Finite Element Analysis on Pulsed Laser Forming of Sheet Metal

Kuntal Maji¹, D. K. Pratihar²*, A. K. Nath³

¹,²,³Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur
Kharagpur-721 302, India

E-mail: ¹kuntalmajiiitkgp@gmail.com, ²dkpra@mech.iitkgp.ernet.in, ³aknath@mech.iitkgp.ernet.in

Abstract

Pulsed laser forming is a non-contact thermal forming process, where sheet metal gets plastically deformed by thermal residual stresses induced by controlled discontinuous laser irradiations. The aim of this paper is to determine the temperature and deformation fields using finite element analysis under different processing conditions. Two types of pulsed laser forming processes, i.e., overlapped and discrete spot forming have been identified depending on the combinations of process parameters. Bending angle is found to increase with the degree of overlap and decrease with the increase of gap in case of the two types of spot forming processes. A comparative study between pulsed and continuous laser forming has also been performed using both finite element simulation and experiments. Bending angle in case of discrete spot pulsed laser forming is found to be more compared to the continuous laser forming. The results of finite element simulations have been found to be in good agreement with the experimental results.

Keywords: pulsed laser forming, Finite element analysis, Experimental Study

1 Introduction

Laser forming is a flexible thermal forming process, in which sheet metal get deformed by thermal stresses induced by a controlled laser beam either in continuous or pulsed mode of irradiations. It has potential applications in macro and micro scale manufacturing for rapid prototyping and precision adjustment in ship building, aerospace, automobile, microelectronics industries (Steen and Mazumder, 2010). Extensive studies had been carried out by various researchers (Shen and Vollertsen, 2009) to investigate the continuous laser bending process. Sheet metal forming using pulsed mode of laser irradiation was also investigated by some researchers to study the effects of different process parameters on the deformation and properties of the laser formed samples. Numerical and experimental investigations were carried out by various researchers (Chen et al., 1999; Lee and Lin, 2002; Zhang et al., 2002; Hseih and Lin, 2004) to determine the temperature and deformation fields, and others in pulsed laser forming considering different process parameters, i.e., laser parameters, laser beam shapes, single and multiple pulses etc. Good correlations were found between the numerical and experimental results of deformation in their studies. Transient nonlinear 3D finite element (FE) simulation of pulsed laser forming process is computationally expensive because of finer mesh sizes at the laser irradiated zone and the small time steps required for the convergence and good accuracy. Zhang et al. (2002) proposed an efficient method to reduce the computational time in determining bending angle using FE method in pulsed laser bending of thin stainless steel sheet. Experimental investigations and empirical modeling were carried out by Gollo et al. (2008) in laser bending of sheet metal with a Nd:YAG pulsed laser. Taguchi experimental design was used and regression analysis was performed considering the various process parameters like laser power, beam diameter, scan speed and pulse duration to express the bending angle in terms of process parameters. Yang et al. (2010) investigated the metallurgical changes of surface properties of stainless steel due to pulsed laser forming. The effects of different process parameters on the surface properties of heat
affected zone (HAZ) like microstructure, micro-hardness etc. was studied with the metallographic microscope, scanning electron microscope (SEM) and micro-hardness tester, respectively. 

Gollo et al. (2011) investigated further the effects of different process parameters, such as laser power, beam diameter, scan speed, sheet thickness, number of passes and pulse duration on bending angle using FE simulations and experiments. Significant process parameters were identified through Taguchi experimental design method and regression analysis was also performed to predict the bending angle in pulsed laser forming process. However, a few studies had been done on the different types of processing conditions and their effects on deformation in pulsed laser forming process. Moreover, much less attention had been given on comparative study of continuous and pulsed laser forming processes for energy efficiency. Recently, Maji et al. (2012, 13) have performed empirical modeling of pulsed laser bending process using statistical and soft computing-based methods to predict bending angle and study the effects of different process parameters. However, transient temperature and deformation fields determined through FE analysis gives better insight of the process.

