Alexandria Engineering Journal (2016) 55, 1941–1949

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ORIGINAL ARTICLE

Experimental and numerical investigation of laser forming of cylindrical surfaces with arbitrary radius of curvature

Mehdi Safari [a,*], **Hosein Mostaan** [b]

[a] Department of Mechanical Engineering, Arak University of Technology, Arak 38181-41167, Iran
[b] Department of Materials and Metallurgical Engineering, Faculty of Engineering, Arak University, Arak, Iran

Received 28 January 2016; revised 25 July 2016; accepted 28 July 2016
Available online 17 August 2016

KEYWORDS
Laser forming;
Cylindrical surface;
Arbitrary radius of curvature

Abstract In this work, laser forming of cylindrical surfaces with arbitrary radius of curvature is investigated experimentally and numerically. For laser forming of cylindrical surfaces with arbitrary radius of curvature, a new and comprehensive method is proposed in this paper. This method contains simple linear irradiating lines and using an analytical method, required process parameters for laser forming of a cylindrical surface with a specific radius of curvature is proposed. In this method, laser output power, laser scanning speed and laser beam diameter are selected based on laser machine and process limitations. As in the laser forming of a cylindrical surface, parallel irradiating lines are needed; therefore key parameter for production of a cylindrical surface with a specific radius of curvature is the number of irradiating lines. Hence, in the proposed analytical method, the required number of irradiating lines for production of a cylindrical surface with a specific radius of curvature is suggested. Performance of the proposed method for production of cylindrical surface with a specific radius of curvature is verified with experimental tests. The results show that using proposed analytical method, cylindrical surfaces with any radius of curvature can be produced successfully.

1. Introduction

Laser forming is a non-contact method of 2D bending, 3D shaping and precision alignment of metallic and non-metallic components. In the laser forming process a temperature gradient across the thickness of heated zone generates different expansions across the thickness and thus a counter bending occurs in the plate. In this state, plastic deformation occurs in the region under 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.

For the first time in 1986, Namba used laser beam as a tool for sheet metal forming [1]. After Namba, many researchers have done a lot of works in the laser bending of sheet metals. Some of those researches focused of laser

* Corresponding author. Fax: +98 861 3670021.
E-mail addresses: ms_safari2005@yahoo.com, m.safari@arakut.ac.ir (M. Safari).
Peer review under responsibility of Faculty of Engineering, Alexandria University.

http://dx.doi.org/10.1016/j.aej.2016.07.033
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bending of sheet metals with a single irradiating path. In 1993, Geiger and Vollertsen [2] identified three key mechanisms called temperature gradient mechanism (TGM), buckling mechanism (BM) and upsetting mechanism (UM) to explain the thermo-mechanical behavior in laser bending based on geometrical and laser beam parameters. Several works have been reported on numerical modeling of laser bending. In 1994, Holzer et al. [3] modeled buckling mechanism using the commercial finite element package ABAQUS. They used a user defined subroutine to model heat input. In 2001, Li and Yao [4] proposed a new scanning scheme with starting point from the middle of the work-piece and then they produced a convex shape plate. In 2005, Yanjin et al. [5] investigated the influence of material properties on the laser forming process of sheet metals. In their work, the relationship between the bending angle and material property parameters, such as Young's modulus, yield strength, thermal expansion coefficient, specific heat, and thermal conductivity, were studied in detail by FEM simulation. The simulations showed that the material with lower Young's modulus and yield strength can produce a larger bending angle. The thermal expansion coefficient is nearly in direct proportion to the bending angle. The bending angle decreases with the increase in the heat conductivity. A bigger bending angle can be obtained for the material with lower specific heat and density. In 2007, Zhang et al. [6] investigated the laser curve bending of sheet metals. In their work, a finite element model of heat flux based on scanning path described with B-spline curve was built. Then, FE simulation of laser beam scanning on the forming sheet metals was carried out. The simulated results showed that the peak temperatures of the upper surface increase when the laser power or the path curvature increases, but decrease when the laser spot diameter or the scanning velocity increases. In 2010, Liu et al. [7] investigated the negative laser bending process of steel foils. Their results showed that negative bending angles could be produced conveniently when the pre-stresses were induced by elastic pre-bending which direction away from the laser beam, and the angles increase remarkably with the pre-stresses increasing. In 2012, Knupfer et al. [8] measured the through-thickness transverse residual strain distribution by neutron diffraction in laser-formed low carbon steel and aluminum alloy specimens. In their work, the specimens were formed with a wide range of laser line energies covering the temperature gradient mechanism and upsetting mechanism, and for single and multi-pass forming (up to 3 laser passes). Their results showed that below the saturation line energy where the TGM dominates, the gradient of the through-thickness strain distribution was found to increase with increasing line energy and number of laser passes; the gradient decreased again at line energies above the saturation line energy where the efficiency of the TGM decreases. In 2013, Pence et al. [9] studied the laser shock bending of aluminum sheets in order to investigate the different deformation mechanism, positive or negative. Their investigations were conducted with different sheet thicknesses and laser pulse energies. In their work, a critical thickness threshold was found that the transition of positive-negative bending mechanism occurs. Also, a statistic regression analysis was developed to determine the bending angle as a function of laser process parameters for positive bending cases.

