EXPERIMENTAL AND NUMERICAL INVESTIGATION OF LASER FORMING OF A DOUBLY CURVED SADDLE SHAPE WITH SPIRAL IRRADIATING SCHEME

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ABSTRACT: In this work, laser forming of a doubly curved saddle shape was investigated experimentally and numerically. Experimental tests were carried out with a continuous wave CO2 laser of 150 Watts maximum power. Numerical simulations were also performed using commercial finite element package ABAQUS/Implicit. Experimental and numerical results showed that a doubly curved saddle shape could be produced successfully with spiral irradiating scheme. In addition, the numerical results weree in good agreement with experimental observations. The experimental and numerical results yielded that curvatures associated with obtained saddle shape was considerably large and a considerable and suitable symmetry was produced in the obtained saddle shape with spiral irradiating scheme. Spiral irradiating scheme was indeed a powerful and suitable path to produce a doubly curved saddle shape with considerable amounts of curvatures and symmetries.

KEYWORDS: Laser forming, Doubly curved saddle shape, Spiral irradiating scheme

1.0 INTRODUCTION

Metal forming with a moving heat source such as laser beam is one of the most economical methods for forming three-dimensional complex shapes which are used in ship, automobile and airplane bodies. The laser beam can be used for producing complicated shapes with double curvature by developing necessary thermal strains in the plate in order to generate the desired shapes. Considerable number of studies has been carried out on two dimensional laser forming. However, three dimensional laser forming is more applicable in various industries. Three dimensional laser forming studies have recently been investigated and only few studies have been reported in this field due to extreme complexities.

In 1994, Ueda et al. [1] developed a computer-aid process planning system for bending a plate with line heating. They computed strains by finite element method and decomposed the strains into in-plane and bending strains. They chose regions with large in-plane strains as heating zones and selected heating direction normal to the minimum principal strain. In 1998, Jang et al. [2] developed an algorithm to determine heating lines for plate forming by line heating method. They first calculated the lines of curvature of a prescribed surface and evaluated the points of extreme principal curvatures along the lines. They then classified and grouped those points based on their principal directions and their distances.

In 2000, Yu et al. [3] presented algorithms for optimal development of a smooth continuous curved surface into a planar shape. The development process is modeled by in plane strain from the curved surface to its planar development. In 2000, Ishiyama et al. [4] proposed a method to determine heating paths where the heating lines for bending strain and in-plane strain were independently calculated using contour heating method and conversion algorithm to the orthogonal compressive inherent strain. In 2000, Hennige [5] investigated the differences in the forming behavior of sheet metal parts using straight and curved irradiations. In addition, using radial and circular laser scan paths, he produced a dome shape plate from a circular blank. In 2002, Shin et al. [6] proposed a non-dimensional relationship between input parameters and final deformation during line heating process by using the flame heat. In 2003, Kim et al. [7] developed a method which was reliable and easy to apply in order to solve the inverse problem in the laser forming process. In 2004, Liu et al. [8] suggested an optimal process planning strategy to determine scanning paths and heating condition for laser forming of general doubly curved shapes. They also studied two distinctive types of doubly curved surfaces, pillow and saddle shape and validated their proposed methodology by experiments. In 2007, Zhang et al. [9] simulated laser forming of a plate with a B-spline curve path. They also investigated various temperature fields, displacement fields, stress and strain fields and the results showed that peak temperatures of the upper surface and the warped curvature increased when the path curvature increased.

In 2009, Kim and Na [10] proposed a new method for 3D laser forming of sheet metals. Their method used geometrical information rather than a complicated stress-strain analysis. Using this method, they showed that total calculation time is reduced considerably while provided enhanced accuracy. In 2012, Chakraborty et al. [11] used a combination of radial and circular laser scan paths and produced a bowl shaped surface. The effects of various process parameters such as laser spot diameter, laser power and scan speed, on the in-plane and out-of- plane forming of stainless steel circular blanks for various circular and radial scan schemes were also investigated. In 2013, Safari et al. [12] proposed spiral irradiating scheme for flame forming of a bowl shaped surface. Their investigations were performed experimentally and numerically and the results showed that the proposed spiral irradiating scheme was a very good and suitable method for flame forming of bowl shaped surfaces. Using this irradiating scheme, an approximately symmetric bowl shaped surface is obtained.