The objective of this study is to investigate the effects of different types of pulsed laser forming, i.e., effects of gap and overlapping on deformation in discrete spots and overlapped spots pulsed laser forming, respectively. The efficiency of continuous and pulsed laser forming processes is also investigated in terms of energy requirement and produced deformation.

2 Theory of pulsed laser forming

In pulsed laser forming process, the laser spot becomes elliptical in the scan direction (Tzeng, 2000; Yang, 2010). Depending on the combinations of process parameters, like scan speed (v), spot diameter (d), frequency (f) and duty cycle (C_d), two types of spots, i.e., discontinuous or discrete and overlapping may be formed as shown in Fig. 1. The major diameter of the elliptical spot can be determined as 

\[ d_m = d + v \times \tau ; \]

And the distance moved by the spot during a cycle time (T_c) can be calculated as 

\[ d_c = v \times T_c . \]

For forming overlapping spots, \( d_m \) has to be greater than \( d_c \) (\( d_m > d_c \)). The degree or percent of overlapping can be calculated as 

\[ \left( \frac{d_m - d_c}{d_m} \right) \times 100 \% . \]

Similarly, in case of discrete spots forming, the percent of gap can also be calculated as 

\[ \left( \frac{d_m - d_c}{d_m} \right) \times 100 \% . \]

The frequency (f = 50 Hz), duty cycle (C_d = 50%), pulse duration (\( \tau = 10 \text{ ms} \)), laser power and beam diameter (d = 1.0 mm) have been kept constant. Both finite element simulations and experiments have been performed to study the effects of gap between spots and their overlapping on bending angle.

3 Finite element formulation

Numerical simulation of pulsed laser forming process has been carried out to determine temperature distribution and deformations. Laser bending or forming is a weakly-coupled thermo-mechanical process. A nonlinear transient indirect coupled field analysis has been performed using the ANSYS APDL (ANSYS theory manual, 2011). The simulation process occurs in a few steps. First step involves model generation and selection of input process parameters. The next step deals with the thermal and structural analyses. The thermal equilibrium equation for heat transfer analysis of an isotropic material can be written as given in equation (1).

\[ k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + q = \rho c \bar{T} , \quad (1) \]

where \( \rho \), \( c \) and \( k \) are the density, specific heat and thermal conductivity of the material, respectively, and \( q \) is the rate of heat generation per unit volume of the material. The heat flux density of moving laser beam (Fiber laser) is assumed to obey the normal distribution along radial direction as given in equation (2).

\[ I = \frac{2AP}{\pi r_p^2} \exp \left( -\frac{2r^2}{r_p^2} \right) . \quad (2) \]
where \( I \) is the heat flux density at a radial distance \( r \) from the center of the laser beam. The symbols A, P and \( r_0 \) stand for the absorptivity of the sheet metal surface, laser power and laser beam radius, respectively. The basic FEM equation for the indirectly-coupled thermo-mechanical calculation can be written as given in equation (3).

\[
\begin{bmatrix}
0 & [u] & \{F\} \\
{0} & 0 & 0 \\
{0} & 0 & \{F\}
\end{bmatrix} + \begin{bmatrix}
[k] & \{0\} \\
{0} & 0 \\
{0} & \{0\}
\end{bmatrix} \begin{bmatrix}
[u] \\
{0} \\
\{0\}
\end{bmatrix} = \begin{bmatrix}
[F] + \{F_{th}\} \\
{0} \\
\{0\}
\end{bmatrix}
\]  

(3),

where \([C] = \int \rho c [N] [N] d\Omega\) is the heat capacity matrix; \([k] = \int \{\beta\} [D] [\beta] d\Omega\) is the tangential stiffness matrix; \([K_T] = \int \{\gamma\} \{\gamma\} d\Omega\) represents the heat conduction matrix; \(\{u\}\) and \(\{T\}\) are the nodal displacement and temperature vector, respectively; \([N] \) and \([\beta]\) denote the shape function matrix and the general geometric matrix, respectively; \([D] \) is the elasto-plastic stress-strain matrix; \(F\) and \(F_{th}\) are the applied nodal force and the force caused by the thermal strain, respectively; \(\{Q\}\) is the heat flux vector. Solid 70 and solid 185 elements (ANSYS theory manual, 2011) have been used for the thermal and structural analysis, respectively.

