IJMF, Iranian Journal of Materials Forming, Vol. 4, No. 2, pp 1-14
Printed in The Islamic Republic of Iran, 2017

A Novel Method for Laser Forming of Two-Step Bending of a Dome Shaped Part

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Abstract: In recent decades, one of the challenges in sheet metal forming was production of two-step bending surfaces without mechanical tools and external force or by a combination of heat source and mechanical tools. Forming with a heat source such as laser beam has the potential of forming arbitrary 3D shapes such as two-step bending surfaces. In this paper, a novel method for laser forming of complicated two-step bending dome shaped part is proposed. The initial sheets are made from mild steel with thickness of 0.85 mm. In this method, combination of simple straight lines leads to production of a two-step bending dome shaped part. The obtained results show that the proposed method is a powerful irradiating scheme for production of two-step bending dome shapes with considerable deformations and symmetries. In addition, using an analytical study, the mechanics of plate deformation is precisely investigated. All of the investigations are performed experimentally and numerically and it is shown that numerical results are in a good agreement with the experimental observations.

Keywords: Laser forming, Two-step bending, Dome shaped part

1. Introduction

The application of lasers in industry is increasing recently. Laser materials processing such as laser hardening, laser welding, laser drilling, laser cutting and laser forming have been studied by many researchers [1-8]. Metal forming with a moving heat source such as laser beam is one of the most economical methods of forming three-dimensional complex shapes which are used in ship, automobile and airplane bodies. The laser beam can be used to produce complicated shapes with two-step bending by developing necessary thermal strains in the plate in order to generate the desired shapes. Considerable amount of research has been carried out on two dimensional laser forming [9-12]. However, in order to advance the process further to industrial applications, it is necessary to study and digest 3D laser forming. 3D laser forming studies have recently been investigated and few research have been reported in this field due to its extreme complexities. Ueda et al. [9] 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. Jang et al. [10] 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. They obtained heating lines by linear regressions on the grouped points. Yu et al. [11] presented

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Received by the editors February 11, 2017; Revised May 15, 2017 and Accepted May 24, 2017.

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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. Ishiyama et al. [12] proposed a method to determine heating paths where the heating lines for bending strain and in-plane strain are independently calculated by using two procedures: (1) contour heating method and (2) conversion algorithm to the orthogonal compressive inherent strain. Hennige [13] investigated the differences in the forming behavior of sheet metal parts using straight and curved irradiations. Moreover, using radial and circular laser scan paths, he produced a dome shape plate from a circular blank. Shin et al. [14] proposed a non-dimensional relationship between input parameters and final deformation during line heating process by using the flame heat. Kim et al. [15] developed a method which is reliable and easy to be applied, to solve the inverse problem in the laser forming process. They proposed a distance-based method and an angle-based method to generate an irradiation path strategy and to obtain desired angles at each irradiation path. Liu et al. [16] 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. Zhang et al. [17] simulated laser forming of a plate with a B-spline curve path. They also investigated various temperature fields, displacement fields, stress and strain fields. Their results showed that peak temperatures of the upper surface and the warped curvature increase when the path curvature increases. Kim and Na [18] 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. Chakraborty et al. [19] produced a bowl shaped surface with combination of radial and circular laser scan paths. Also, they investigated 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. Safari et al. [20] proposed spiral irradiating scheme for laser forming of a two-step bending saddle shaped part. Their results showed that spiral irradiating scheme is a suitable and powerful method for production of saddle shapes.

In all of the previous research mentioned above, nothing was suggested regarding a comprehensive and easy methodof producing two-step bending dome shaped part. Some of them have limited capabilities in the production and the others have very much complexities in the prediction of heating lines for proposing an irradiating scheme. Furthermore, heating lines that are suggested with those methods are very complex curves and some of them are difficult to use in a CNC controller.

In this work, a new irradiating scheme is proposed to produce two-step bending dome shaped part. This method is a very simple and industrial irradiating scheme that only contains straight heating lines. Using this irradiating scheme, a two-step bending dome shaped part can be successfully produced with considerable deformations. Also, obtained dome shaped part with this irradiating scheme has noticeable symmetries. In this paper, all of investigations are performed experimentally and numerically and the results indicate that numerical results are in a good agreement with the experimental observations.

2. Experimental Work

In the experiments, the samples are made from mild steel with 100 mm (length) × 60 mm (width) × 0.85 mm (thickness). First curvature of the specimens is created using a mechanical roller. The radius of curvature that is created with roller machine is 120 mm. After rolling, all of specimens are heat treated for relieving the residual stresses. In Fig. 1, a specimen after rolling and heat treating is shown.

Fig. 1. A specimen after rolling and heat treatment with radius of curvature of 120 mm.

Second curvature is created using a continuous laser beam. Laser forming experiments are carried out with a continuous CO_2 laser with the maximum power of 150 Watts. The Focal plane position of the laser beam (distance between spot point and material workpiece) is 190 mm. The samples are first cleaned with acetone and then coated with graphite in order to improve the heat absorptivity of the irradiated surface. It should be mentioned that the purpose of this work is proposing a new irradiating scheme for production of second curvature of a dome shaped part. It is assumed that all of the specimens have a first curvature with a specific radius of curvature of 120 mm. Therefore, in this work, all of the investigations are focused on laser forming of a dome shaped part from a specimen with initial curvature. In Fig.2, experimental set up for laser forming of a dome shaped part is shown.

