical results.

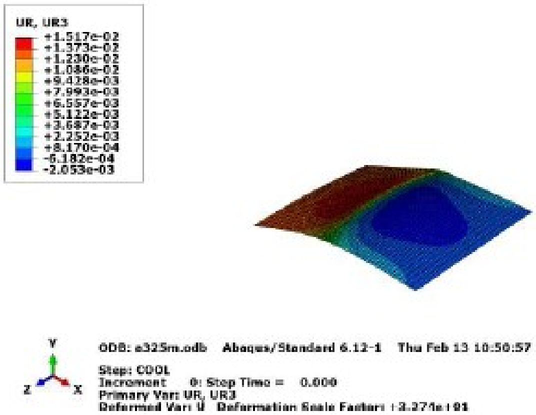

Fig. 4. Bending angle contour plot of the formed FGM plate, beam diameter =3.25 mm, q=250w/m^2, scan velocity=50mm/s, single path.

Table 1. Comparison of bending angle (degree) obtained from simulation by Geiger, Volresten, and Yan formulas

Model	Present	Geiger	Volreston	Yan
1	7.2765	8.0497	7.1625	7.2912
2	1.3344	1.2391	1.6719	1.2991

1. Results

The value of the beam linear speed and the laser diameter effectuate a change in the transverse deflection angle value. As observed in Fig. (5), the more the diameter of the laser beam is increased, the less the FGM steel bending angle is. One of the reasons is that due to an increase in the laser beam diameter, the laser beam will be more divergent and its focus on the scan region is reduced. Therefore, its effect on the bending angle is also reduced. This result is obtained for a plate model with a length, width, and thickness of 78, 55, and 2 millimeter, respectively. The specifications of the laser device including power and the speed of the laser scan are also 350 Watts and 50 mm/s, respectively. The above results are obtained for one time of laser scanning.

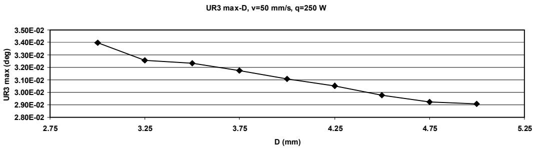

Fig. 5. The effect of the laser beam diameter on the bending angle of plates with a thickness of 2 mm.

The analysis of the effect of laser scanning speed on bending angle at a thickness of 5 mm, a power of 350 Watts, and a laser beam diameter of 3.25 mm can also be studied in Fig. (6). As observed in this figure, with an increase in the speed of laser scanning, we will have the same reduction in the bending angle for an increase in the laser movement speed. The trend of the effect of laser device movement speed also conforms to the physical analysis. In fact, the slower the speed of the laser movement, the more the effect of laser heat and conductive heat transfer rate on the FGM plate will be. As a result, with the constant cooling time at each of these stages, the plate bending rate will increase more. But, we also face some limitations to slow down the speed. To prevent the plate from reaching the critical melting point of aluminum present in FGM, there should always be an equilibrium between the two parameters of power and laser movement speed.

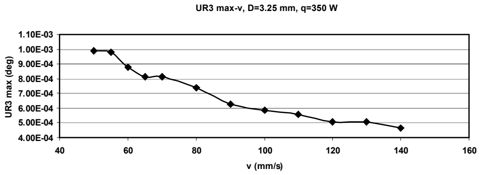

Fig. 6. The effect of the laser beam speed on the bending angle of plates with a thickness of 5 mm.

We prepare the plate model with a length and a width of 78 mm and 55 mm, respectively. To study the effect of the laser power on the maximum bending angle of FGM plate, we execute it on several thicknesses. As observed in Fig (7), with an increase in the laser device power, the bending angle increases further. With regard to the critical parameters mentioned, with the thickness of 3 mm, a speed of 50 mm/sec, and a laser beam diameter of 3.25 mm for the definite plate geometry from the point of length and width, it is observed that by increasing the laser device power, the maximum bending angle of FMG plate with a combination of steel and aluminum also increases.

