Numerical modelling of laser forming of curved surfaces

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Abstract

Sheet metal parts with convex and concave curvature find wide applications in automotive, aerospace, shipbuilding and biomedical industries. Traditional techniques for generating such surfaces are matched die forming, multipoint rolling, hydroforming, stretch forming and incremental forming. All these techniques are contact type and thus require costly specialized tools and more time for changeover of tooling. To address these challenges, laser forming is emerging as an alternative method for forming of 2D and 3D sheet metal parts. Laser forming is a thermal process utilizing thermal stresses for localized deformation of sheet metal. Selection of laser parameters and irradiation strategy is found to be challenging for precision forming of complex shapes since the relationship between the desired shape and the process variables is quite complex. In the present study, an attempt is made to develop a numerical model for simulating the capability of laser forming technique for producing concave surface with any radius of curvature. A three dimensional finite element based numerical model is developed to study thermal and structural phenomenon of laser forming process. From the simulation results, it is found that laser power, laser beam diameter, scanning speed and spacing between two adjacent passes influence the mechanism of deformation. This study will help to analyse the role of different process parameters and the mechanisms responsible for generating 3D features on sheet metal by laser forming.

Keywords: Laser forming, curved surface, FEM analysis.

1. INTRODUCTION

Demand for three dimensional sheet metal parts with convex and concave curvatures such as aircraft panels, ship hulls, vehicle doors, bio-implants, MEMS devices like micro actuator, heat sink etc., is increasing owing to their use in several industries such as shipbuilding, automotive, aerospace, biomedical, space industries and microelectronics. Traditional methods of manufacturing such curved surfaces are matched die forming, hydroforming, multipoint rolling and incremental forming. Among them, matched die forming and hydroforming are still the popular methods for high productivity. For small batch production and for specialized shapes, these methods are not economical since they need specialized tools with high cost and large time for changeover of tooling. To address these challenges, laser forming is emerging as a new technology in the area of rapid manufacturing where customized products are produced in small-batched. In laser forming, thermal stresses induced by laser irradiation are used for localized deformation of sheet metal. In this process, a defocused laser beam traversed over the sheet surface causes localized heating, as shown in figure.1.

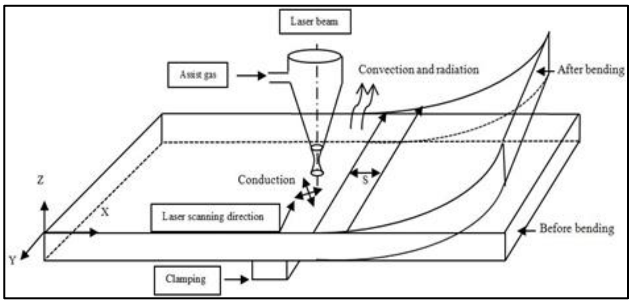


Fig. 1. Schematic representation of curvilinear laser forming process

Heating of sheet surface causes localized thermal expansion of the material as the heating is limited to a small size within laser spot diameter. Further expansion of sheet surface is restricted by the surrounding material inducing compressive thermal stresses across the thickness of sheet. Thermal stresses may exceed the temperature dependent flow stress of material and originates plastic deformation. Laser forming is a highly flexible process and does not require any external tooling or external forces; all class of materials from metals to nonmetals and alloys to composites can easily deform with insignificant amount of spring-back effect, which is a major advantage of this process.

Earliest work on laser forming began in the mid of 1980s and an extensive research was carried out on deformation mechanism, sheet material behavior, equipment and system design and process control for straight line or V shape bending. Geiger and Vollertsen [1] introduced three fundamental mechanisms of deformation, namely temperature gradient mechanism (TGM), buckling mechanism (BM) and shrinkage mechanism (SM). Out of which TGM and BM induce out of plane deformation, while SM induces in plane deformation. The degree of deformation in each mechanism depends on the interactive effects of material properties, dimensional features and laser parameters. In straight line or V-shape bending, it is quite easy to select the laser parameters for achieving required bend angle. But, for precision forming of complex shapes, controlling the degree of deformation becomes a challenge since the relationship between the desired shape and heating paths and heating conditions is quite complex [2]. Therefore, in precision forming of three dimensional shapes, it is important to define laser irradiation path and correct combination of laser energy parameters [3, 4]. For the development of 3D features using laser forming, the research is mostly focused on process synthesis following different strategies based on geometrical, principal curvature, strain field and genetic algorithm approach [2-7]. However in laser forming of continuous curved surfaces maintaining uniform strain field becomes a challenge. In the present study, finite element model is developed to analyse the influence of process parameter for laser forming of concave surfaces.

