NUMERICAL INVESTIGATION ON EFFECT OF POWER VARIATION IN LASER FORMING OF SHEET METALS

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ABSTRACT

One of the newest methods in sheet metal forming is laser forming process. In this forming process, sheet metal is formed under high thermal stresses caused by laser heat. Some parameters are effective to sheet metal forming by a laser that analyzed, such as laser beam diameter, scanning acceleration, laser power and etc. In all of previous researches on sheet metal forming by laser, laser power was constant. In this research, effects of variations of heat flux in laser forming of sheet metals are investigated by finite element method. To perform better sheet deformation by laser it is necessary to use an optimal function of the laser power. However, it was observed that the non-constant power path leads to a non-uniform deformation.

KEYWORDS: Laser forming, Power variation, Finite Element Method (FEM)

Laser forming is a type of non-contact thermomechanical metal forming process, which is used to bend or deform metallic sheets. Sheets are formed under high thermal stresses caused by laser heat-flux. Laser beam scanning can be used under different patterns (Hyung-Chul, 2006; Namba, 1986). Figure 1 shows an schematic of sheet metal forming process by laser.

In laser forming process, stress, strain and temperature are related together. On the other hand, this relevance is indirect and non-linear. There are some other parameters that are effective in laser forming such as scanning acceleration, laser power, cooling conditions, etc. (Deaden and Edwardson, 2003). The important advantages of laser forming are high ability, high flexibility to produce complicate components, rapid prototyping, low circulation and high accuracy (Kitamyra, 1983; Masubushi et al., 1998).

Sheet metal deformation by laser occurs by three principal mechanisms (Mucha et al., 1997) namely, the temperature gradient mechanism which is known as TGM, the buckling mechanism (BM) and the upsetting mechanism (UM). The temperature gradient mechanism is dependent to high temperature gradient on lower surface and the upper surface of sheet metal. Also, buckling mechanism is performed by lower temperature gradient and the laser beam diameter is much larger than the sheet thickness. On the other hand, upsetting mechanism occurs in a similar condition to the BM, whereas the dimension of the heated zone is much smaller compared to the sheet metal thickness (Kyrsanidi et al., 2000). Vollertsen and Geiger predicted bending angle by two formulas (Vollertsen et al., 1993).

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\alpha = \frac{180\sqrt{2} \ AP \ \alpha_{th} \sqrt{a}}{5\pi \sqrt{\pi} \sqrt{r \bar{v}}} \frac{1}{k S_0}
\]

\[
\alpha = \frac{3\alpha_{th} PA}{\rho C_p v S_0^2}
\]

Where \( A \) is the absorption coefficient, \( P \) is the laser power, \( r \) is the laser spot radius, \( \alpha \) is the thermal expansion coefficient, \( k \) is the thermal conductivity, \( C_p \) is the specific heat, \( \rho \) is the density, \( a \) is the conductivity factor, \( v \) is the scanning velocity, and \( S_0 \) is the thickness of the sheet metal. These equations demonstrated a numerical association between bending angle and some material property parameters (Shen et al., 2006; Shi et al., 2008). In most researches, laser scanning paths with To produce complex components, such as spherical shapes and bowl shaped surfaces by laser, two different strategies can be used. The first strategy is to form sheet metals by circular linear patterns achieves have been investigated and used for laser bending applications. In order to produce complicated parts with three dimensional surfaces such as saddle shapes and bowl shaped surfaces, different scanning strategies with complex patterns should be developed. Generally, to deform 3-D complicated shapes, circular patterns are better than linear scanning under TGM mechanism (Fig. 2). The second strategy is named radial-strategy. A sheet metal can be formed by radial patterns under the BM mechanism (Fig. 3).

![Fig.2. First strategy (Circular strategy)](image1)

![Fig.3. Second strategy (Radial strategy)](image2)

Both above strategies have different advantages and disadvantages. In order to obtain required accuracy and symmetry in a laser forming by a radial strategy, it is necessary to overcome negative effects of start points and end points of scanning in a forming process. Because, some results indicated that the large number of start points and end points of scanning path, leads to non-adequate residual stress and asymmetrical forming. Therefore, conditions of laser scanning with radial strategies are crucial (Shayan Dehghan et al., 2013).

In addition, although circular strategy seems to be more appropriate to form dome shaped parts, symmetrical degrees of deformed parts are deteriorated for this pattern. One of the effective parameters of laser forming is laser power. High heat flux is efficient for sheet metal forming, which leads to increase cost of process. From the other point of view, low heat flux is not effective in laser forming. In most last researches and papers, the effects of beam laser on sheet metals have been investigated only for the constant power of laser. In this paper, a laser forming process with varying laser power is investigated by the finite element method. In addition, deformation behavior of workpieces is examined for a constant laser power and two other varying power equations.

**FINITE ELEMENT SIMULATION**

The numerical study conducted for a mild steel sheet with 2 mm thickness, 40 mm width and length of 40 mm. During laser scanning, one side of sheet metal is fixed by a gripper. Three types of laser power diagrams were used for numerical simulations. The first laser power diagram, is a constant power of 200 W (Fig. 4. a). The second one is expressed by a parabolic equation with an initial power of 200 W and peak at 350 W (Fig. 4. b). The third type is a reverse direction of the second one (Fig. 4. c).
For the numerical investigation, the finite element method with the ABAQUS implicit code has been used for thermal and mechanical analysis of laser forming. In the simulations, mechanical calculations can be a decoupled analysis from thermal ones and the reason of this work is negligible energy dissipation from plastic deformation as compared with the high laser energy used in the process. In a decoupled solution, the thermal analysis is performed first to obtain the temperature field, and then the results of thermal calculations are used as the thermal loading for the mechanical analysis. Laser forming is depended with the energy absorption into the metal sheet because the process is based on the surface heating by a laser beam. The heat flux into the surface of the sheet metal with a laser beam follows a normal distribution, and is expressed as a function of the beam radius as follows:

$$q(r) = \frac{2nP}{\pi R^2} \exp\left(-\frac{4r^2}{R^2}\right)$$

Where q is the heat flux density, η is the absorbency on the sheet metal surface, P is the laser beam power, R is the laser beam radius and r is the distance from the center of the laser beam. Absorbency of the as-received sheets of Mild Steel were estimated 0.5 as mentioned in Shen et al. (2006).