Fig. 2. Experimental setup for laser forming of a dome and saddle shapes.

Also, in Fig. 3 schematic view of the proposed irradiating scheme for production of a dome shaped part from a specimen with initial curvature is shown.

As it is seen in Fig. 3, in this irradiating scheme discontinuous heating lines are used. Also, in order to balancing the heat distribution in the plate and consequently more symmetries in the obtained dome shaped part, sequential heating paths are arranged in the opposite directions. It should be mentioned that the distance between heating paths has been adjusted so that each heating line is not reacted with thermal effects of neighbor heating lines. In the experiments, the power of laser, beam diameter and scanning speed are adjusted as 100 Watts, 1 mm and 300 mm/min respectively. In Fig.4, obtained dome shaped part from laser forming with the proposed irradiating scheme is shown.

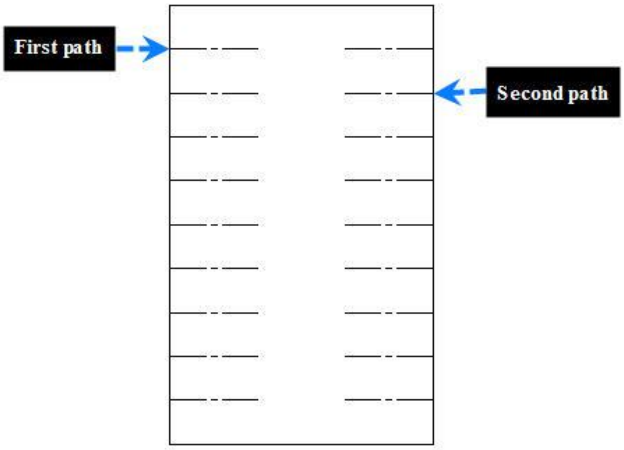


Fig. 3. Schematic of the proposed irradiating scheme.

Fig. 4. Obtained dome shaped part with the proposed irradiating scheme.

As it is seen from Fig. 4, a dome shaped part can be successfully produced with the proposed irradiating scheme in the laser forming process.

3. Numerical Work

In the numerical investigations, the finite element method has been used for thermal and mechanical analysis of laser forming. For this purpose, ABAQUS implicit code has been used. In these simulations, mechanical calculations can be decoupled from thermal ones. This is because of negligible energy dissipation by plastic deformation as compared with the high laser energy used in the process. In the 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. The surface heat flux distribution is computed according to Gaussian distribution from 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 η is the laser absorption coefficient of the irradiated surface, P is the laser beam power, R is the radius of laser beam irradiated to the surface of sheet metal and x and z are the distances of a point away from the center of the laser beam. The material used in this research is mild steel with an absorption coefficient of about 0.65. Boundary heat transfer is modeled by natural heat convection and radiation. Convection follows Newton's law, the heat loss rate per unit area in Wm^{-2} due to convection is:

$$q_c = h_c(T_s - T_a) \tag{2}$$

where h_c is the coefficient of convection heat transfer, T_s is the temperature of irradiated surface and T_a is the ambient temperature. The heat loss rate per unit area in Wm^{-2} due to radiation is:

$$q_r = 5.67 \times 10^{-8} \varepsilon (T_s^4 - T_a^4) \tag{3}$$

where ε is the surface emissivity, whose value depends on the surface conditions and the temperature of the metal plate. A constant surface emissivity of $\varepsilon = 0.5$ is used for estimation of heat loss due to radiation. For boundary condition in mechanical analysis, necessary constraints are added to eliminate rigid body movement. In the mechanical analysis, the twenty-node 3D element, C3D20 has been used. This element type has no shear locking or hourglass effects and therefore is suitable for a bending dominated process such as laser bending. A twenty-node element, DC3D20, is also used in the thermal analysis. In order to optimize the mesh size in the numerical simulations, the mesh sensitivity is conducted. The material properties of the mild steel are temperature dependent and the various values of thermal and mechanical properties at different temperatures are listed in Tables 1 and 2, respectively [14]. Figure 5 depicts the obtained dome shaped part with the proposed irradiating scheme.

Table 1. Thermal properties of mild steel [7].

Temperature ($^\circ C$)	Thermal conductivity (W/mm/$^\circ C$)	Specific heat (KJ/Kg/$^\circ C$)
00	51.9E-3	486
100	51.1E-3	486
200	48.6E-3	498
300	44.4E-3	515
400	42.7E-3	536
500	39.4E-3	557
600	35.6E-3	586
700	31.8E-3	619
800	26.0E-3	691
900	26.4E-3	695
1000	27.2E-3	691
3000	120.0e-3	700

Table 2. Mechanical properties of mild steel [7].