The reported researched in the laser forming with multi-irradiating lines are lower than laser forming with one irradiating line due to more complexity of laser forming with multi-irradiating lines. In 2007, Shen et al. [10] in a numerical work used two simultaneous laser beams along two parallel lines. They concluded that if the distance between two laser beams is not too large then plastic deformation generated in this state is larger than that generated by single sequential scans along the same lines. They also numerically investigated the effects of time intervals and overlapping on bending angles in laser bending using two simultaneous laser beams [11,12]. In 2003, Kim and Na [13] investigated free curve laser forming using multi irradiating lines by a geometrical approach. In their work, experimental investigations were performed by using the linear relationship between the bending angle and the line energy. The results of experiments were relatively good. However, the proposed geometrical method in this paper was very complicate for industrial applications. In other words, application of this geometrical algorithm is not possible for many of artisans and a new simple method for production cylindrical surfaces is needed.

In this work, laser forming of cylindrical surfaces with arbitrary radius of curvature is investigated experimentally and numerically. Experimental tests are performed using a continuous wave CO_2 laser machine with maximum power of 150 W. Numerical simulations are done with ABAQUS implicit code. Continuous moving heat source is implemented in the ABAQUS using DFLUX subroutine written in FORTRAN language. For laser forming of cylindrical surfaces with arbitrary radius of curvature, a new and comprehensive method is proposed in this paper. This method contains simple linear irradiating lines and using an analytical method, required process parameters for laser forming of a cylindrical surface with a specific radius of curvature is proposed. In this method, laser output power, laser scanning speed and laser beam diameter are selected based on laser machine and process limitations. As in the laser forming of a cylindrical surface, parallel irradiating lines are needed; therefore key parameter for production of a cylindrical surface with a specific radius of curvature is the number of irradiating lines. Hence, in the proposed analytical method, the required number of irradiating lines for production of a cylindrical surface with a specific radius of curvature is suggested. Performance of the proposed method for production of cylindrical surface with a specific radius of curvature is verified with experimental tests. The results show that using proposed analytical method, cylindrical surfaces with any radius of curvature can be produced successfully.