2.0 EXPERIMENTAL WORK

In the experiments, the samples were prepared from mild steel with the dimensions of 100 mm (length) × 100 mm (width) × 0.85 mm (thickness). A CO2 laser with continuous wave and maximum power of 150 Watts was used for laser forming experiments. In order to increase the heat absorptivity of the irradiated surface, the samples were first cleaned with acetone and then coated with graphite. Fig.1 shows experimental set up for laser forming of a saddle shape part and formed specimens are shown while Fig.2 shows a square plate and schematic view of a spiral path. A coordinate measuring machine (CMM) was used to measure the deformations of obtained saddle shape part.

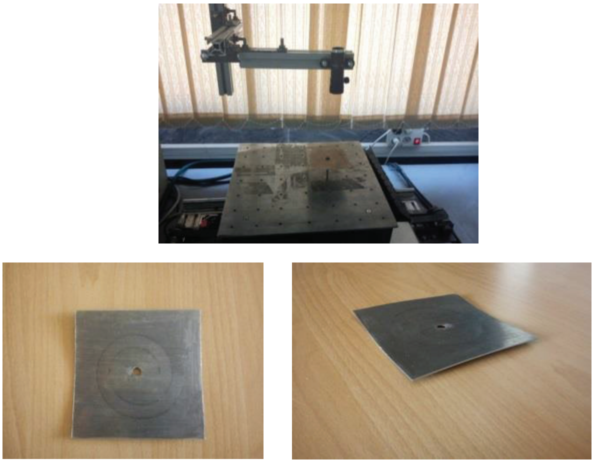
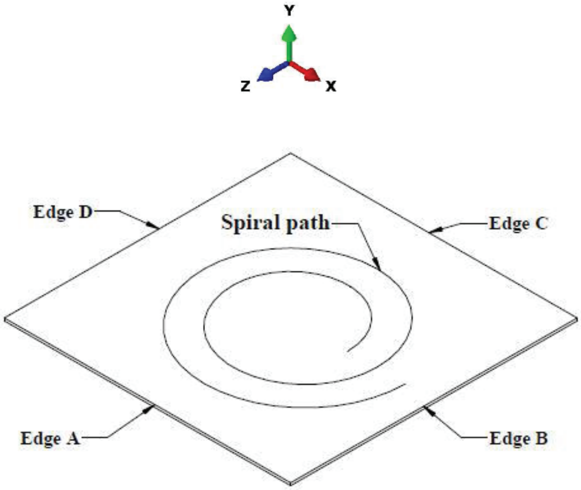


Figure 1: Experimental set up for laser forming of a saddle shape and formed specimens



Spiral path information	
First circle radius	20 mm
Spiral pitch	10 mm

Figure 2: Schematic view of a square plate and its spiral path information

3.0 NUMERICAL WORK

Numerical simulations were performed using finite element method and ABAQUS implicit code. In the numerical simulations of laser forming process, energy dissipation by plastic deformations is negligible in comparison with high laser energy. Therefore, in all simulations, mechanical analyses were performed decoupled from thermal analyses. The surface heat flux distribution was computed according to the following formula:

$$Q(x,z)=\frac{3\eta P}{\pi R^{2}}Exp\left(-3\left(\left(\frac{x}{R}\right)^{2}+\left(\frac{z}{R}\right)^{2}\right)\right) \tag{1}$$

where is the laser absorption coefficient of the irradiated surface, is the laser beam power, is the radius of laser beam irradiated to the surface of sheet metal and and are the distances of a point away from the center of the laser beam. The material used in this study was mild steel with an absorption coefficient of about 0.50. Boundary heat transfer was modeled by natural heat convection and radiation. For boundary condition in mechanical analysis, necessary constraints were added to eliminate rigid body movement. The material properties of the mild steel were temperature dependent, such as heat conductivity, specific heat, Young's modulus, expansion coefficient and yield stresses and the required data have been taken from [12]. Fig.3 shows obtained saddle shape part from laser forming with spiral irradiating scheme in the numerical simulation. A saddle shape part was produced successfully with spiral irradiating scheme.