Temperature ($^\circ C$)	Elasticity modulus (N/mm^2)	Poisson's ratio	Expansion	Yield stress for $e_p = 0$ (N/mm^2)	Yield stress for $e_p = 0.1$ (N/mm^2)
20	0.206E+06	0.296	0.117E-04	344.64	422.64
100	0.203E+06	0.311	0.117E-04	331.93	409.93
200	0.201E+06	0.330	0.122E-04	308.30	386.30
300	0.200E+06	0.349	0.128E-04	276.07	342.57
400	0.165E+06	0.367	0.133E-04	235.22	290.22
500	0.120E+06	0.386	0.138E-04	185.77	230.77
600	0.600E+05	0.405	0.144E-04	127.71	162.71
700	0.400E+05	0.423	0.148E-04	68.55	96.05
800	0.300E+05	0.442	0.148E-04	64.35	84.35
900	0.200E+05	0.461	0.148E-04	46.65	60.65
1000	0.100E+05	0.480	0.148E-04	11.32	21.32
3000	0.100E+05	0.480	0.148E-04		

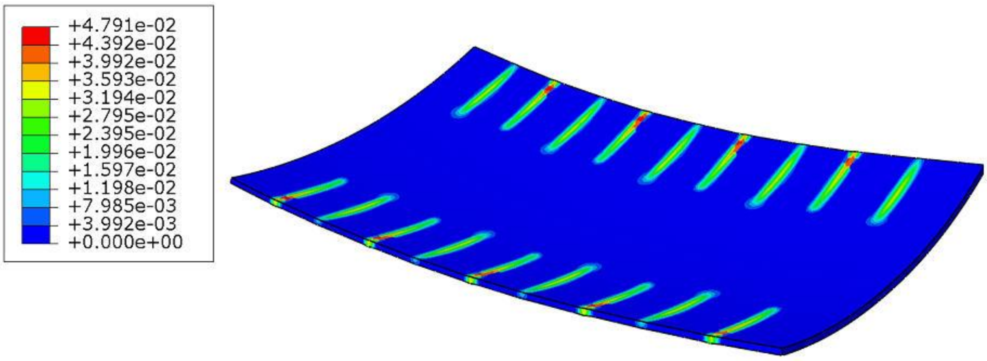


Fig. 5. Effective plastic strains of a dome shape part obtained from the proposed irradiating scheme

4. Results and Discussion

In the numerical simulation, it is necessary to evaluate the true heat flux distribution from a laser beam. To evaluate the laser true heat flux in the experiments, a sample plate is selected from mild steel with 60mm (length) × 50mm (width) and 1 mm thickness. Also, in a case study laser output power, beam diameter and scan velocity are adjusted as 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 heating line are measured using two thermocouples (type K) stuck at these locations.

Figure 6 illustrates the experimental setup of this test. 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 heating line by adjustment of heat flux parameters (laser absorption coefficient of the irradiated surface, coefficient of convection heat transfer and surface emissivity) are obtained. Temperature profiles are 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 Fig.7. As it is seen in this figure, by adjusting heat flux parameters in the simulation, a good agreement between experimental and numerical measurements can be obtained.