The following assumptions have been considered for the FE analysis of pulsed laser bending process. (i) The workpiece material has been assumed to be isotropic, and considered flat and free of residual stresses. (ii) The laser beam energy follows a Gaussian distribution. (iii) Melting of the workpiece surface has been neglected and no external force has been applied to the sheet metal. (iv) Cooling of the irradiated material occurred through free convection to air and radiation has been neglected. (v) Temperature dependent properties (i.e., thermal conductivity, specific heat, density, Young’s Modulus, Poisson’s ratio etc.) have been considered and their variations have been determined by means of linear interpolation of the data given in Cheng and Lin (2000). (vi) Von Mises Criteria has been used for plastic yielding in the simulation process. (vii) The hardening effect of material behaviour has been considered as bilinear isotropic hardening model. (viii) The dissipation of energy due to plastic deformation has been neglected compared to energy input from the laser beam. For the application of the proposed FE model, the required different parameters are the plate dimensions (length, width and thickness), laser power, laser beam diameter, scan speed, material absorption coefficient etc. The calculated outputs are mainly the transient temperature and deformation fields, and the final bending angle. The FE model results have been validated through experiments as discussed in the following sections.

Numerical simulations have been carried out for studying the effects of gap and overlap on bending angle in the two types of pulsed laser forming processes. Simulation has been conducted by taking the model size to be equal to the size of workpiece excluding the clamped length, and laser irradiation has been done at the middle of the workpiece and parallel to the free edge of the sample as shown in Fig. 2. Fine mesh size has been used in the laser irradiated zone and gradually coarse meshing has been used away from the irradiated zone to reduce the computational time as shown in Fig. 2.

![Fig. 2: Model of the sample with meshing.](image)

The laser beam has been moved for a small distance at each time-step for simulating the moving pulsed laser beam. A small time-step has been taken during laser heating for convergence and gradually increasing time-steps have been taken during cooling to reduce the total computational time. For studying the effects of gap and overlap, other process parameters, i.e., laser power and spot diameter have been kept constant. AISI304 steel samples of the size of 100×30×0.5 mm² have been used for the study. One end of the sample has been clamped, therefore, this end has been kept fixed or the displacement of that end has been made zero as boundary condition.

### 4 Experimental validations

Laser bending experiments have been conducted on a fiber laser (wavelength = 1.07 µm, Model YLR-2000) having a maximum laser power of 2.0 kW (refer to Fig. 3). A 10 mm diameter collimated laser beam is delivered through an optical fiber.
onto a focusing optical system consisting of a lens of 200 mm focal length. This minimum spot diameter available is 250 µm at the focal plane, and nitrogen gas at 0.5 bar pressure has been used for shielding to protect the optical system.

![Fig. 3: 2 kW Fiber laser system.](image)

The work-pieces are AISI 304 stainless steel sheets of 120 mm×30 mm×0.5 mm dimensions. The samples have been cleaned using acetone to remove any unwanted dirt and grease. A 10000 W-LpOphir power meter has been used to measure the laser power. By measuring the incident and reflected laser power, the average absorption coefficient of the work-piece surface was estimated to be in the range of 0.35 to 0.45. During laser bending experiment, one end of the rectangular workpiece is held in a clamp and laser scans have been performed parallel to the free edge of the samples, as shown in Fig. 4.

![Fig. 4: Experimental setup.](image)

The deflection of the sample has been measured using a laser displacement sensor (Make: Micro-Epsilon, Model: Opto-NCDT 1402). Measurements have been taken at 3-4 locations along the scanning direction and their average value has been calculated. Bending angle has been calculated by the triangulation method. Results have been compared with that obtained from the finite element simulations of the laser bending process.