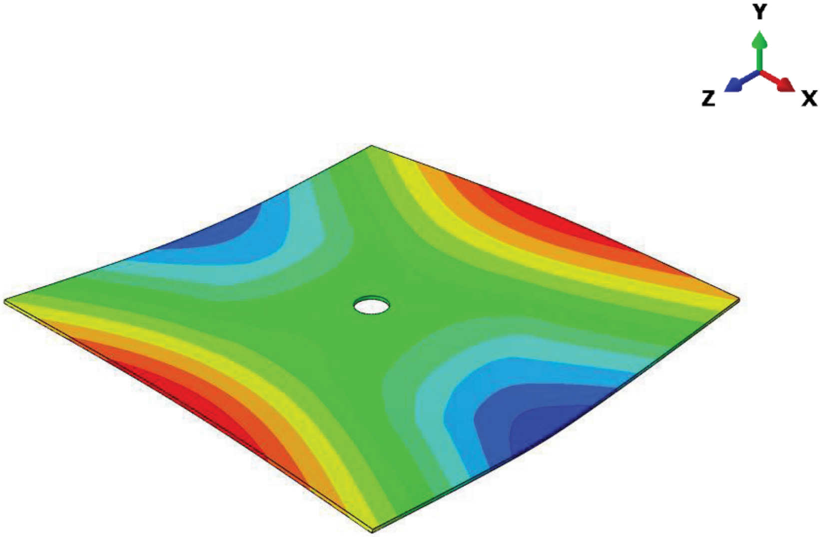


Figure 3: Doubly curved saddle shape that is obtained from laser forming with spiral irradiating scheme in the numerical simulation

4.0 RESULTS AND DISCUSSION

In the numerical simulation, it is necessary to evaluate the true heat flux distribution from a laser beam. In the experiments, a sample plate was made from mild steel with 60mm (length) × 50mm (width) and 1 mm thickness. As in the caseof laser output power, beam diameter and scan velocity were adjusted to 120 Watts, 0.85 mm and 50 mm/min respectively. Temperature profiles on the bottom surface under the heat line and on the top surface with 1 mm distance from the center of heat line were measured using two thermocouples (type K) stuck at these locations. Figure 4 shows experimental setup of this test.

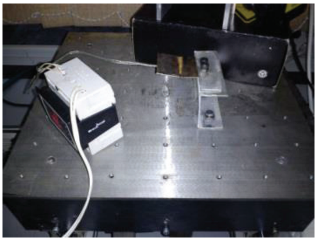


Figure 4: Experimental setup for measuring of temperature profiles on the bottom surface under the heat line and on the top surface with 1 mm distance from the center of heat line with thermocouple

In the numerical simulations, (with power of 120 Watts, beam diameter of 0.85 mm and scanning velocity of 50 mm/min) temperature profiles on the bottom surface under the heat line and on the top surface with 1 mm distance from the center of heat line by adjustment of heat flux parameters (laser absorption coefficient of the irradiated surface, coefficient of convection heat transfer and surface emissivity) were obtained. Temperature profiles were compared with finite element simulations to obtain the corresponding heat flux distribution. Predicted temperature profiles of the numerical simulations and experimental measurements are shown in Figure 5. By adjusting heat flux parameters in the simulation, a good agreement between experimental and numerical measurements could be obtained. Although there are many parameters that affect temperature field such as thermal properties of the blank, heat transfer coefficients, beam diameter and laser output power, experimental and numerical temperature fields are within an acceptable close range.

In the forming of a saddle shape, curvatures values on the edges and also symmetry of final shape are important parameters that should be checked. In Figs. 6 and 7, Y-displacements of the free edges A, B, C and D for obtained saddle shape with the above mentioned spiral irradiating scheme in experimental and numerical works are shown. In the experiments, Y-displacements were measured with a coordinate measuring machine (Name and model of the CMM: Easson ENC-565). The accuracy of measurements for this machine was $0.5\mu m$.

Figures 6 and 7 show that curvatures of the obtained saddle shape are noticeably large. Hence, spiral irradiating scheme is a very suitable heating path to produce saddle shapes with large curvatures. The magnitude of Y-displacements of similarly formed edges can be defined as a criterion for symmetry in a saddle shape part. According to this criterion, symmetry of similarly formed edges in the obtained saddle shape was defined with average value of differences between Y-displacements of some similar points on these edges. Table 1 shows the magnitudes of symmetry of obtained saddle shape in experimental and numerical works for free edges of A and C .