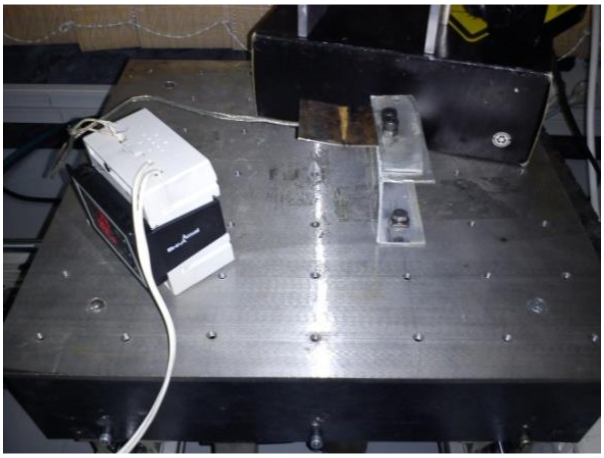
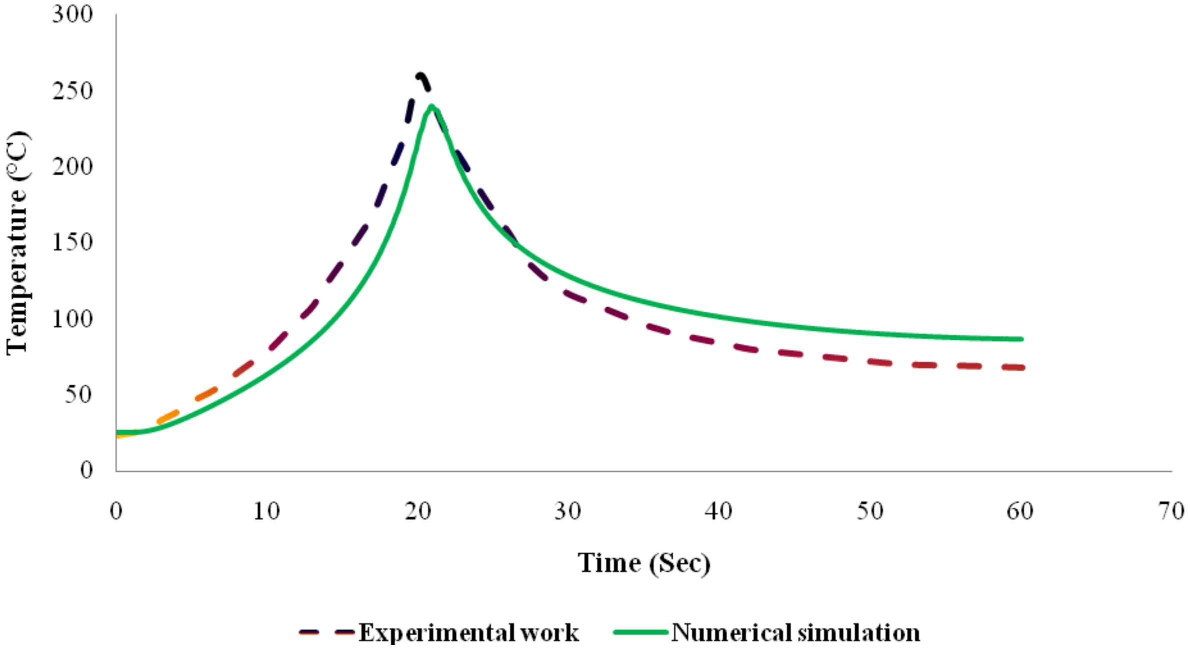
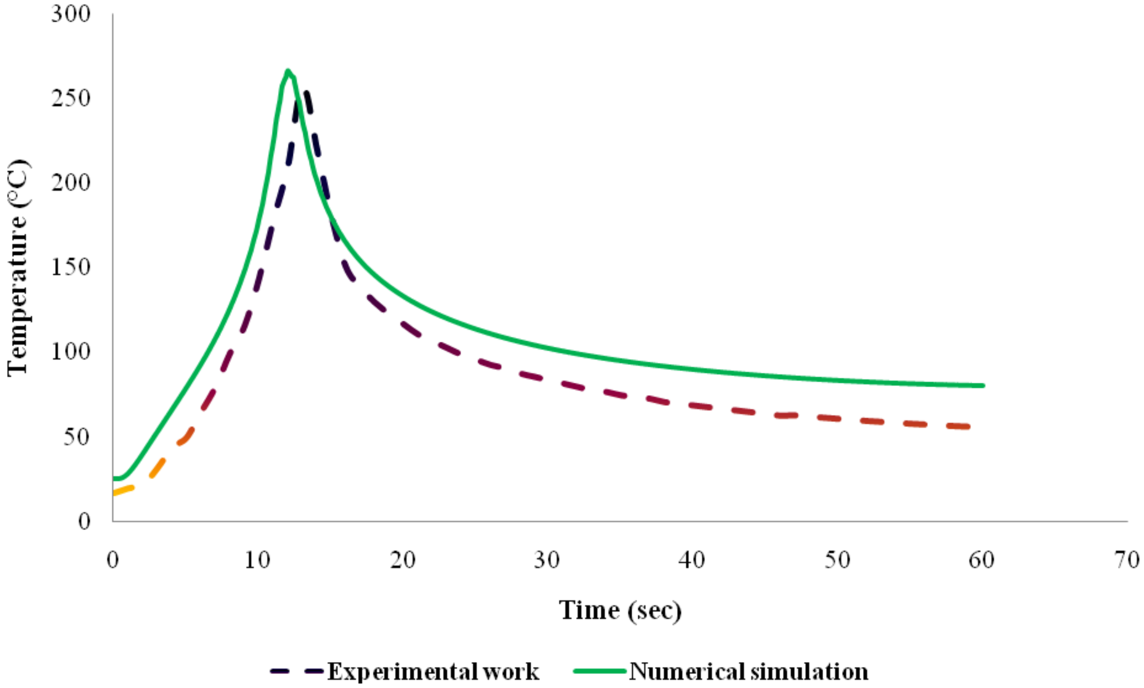


Fig. 6. Experimental setup for measuring temperature profiles on the bottom surface under the heat line and on the top surface with 1 mm distance from the center of heat line with thermocouple.



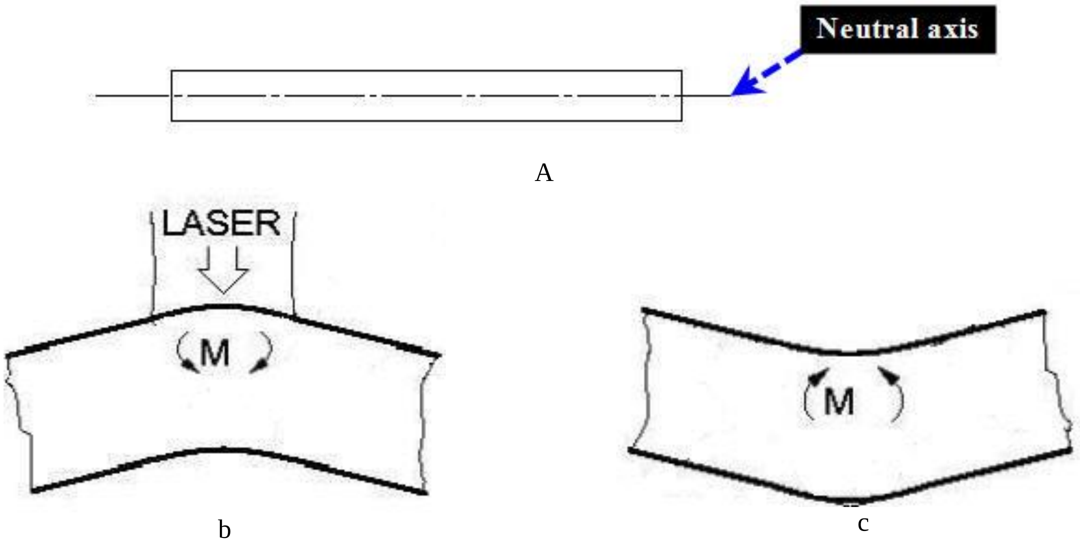
a



b

Fig. 7. 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.