After laser irradiation of a sheet metal in this process, the temperature in the heated zone increases naturally in the air.

$$-K\left(\frac{\partial T}{\partial n}\right) = h_c(t - t_{\infty})$$

Where K is the heat conductivity, $h_c$ is the heat transfer coefficient, t is the temperature of irradiated surface, and $t_{\infty}$ illustrates the environmental temperature. Based on the ambient condition in laser forming, the natural convection exchange coefficient is set to 30 W/m² °C. In relation to irradiation law, the equivalent irradiation exchange coefficient can be proposed as follows:

$$q_r = 5.67 \times 10^{-8} \varepsilon (T_s^4 - T_\alpha^4)$$

(5)

Where $\varepsilon$ is the surface emissivity, and this value depends on the temperature of the metal plate and condition of sheet surface. Furthermore, a constant surface emissivity of $\varepsilon = 0.5$ is used for assessment of heat loss due to radiation as mentioned in Yu’s et al. reported (Yu et al., 2001). 3D Solid elements, C3D8R were used in FE simulation. In mechanical analysis, necessary constraints were defined for boundary conditions to establish rigid body movement. For this, a central hole with 7 mm diameter was created in the circular plates and all of its degrees of freedom were constrained. 3D Solid elements, DC3D8, were also used in the thermal analysis. The material properties are very important in hot metal forming such as laser forming. Thus, material properties of the mild steel are temperature dependent, such as specific heat, heat conductivity, thermal expansion coefficient, density, Young’s modulus, yield stress. All required data of material properties have been taken from Ref. (Shen et al., 2007). In addition, the
same mesh was used for both thermal and mechanical simulations (Fig. 5).

NUMERICAL RESULTS

Forming and displacement on the edge

According to the obtained results from the simulation, the deformations of the sheets for the three types of laser scanning power are shown in figures 6-8. A large deformation scale factor was used for a better illustration of the forming process. By comparing these figures it can find that the maximum displacement occurred on the edge that was deformed by the second type of laser power which is parabola with a negative concave (figure 4-b) and the minimum displacement occurred on the edge of the sheet that was deformed by the constant power (figure 4-a).

It is observed that, the equation of time-power of the laser irradiation is one of the laser forming parameters which is very effective on the deformation behavior of a sheet metal in a laser forming process. Deformation process is improved by providing a suitable equation of the laser power.
Figure 8. Edge displacement distribution by parabolic power with a positive concave

Figure 9 illustrates a comparison between displacements of the sheet edges of three types of laser irradiation powers. The behavior of the edge displacement shows that in spite of the maximum value of displacement occurred for the third type of laser power (parabolic power with a positive concave), it did not deform the sheet uniformly. The uniform displacement means an equal displacement along an edge of the sheet. However, the amount of uniformity for the first and second types of power equations is more than that for the third one.

For the three power equations in this study, sheets have been deformed into concave shapes after forming process because of the temperature gradient mechanism. This mechanism has occurred as follows: heating of sheet surface, thermal expansion of the material, re-heating and plastic compression of surface, bending and unbending. Because of expansion caused by surface heating an un-bending or negative bending appears in the sheet against the laser irradiation. The amount of un-bending is very small since the heated area is approximately equal to the diameter of the laser beam.

Further heating leads to a decrease in the flow stress and greater thermal expansion of the heated surface. Moreover it can increase temperature that leads to change the heat expansion and also plastic compressive strain. These plastic compressive strains extend until heating process stops or melting occurs. After moving the laser beam on the sheet surface, the heating was stopped and cooling process will start.

1.1. Stress distribution

Stress distributions of the deformed sheets by different power paths are shown in figures 10-12. It seems from these figures that in terms of residual stresses in the sheet metal and also due to uniform stress distributions, the maximum stress on the plate under three power equations are almost similar. It is noteworthy that the first and third sheets, stress concentrates closer to the edge of the sheet and thus have better conditions.
than laser forming by the second radiation equation. Also the residual stresses in sheet forming by the second radiation pattern significantly higher than that for the other two sheets.

![Fig.10. Calculated stress distribution for constant power](image1)

![Fig.11. Calculated stress distribution for parabolic power with a negative concave](image2)

![Fig.12. Calculated stress distribution for parabolic power with a positive concave](image3)

### 1.2. Strain distribution

The figures 13, 14 and 15 show the behavior of strain distribution in the deformed sheet by the laser. By comparison of these figures, it can be found that a more uniform strain on the sheet occurs for the constant power equation, because, a constant and uniform power in the plate was employed. Furthermore the amount of maximum plastic strain for the constant power is less than that for the other varying powers due to amount of deformatons. Since in the second power equation (parabolic power with a negative concave), the maximum value of laser power has occurred in the middle of the path, thus the maximum strain occurred in the middle of the sheet. In addition, the effective plastic strain distribution is more non-uniform. It can be due to un-bending effects at the start and end of the irradiation path.
CONCLUSION

According to the simulation results, it can be found that laser scanning with varying power has different effects on the laser forming process, especially on the values of displacements and deformations. Thus, in order to perform better sheet deformation it is necessary to use an optimal function of the laser power. However, it was observed that the non-constant power path leads to a non-uniform deformation.

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