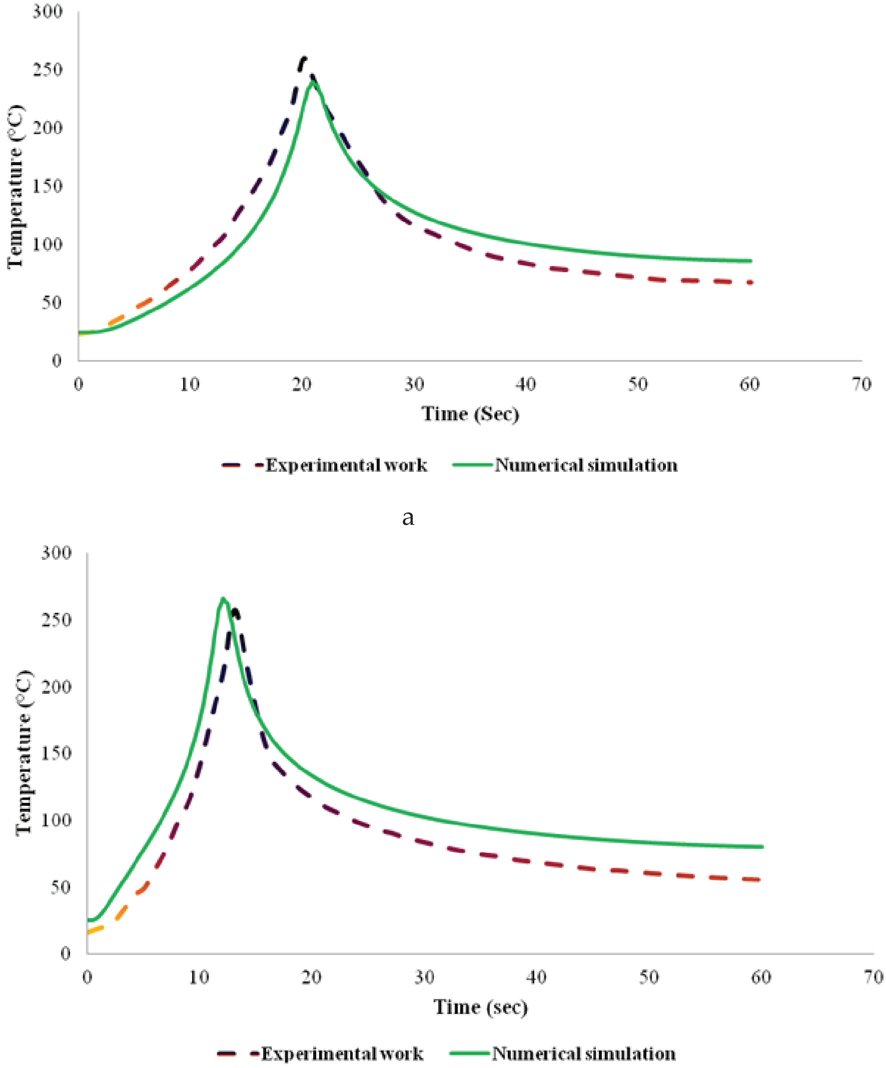


Figure 5: Temperature profiles obtained from experimental and numerical works for two sample points of the plate at the end of heating step: a- on the top surface with 1 mm distance from the heat line, b- on the bottom surface under the heat line