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, however these results indicate that experimental and numerical temperature fields are in an acceptable close range. In this section, it is necessary to investigate the differences between laser forming of flat sheets and the sheets with initial curvature (curved sheet). In a laser forming process with temperature gradient mechanism (TGM), when a laser beam irradiates a flat sheet, a temperature gradient across the thickness of heated zone of plate generates different expansions across the thickness and thus a counter bending occurs in the plate. In this state, tensile forces in the top layers of the plate leads to create the moments around the neutral axis of plate and these moments lead to counter bending in of the plate in opposite direction to the laser beam. After the plate cools down, as a result of compressive plastic strains, the heated area shrinks and causes the plate to bend in the reverse direction. In other words, in this state the compressive forces in the top layers of the plate leads to create the moments around the neutral axis of the plate and these moments leads to bending of the plate towards the laser beam. In Fig. 8 a flat plate and its neutral axis is shown.



A

b

c

Fig. 8. Position of neutral axis and direction of moments in the laser forming of a flat plate, a) A flat plate and its neutral axis, b) Direction of moments in the heating stage, c) Direction of moments in the cooling stage

Figure 9 depicts a curved plate and position of its neural axis.

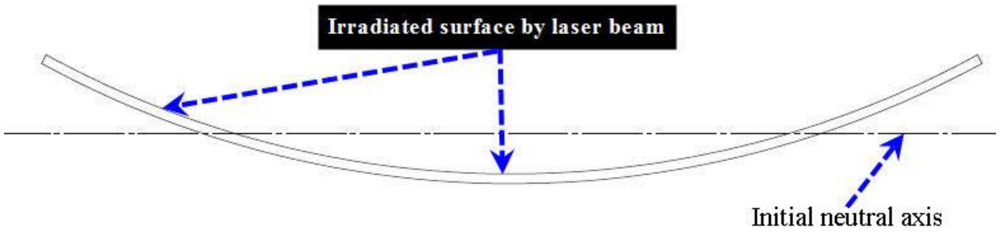


Fig. 9. A curved plate and position of its initial neutral axis.

As it is seen in Fig. 9, positions of irradiated surfaces in an irradiating path are over and under the neutral axis of the curved plate. In the heating stage of laser irradiating of curved plate, the moments of tensile forces for surfaces that are positioned over the neutral axis leads to a counter bending in the plate. In the cooling stage, an inverse behavior hashappened for the moments of compressive forces of surfaces that are positioned over and under the neutral axis. Final direction of bending of a curved plate is dependent on the amounts of moments for surfaces that are positioned over and under the neutral axis. It is seen that the behavior of bending of a curved plate is more complicated than a flat plate. As an important result from analysis of forming behavior of a curved plate, it is concluded that a dome or saddle shape can be successfully obtained with irradiating the areas over and under the neutral axis of a curved plate respectively. As a result, it should be mentioned that in laser irradiating of a flat plate, all of irradiating areas are over the neutral axis while in the laser irradiating of a curved plate some of irradiating areas are over the neutral axis and the other areas are under the neutral axis. In other words, in the laser irradiating of a flat plate, final bending direction of the plate is always towards the laser beam but in curved plate, the final bending direction is related to amount of bending moments over and under the neutral axis.

It is obvious that a dome shape with maximum deformations can be obtained from irradiating a curved plate with proposed irradiating scheme, if the areas positioned from rim of the curved plate up to neutral axis (over the neutral axis) are irradiated with the laser beam. For investigating the effect of irradiating length on the deformation of obtained dome shaped part, a curved plate that its information is presented in Fig.10 is irradiated with different lengths of the proposed irradiating scheme. The dimensions of the initial flat plate are 100 mm (length) × 60 mm (width) × 0.85 mm (thickness). Moreover, the radius of curvature that is created with roller machine is 120 mm. For this specimen, the maximum length of irradiating path from rim of the plate up to neutral axis is calculated as 21.21 mm. For investigating the effect of irradiating path on the deformation amount of curved plate, the plate is irradiated with different lengths (from rim of the plate up to neutral axis) and then Y-displacement of sample point A is measured with a CMM machine. As it is seen in Fig. 10, sample point A is located in the center of the edge of the curved plate. In Fig. 10, Y-displacement of sample point A for different values of heating path is presented. As it is seen in this figure, there is a good agreement between experimental measurements and numerical results. Furthermore, it is concluded from Fig. 10 that maximum deformation for sample point A is 21.5 mm for experimental measurements and 22 mm for numerical results.