2. DEVELOPMENT OF FINITE ELEMENT MODEL

In the present study, a transient three dimensional finite element based numerical model is developed using commercial software COMSOL MULTIPHYSICS version 5.2., Wherein both thermal and structural physical phenomena are coupled. In thermal analysis, laser energy parameters are defined to develop localized thermal field across sheet thickness. In mechanical analysis, thermal field developed in thermal analysis is imported as input boundary condition and output parameters such as thermal stress and strain distribution are computed.

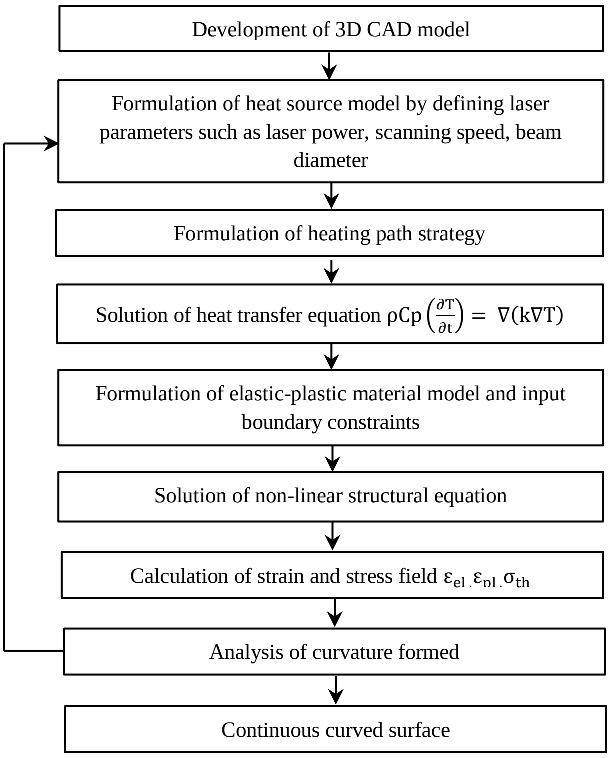


Fig.2. Schematic representation of development of FEM model

2.1 Assumptions:

In the development of numerical model, it is difficult to define non-linear behavior of material properties. Few important assumptions made in solving the problem are: thermo-mechanical properties of work material is isotropic and homogeneous; laser operates in continuous wave mode and distribution of heat flux is in Gaussian mode; cooling of irradiated sheet surface occurs through natural convection; no surface melting occurs during laser heating; the von Mises criteria is considered as plastic yielding criteria, since it is best suited for ductile materials, dissipation of energy during plastic deformation is ignored.

2.2 Heat source model:

Heat flux of Q is applied on top surface of sheet which is moving with constant velocity of V along sheet width. The distribution of heat flux over sheet surface is considered as in Gaussian mode which is expressed by following equation:

$$Q(x, y, t) = \frac{2AP}{\pi R^2} \exp\left(-\frac{2r^2}{R^2}\right)$$

Where, Q is heat flux in W/mm^2, A is laser absorption coefficient which is considered as 0.6 in the model [8], P is laser power in W, R is laser beam radius in mm and r is distance from center of laser beam in x and y direction in mm.

2.3 Heat transfer model:

In thermal analysis, three fundamental mechanisms of heat transfer, conduction, convection and radiation are considered. In laser forming process the transient temperature distribution is calculated based on heat conduction equation. Here the governing equation for heat transfer by conduction is defined with Fourier's law of heat conduction written as follow:

$$\rho Cp\left(\frac{\partial T}{\partial t}\right) = \nabla(k\nabla T)$$

Where, ρ is density in kg/m^3, C_p is specific heat capacity in J/kgK, T is temperature in K, t is time in s and k is thermal conductivity in W/mK.

The term ∇ is differential operator for three dimensional Cartesian co-ordinate systems.

In the model, heat loss due to convection and radiation are considered, although the losses occurred are not as considerable as in heat conduction. The convection heat loss is defined as follows:

$$q = h(T_s - T)$$

Where, h is heat transfer coefficient in W/mK and T_s is surface temperature in K.

Similarly, heat loss due to radiation is defined as follows:

$$q = \varepsilon\sigma(T_s^4 - T_{amb}^4)$$

Where, ε is surface emissivity, T_{amb} is ambient temperature is 293K and σ is Stefan Boltzmann constant whose value is 5.67x10^{-8} in W/m^{2}K^4.