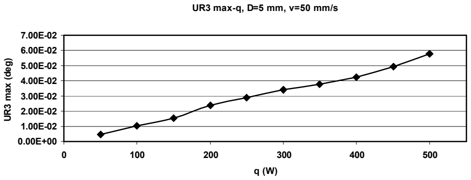

Fig. 7. The effect of laser power on the bending angle in plates with a thickness of 3 mm.

Conclusion

With regard to the simulation performed, the less the speed of scanning due to the absorption of more energy in time unit, the more the bending angle for each pass will be. Of course, it should be noted that this speed should not be so small that it leads to the elimination of the thermal gradient in the depth of the plate. Also, the resting time between the passes results in an increase in the thermal gradient generated in subsequent passes of the laser movement. This fact results in a more bending angle in the plate. Therefore, the rate of plate forming depends on parameters like scanning speed, resting time between passes, beam diameter, and as a result, the type of forming mechanism. Also, the more the laser beam diameter increases, the less the FGM plate bending angle will be. Simulation and software analyses of the process have shown that FGM elasticity is feasible if the components are selected of suitable materials with proper mechanical properties. Even in some cases, the results have shown that FGM elasticity in combination with steel and aluminum is better than that of pure materials. By comparing simulation with analytical formulas, it is specified that the simulations performed are very close to the formulation. With regard to the simulation, if the thickness of the plate increases, the bending angle is decreased. Therefore, the rate of plate forming depends on parameters like the laser power, the number of laser passes, and the plate thickness. The more the number of the laser scanning is increased, the more the tendency of the plate for bending and curving at the same rate will be. Also, the more the rate of the power of the laser forming device, the more the maximum bending angle will be.

NOMENCLATURE

α: Expansion coefficient
ε: Surface emissivity
h_c: Heat transfer coefficient
k: Thermal conductivity
NT11: Temperature distribution in FEM contours
q: Rate of the heat per unit area
t: Plate Thickness (mm)
$T_{\circ}$: Environment temperature
T: Plate temperature (℃)
UR3: Bending angle (deg)
V: Scan Velocity (mm/s)
D: laser beam diameter

References

[1] F.Vollersten, and S.Holzer, 3D-thermomechanical Simulation of Laser Forming, *Simulation of Material Processing: Theory, Methods and Applications*, pp.785, Balkema, Rotterdam, 1995.

[2] K.Y. Dai, G.R. Liu, K.M. Lim, X. Han, and S.Y. Du, A meshfree radial point interpolation method for analysis of functionally graded material (FGM) plates, *Computer Mech,* vol. 34,pp. 213–223, 2004.

[3] M. Nemat-Alla., H. Ata., R. Bayoumi., and W. Khair-Eldeen, Powder Metallurgical Fabrication and Microstructural Investigations of Aluminum/Steel Functionally Graded Material, *Material Sciences and Applications*, Vol. 2, pp. 1708-1718, 2011.

[4] F. Vollertsen., *Lasers in Engineering*, Chap.2, pp. 261–276, 1994.

[5] Y. Guan, S. Sun, G. Zhao, and Y. Luan, Influence of Material Properties on the Laser-Forming Process of Plate Metals, *Journal of Material Processing Technology*, Vol. 167, pp. 124–131, 2005.

[6] E.Ghadiri, Experimental and theoretical investigation of sheet forming processes by using LASER beam technology, M.Sc. Thesis, K.N. Toosi University of Technology, Tehran, Iran, 2011.

[7] X. Zhao, Y.Y. Lee, and K.M. Liew, Mechanical and thermal buckling analysis of functionally graded plates, *Composite Structures*, Vol.90, pp. 161–171, 2009.

[8] G.N. Labeas, Development of a local three-dimensional numerical simulation model for the laser forming process of aluminum components, *Journal of Material Processing Technology*, Vol. 207, pp. 248-257, 2008.

[9] M.Geiger, and F.Vollertsen, *The Mechanism of Laser Forming*, CIRP Ann., Vol. 42, No.1, pp. 301–304.