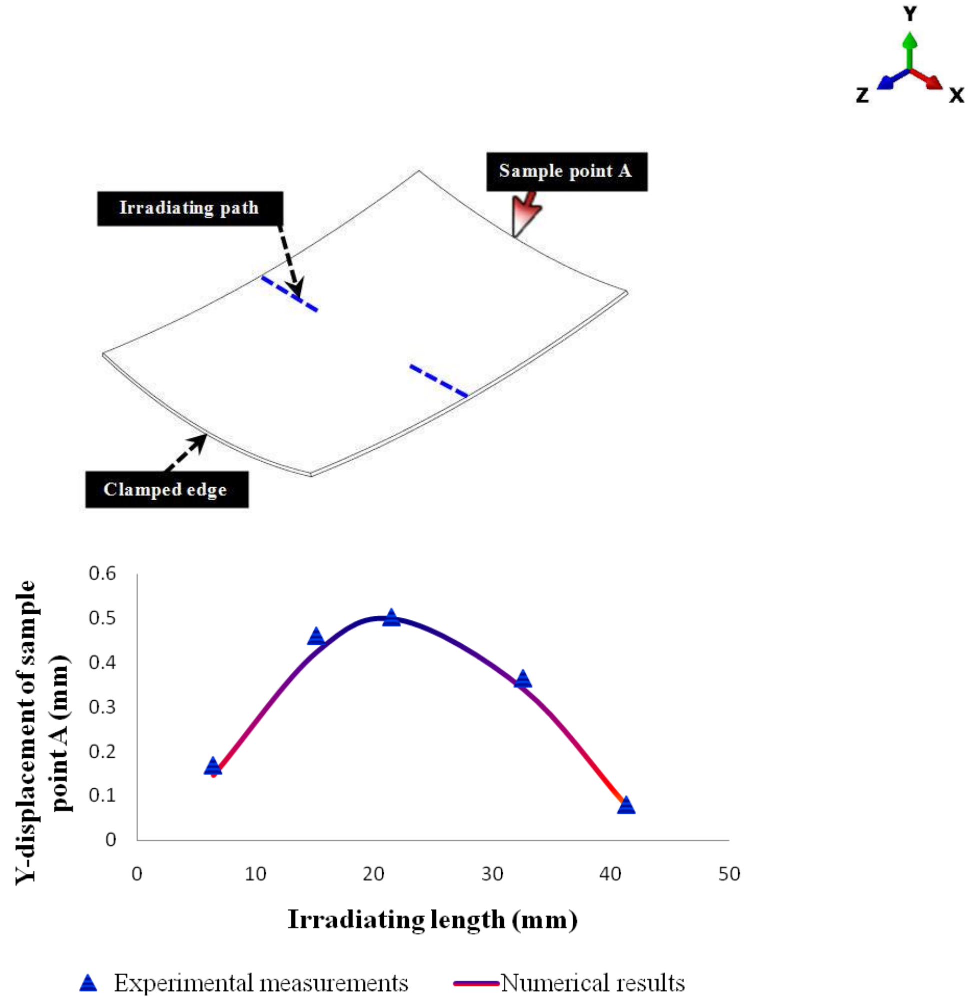


Fig. 10. Y-displacements of sample point A with different values of irradiating length over the neutral axis for production of a dome shapes part.

As the calculated length from rim of the curved plate to its neutral axis is 21.21 mm, the results of Fig.10 prove that maximum deformation of the dome shaped part with the proposed irradiating scheme is achievable with irradiation of the curved plate from rim of the plate up to its neutral axis. In the following, the characteristics of the obtained dome shaped part are presented. In the production of a dome shaped part, amount of deformations and also symmetry of obtained dome shape are important parameters that should be checked. In Figure 11, Y-displacements of the obtained dome shaped part with the proposed irradiating scheme are shown.