2.4 Elastic-plastic deformation analysis:

In laser forming plastic deformation is observed when thermal strain (ε_{th}) induced by thermal load exceeds elastic strain (ε_{el}) of work material, hence the total strain (ε) induced in laser forming is expressed as follows:

$$\varepsilon = \varepsilon_0 + \varepsilon_{th} + \varepsilon_{el}$$

Where, ε_0 is initial strain, ε_{el} is elastic strain which is calculated from Hook's law, ε_{th} is thermal strain given as;

$$\varepsilon_{th} = \alpha_{th}(T - T_{inf}).$$

In the model, large strain formulation has been adopted for considering geometric non-linear behavior during laser heating and cooling phase.

2.5 Mesh Size

In this numerical model, a three dimensional tetrahedral shape mesh is used. The maximum size of mesh is 0.6 mm and minimum size of 1μm. Complete mesh consist of 26194 domain elements, 11068 boundary elements and 552 edge elements.

2.6 Material properties

In the model, AISI 304 steel is considered as work material, with dimensions of 100 mm length, 50 mm width and 1 mm thickness. Temperature dependent material properties are defined using interpolation function in the model, as shown in table 1 [9].

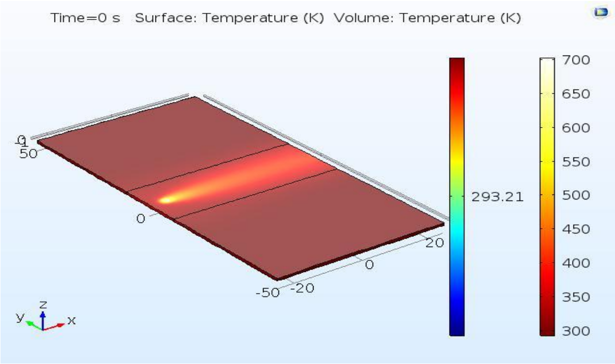
Table 1: Temperature dependent material properties of AISI 304

Temp. (°C)	Specific heat (J/g°C)	Thermal conductivity (J/mm°Cs)	Yield stress (MPa)	Thermal expansion coefficient (°C^{-1})	Young's modulus (GPa)
0	0.462	0.0146	265	1.70e-5	198.50
100	0.496	0.0151	218	1.74e-5	193
200	0.512	0.0161	186	1.80e-5	185
300	0.525	0.0179	170	1.86e-5	176
400	0.540	0.0180	155	1.91e-5	167
600	0.577	0.0208	149	1.96e-5	159
800	0.604	0.0239	91	2.02e-5	151
1200	0.676	0.0322	25	2.07e-5	60
1300	0.692	0.0337	21	2.11e-5	20
1500	0.700	0.120	10	2.16e-5	10

3. VALIDATION OF THE NUMERICAL MODEL

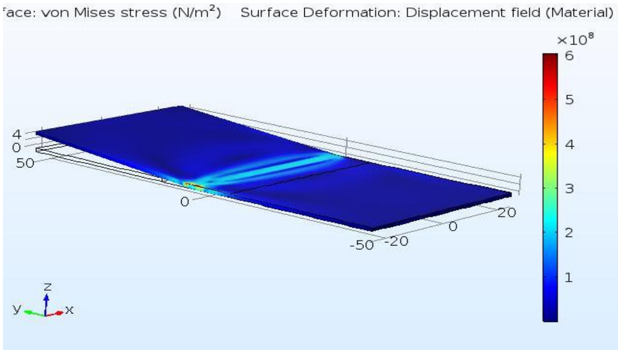
Results obtained from the numerical model are compared with published results of Maji et al. [10], Vollertsen et al. [11] and Shen et al. [12] models. The results shown here are of single laser pass and size of sheet and other process variables are considered same as published literature. Table 2 shows the results of bend angle for different laser power and scanning speed of 84 mm/s. Figure 3(a) and (b) show thermal stress and strain field for laser power of 500W, scanning speed of 84 mm/s, beam diameter of 2mm and sheet thickness of 1mm.

3.1 Temperature field



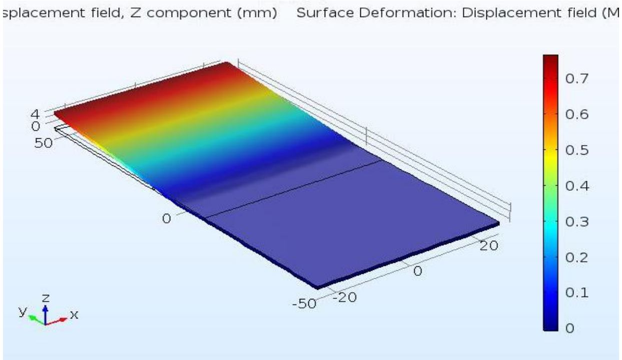
a.

3.2 Thermal stress field



b.

3.2 Thermal strain field



c.