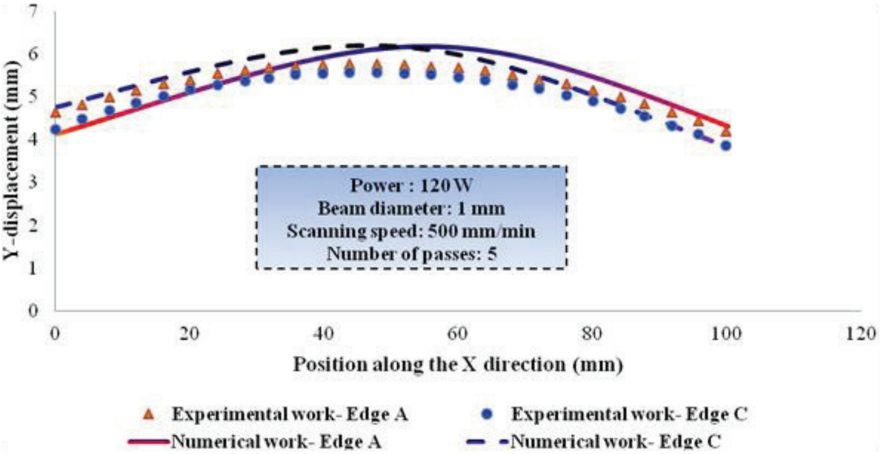


Figure 6: Experimental and numerical results of Y-displacements of the free edges of A and C

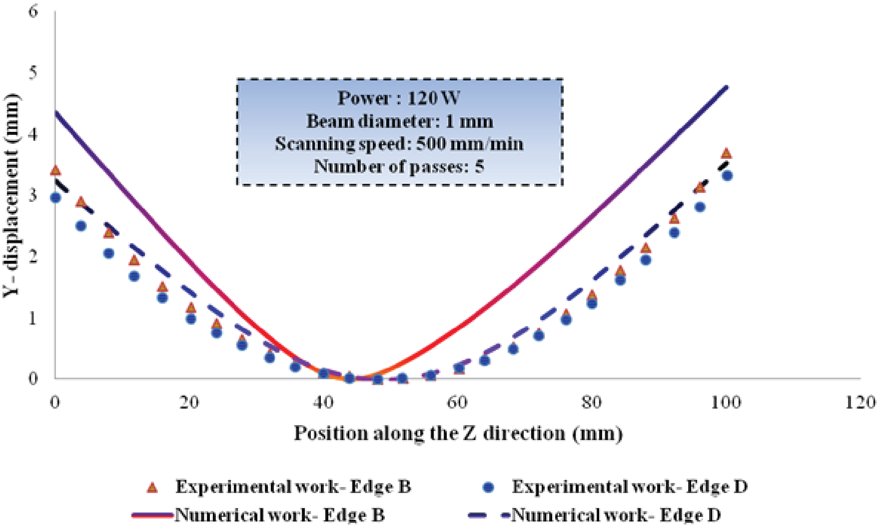


Figure 7: Experimental and numerical results of Y-displacements of the free edges of B and D

Table 1: Symmetry of similarly formed edges of A and C for obtained saddle shape with spiral irradiating scheme in experimental and numerical works

Similarly formed edges of A and C	Experimental work	Numerical work
Symmetry (%)	90.75	85.06

Table 2 shows the magnitudes of symmetry of obtained saddle shape in experimental and numerical works for free edges of B and D.

Table 2: Symmetry of similarly formed edges of B and D for obtained saddle shape with spiral irradiating scheme in experimental and numerical works

Similarly formed edges of B and D	Experimental work	Numerical work
Symmetry (%)	89.89	77.85

In general, both tables show that there is a good symmetry between similarly formed edges of the saddle shape part obtained by spiral irradiating scheme for experimental and numerical works. Therefore, all those results show that production of a doubly curved saddle shape with quite large curvatures with a suitable symmetry between similarly formed edges is possible with spiral irradiating scheme.

5.0 CONCLUSION

In conclusion, The following results are obtained in the study:

- Heat flux distribution in the numerical simulations is defined and calibrated with experimental measurements. The idea is to heat a plate with a laser beam in the experiments and measure the temperature profile on the bottom surface under the heat line and on the top surface with 1 mm distance from the center of heat line. After which the profile is compared to finite element simulations to establish the corresponding heat flux distribution. It is concluded that evaluated heat flux distribution with this procedure is in good agreement with temperature profile obtained from experimental measurements.
- There is a good agreement between experimental and numerical results for Y-displacements of free edges of obtained saddle shape part.
- In general, experimental and numerical results show that the proposed spiral irradiating scheme is a very good method for producing a saddle shape part with considerable amount of curvatures. There is also a suitable symmetry in the similarly formed edges of obtained saddle shape using spiral irradiating scheme.

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