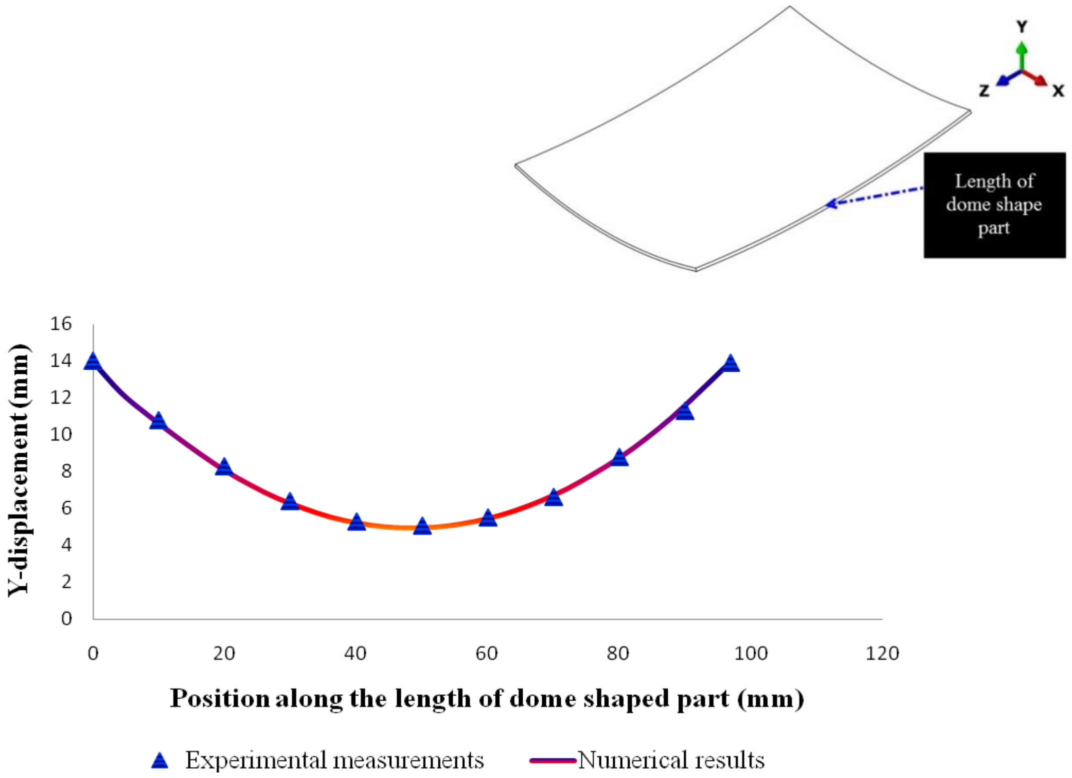


Fig. 11. Y-displacements of the obtained dome shape part with the proposed irradiating scheme.

As it is seen in Fig. 11, using the proposed irradiating scheme, a dome shaped part with considerable amount of deformations can be successfully produced. For investigating the symmetry of the obtained dome shaped part, two different types of symmetries are presented. In Fig. 12, these two types of symmetries are described.

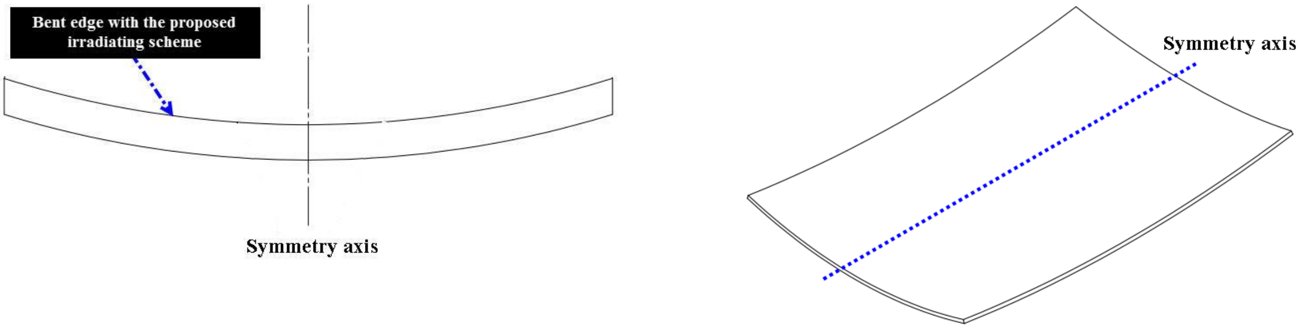


Fig. 12. Two types of symmetries for the obtained dome shaped part.

As it is seen in Fig. 12, for evaluating the first type of symmetry, the difference between Y-displacements of similarly points that are positioned in two sides of the symmetry line is calculated. Therefore, according to this description and using Fig. 11, the first type of symmetry of the obtained dome shaped part with the proposed irradiating scheme can be calculated. However, it is evaluated from Fig. 11 that the first type of symmetry of the produced dome shaped part is approximately 98.44%. Also, in a dome shape part, the magnitude of Y displacements of similarly formed edges can be defined as a criterion for second type of symmetry. According to this criterion, symmetry of similarly formed edges in the obtained dome shape is defined with average value of differences between Y-displacements of some similar points on these edges. In Fig. 13, Y-displacements of both bent edges of the obtained dome shape part with the proposed irradiating scheme are shown. As it is seen in Fig. 13, second type of symmetry for the obtained dome shape part is noticeable both in experimental and numerical results. From Fig. 13, the second type of symmetry in the experimental results is calculated as 98.40% while this value for numerical results is about of 97%. Therefore, it is proved that the produced dome shape part with the proposed irradiating scheme has considerable symmetries and successfully can be used in the relative industries.