5 Results and discussion

Experiments and FE simulations have been performed to study the effects of gap between spots and their overlapping on bending angle in pulsed laser bending (PLB). The degrees of overlap and gap have been controlled by varying the scan speed keeping the other parameters constant.

![Fig. 5: Temperature profile during heating](image)

Fig. 5 shows the temperature profile obtained during heating with a laser power of 600 W and 50% gap. The corresponding deformation field is shown in Fig. 6.

![Fig. 6: Deformation field due to pulsed laser forming with 50% gap and 600 W laser power.](image)

Fig. 6 shows the variations of bending angle, both experimentally obtained and FE calculated, with the degree of gap between spots, obtained at constant laser power (600 W) and laser spot
diameter (1.0 mm). At constant laser power, as the gap is increased by increasing the scan velocity, the discrete line energy input reduces, and the power density also decreases, as the spot size increases at the higher scan speed. As a result, the bending angle decreases.

![Fig. 7: Effect of gap on bending angle.](image)

The bending angle increases with the increase of percentage of overlap at constant laser power, as shown in Fig. 8. Laser power and beam diameter have been kept constant at 300 W and 1.0 mm, respectively, to study the effects of overlapped pulsed laser irradiation. With the increase of overlap, the line energy increases, which increases the thermal energy input and thermal stress, and resulting in a higher bending angle.

![Fig. 8: Effect of overlap on bending angle.](image)

FE simulation results also match well with the experimental trend of the bending angle with the gap and overlap (refer to Figs. 7 and 8). At higher degree of overlap, the workpiece surface melts and this effect has not been taken into account in the FE simulation to calculate the bending angle.

Finite element analyses of pulsed laser irradiations have been carried out, and transient temperature and deformations have been calculated for different processing conditions. Bending angle is found to increase with the increase of overlap and decrease with the increase of gap.

FE simulation and experiments have been conducted to study the deformation and process efficiency in thermal forming of sheet metal under continuous and discrete laser heat inputs. The variation of bending angle with the line energy is plotted in Fig. 9 for both the cases. The line energy for continuous laser bending is given by \( \text{LE}_c = p/v \), and that for pulsed laser bending is calculated as follows:

\[
\text{LE}_p = \frac{D \times \tau}{v \times T} = \left(\frac{p}{v}\right) \times \left(\frac{\tau}{T}\right) = \text{LE}_c \times C_d,
\]

where the symbols carry usual meaning as stated above. The bending angle obtained in case of pulsed laser forming is found to be more compared to that in continuous laser forming for the same line energy as shown in Fig. 9. The larger bending angle in case of discrete spots pulsed laser bending (gap between two spots has been kept 25%) can be attributed to the fact that the discontinuous thermal energy input produces more thermal stress due to the higher resistance imposed by the cold material, which is not getting laser irradiation during laser pulse-off time. The rise in surface temperature at the irradiated spot is also expected to be high in case of pulsed laser forming compared to that of continuous laser forming at constant line energy (McBride et al., 2005). This could also be another reason for producing more bending in case of pulsed laser bending process.

![Fig. 9: Comparison of pulsed and continuous laser forming.](image)

Therefore, pulsed laser forming is found to be more energy efficient compared to that of continuous mode of laser forming. In future, the comparative study will be made for more number of processing conditions and for 3D forming also.
6 Conclusions

Finite element analyses of laser bending process with both continuous wave and pulsed laser irradiations have been carried out. Transient temperature and deformations have been calculated for different processing conditions. The effects of different processing conditions on deformation have also been studied. Deformation in pulsed laser forming has been found to decrease and increase with the increase of gap and that of overlap between spots, respectively. A comparative study of CW and pulsed laser bending processes has been done through FE simulations and experiment. Discrete spot pulsed laser forming has been found to be more energy efficient compared to the continuous laser forming. Results of finite element simulations have been validated through experimental results and these are found to be satisfactory.

References