Fig. 3. Validation of model for single laser pass; a. temperature distribution b. thermal stress distribution c. z – axis displacement of sheet (Laser power of 500W, scanning speed of 84 mm/s, laser beam diameter of 2 mm, sheet thickness of 1 mm and laser absorptivity of 0.6)

Table 2: Validation of bending angle

Power [W]	Angle of bent sheet [degree]				Error
	Present Model	Maji Model [6]	Vollertsen Model [7]	Shen Model [8]	
400	0.744	0.8	1.6	0.3	-0.07
500	0.916	1.2	2.2	0.4	-0.427
600	1.252	1.4	2.5	0.5	-0.105

4. RESULTS AND DISCUSSION

In this section, effects of process parameters such as laser power, laser scanning speed, laser beam diameter and spacing between two adjacent passes on the geometry of curved surface produced by laser forming are investigated using the finite element model.

4.1 Effect of laser power

From numerical simulation, it is found that rate of deformation increases with increasing power of laser as shown in figure 4. However as laser power increases beyond threshold limit, sheet surface starts melting. Similarly as laser power consider below certain limit then no plastic deformation was observed. Therefore, selection of laser power becomes important for controlling deformation mechanism. In present work TGM is maintained for developing concave surface.

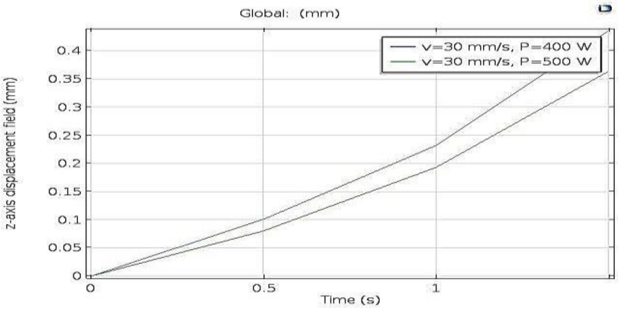


Fig. 3. Rate of displacement with respect to laser power and scanning speed.

4.2 Effect of laser beam diameter

Laser beam diameter is the second important parameter which controls the deformation mechanism, as heat flux distribution depends on it. It is found that as laser beam diameter increases the distortion at sheet edges becomes more significant. The reason for distortion of sheet edges is considered to be the non-uniform distribution of heat flux along sheet edges as shown in the figure 5. Therefore, laser beam diameter needs to be defined properly for controlling edge effects in concave surfaces.

4.3 Effect of scanning speed

From numerical simulation, it is found as scanning speed increases, rate of deformation decreases as shown in figure 4. It happens because of the amount of heat distributed over sheet surface decreases which causes only elastic strain and no plastic strain. However, with decrease in scanning speed, edge distortion becomes considerable; therefore scanning speed needs to be defined properly so that edge distortion can be controlled.

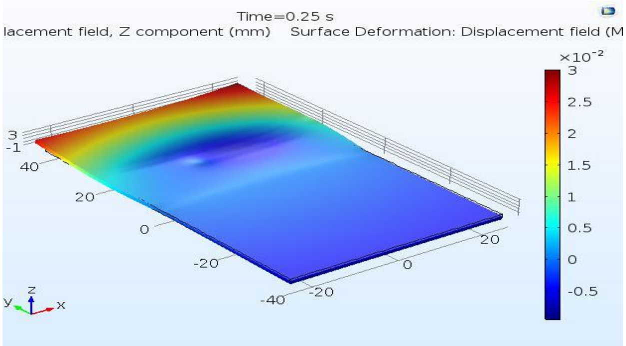


Fig. 4. Schematic representation of curvature formed for laser scan spacing more than laser beam diameter.

4.4 Effect of spacing between adjacent laser passes

In the present study, two scanning schemes used for understanding the effect of spacing between adjacent passes of laser on curvature formed. In the first scheme, spacing between adjacent passes of laser, considered more than laser beam diameter. In second scheme, spacing between two adjacent passes of laser was less than beam diameter. From numerical simulation, it is found if spacing between two adjacent passes of laser is more than laser beam diameter then no continuous curvature forms, because of non-uniform strain distribution. However when spacing between adjacent passes of laser is less than laser beam radius then continuous strain field may induces uniform curvature.

5. CONCLUSION

A finite element based three dimensional numerical model is developed for investigating thermal and structural aspects of laser forming process. The thermal stress and strain distribution and displacement fields are calculated. A parametric study on various parameters such as laser power, laser scanning speed, laser beam diameter and spacing between adjacent passes of laser conducted for laser forming of AISI 304 steel sheet. It has been observed that continuous curved surface can be produce using laser forming technique by selecting correct combination of process parameters and spacing between adjacent passes of laser. This study will help to analyse the role of different process parameters and the mechanisms responsible for generating 3D features on sheet metal by laser forming.

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