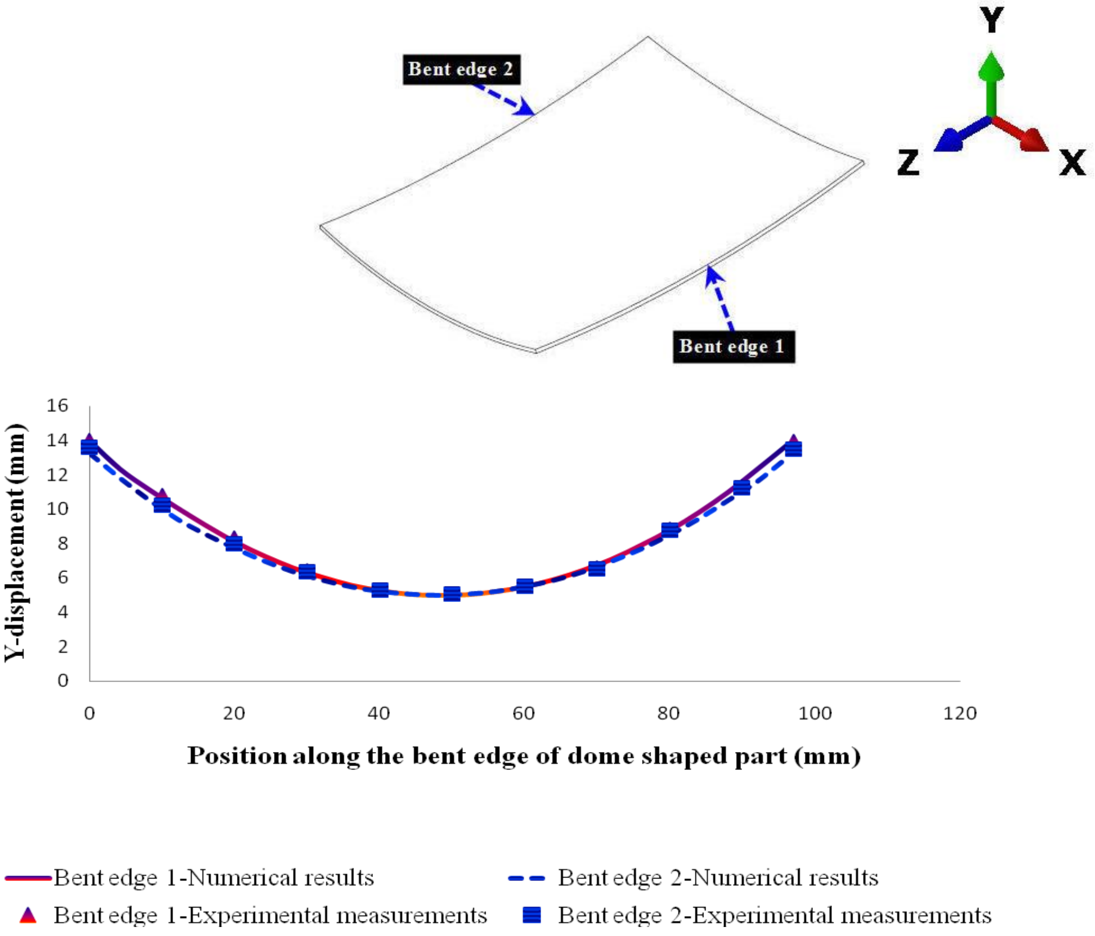


Fig. 13. Y-displacements of both bent edges of the obtained dome shape part.

5. Conclusion

In this work, a novel method for production of a dome shaped part was proposed. Investigations were performed using experimental tests and finite element simulations of laser forming process. Laser forming experiments were carried out with a continuous CO_2 laser with the maximum power of 150 Watts. In the numerical investigations, the finite element method was used for thermal and mechanical analysis of laser forming. For this purpose, ABAQUS implicit code was used. The following results were obtained from this paper:

1) Experimental tests and numerical simulations showed that the proposed irradiating scheme can successfully produce a dome shape part. Also, numerical simulations were verified with the experimental observations.
2) Using an analytical study, the mechanics of deformation of initial curved plate in the laser forming with the proposed irradiating scheme was investigated.
3) Experimental and numerical results showed that using proposed irradiating scheme a dome shape part can be produced with considerable deformations.
4) The results showed that the obtained dome shape part with the proposed irradiating scheme has noticeable symmetries.

Finally, it was concluded from experimental and numerical results that the proposed irradiating scheme is a powerful method for producing dome shape parts and it is very suitable in the relative industries for production of two-step bending shapes.

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یک روش جدید برای شکل دهی به کمک لیزر خمش دو مرحله ای قطعه گنبدی

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چکیده: در دهه های اخیر، یکی از مهمترین چالش ها در شکل دهی ورق های فلزی، تولید سطوح دو منحنی بدون استفاده از ابزارهای مکانیکی و نیروهای خارجی و یا ترکیبی از منابع حرارتی و برخی ابزارهای مکانیکی بوده است. شکل دهی با یک منبع حرارتی مانند پرتوی لیزر پتانسیل شکل‌دهی اشکال سه‌بعدی اختیاری مانند سطوح دو منحنی را دارد. در این مقاله یک روش جدید برای شکل‌دهی قطعه گنبدی پیشنهاد می‌شود. در این روش، ترکیبی از خطوط ساده مستقیم منجر به تولید قطعه گنبدی دو منحنی می شوند. ورق های اولیه از فولاد کم کربن با ضخامت 0/85 میلیمتر تهیه می شوند. نتایج این مقاله نشان می دهند که روش پیشنهاد شده یک الگوی تابش دهی قوی برای تولید قطعات گنبدی دو منحنی با تغییر شکل ها و تقارن قابل توجه می باشد. به علاوه، با استفاده از یک مطالعه تحلیلی، مکانیک تغییر شکل ورق با الگوی تابش دهی پیشنهاد شده دقیقاً بررسی می شود. همه بررسی ها به صورت تجربی و عددی انجام می شوند و نشان داده می شود که نتایج عددی تطابق خوبی با مشاهدات تجربی دارند.

واژه های کلیدی: شکل دهی با لیزر، دو منحنی، قطعه گنبدی