2. Experimental work

All of experimental tests are performed with a continuous wave CO_2 laser machine with the maximum power of 150 W. The samples are made from mild steel with 100 mm (length) × 60 mm (width) × 0.85 mm (thickness). In order to improve the heat absorptivity of the irradiated surface, the samples are first cleaned with acetone and then coated with graphite. In Fig. 1, schematic of proposed pattern for laser forming of cylindrical surfaces with arbitrary radius of curvature, experimental setup and a cylindrical surface that is produced with the proposed analytical method are shown. It

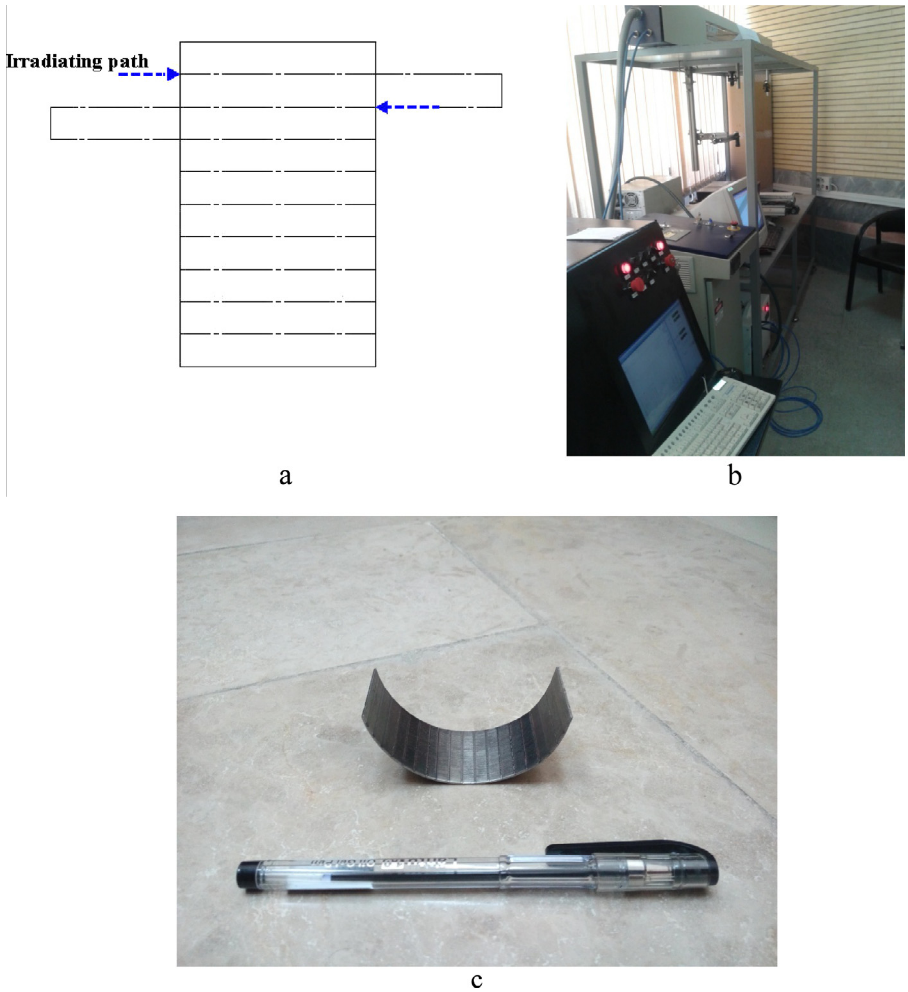

Figure 1 (a) Schematic of proposed pattern for laser forming of cylindrical surfaces with arbitrary radius of curvature, (b) experimental setup, (c) a cylindrical surface that is produced with the proposed analytical method.

should be noted that in the laser forming of a cylindrical surface, process parameters such as laser output power, laser scanning speed and laser beam diameter are selected based on laser machine characteristics and also maximum allowable temperature in the surface of sheet at irradiated area. Therefore, the key parameter in the laser forming of cylindrical surfaces that directly affect the radius of curvature of obtained cylindrical surface is the number of parallel irradiating lines. In the proposed method in this paper, using an analytical procedure the number of irradiating lines for production of a cylindrical surface with a certain radius of curvature is suggested. This analytical procedure is explained in the section of results and discussion. Radius of curvature of the obtained cylindrical surface is measured with a coordinate measuring machine (CMM, Model: Easson ENC-565). In the experiments laser fluence (J/cm^2), beam diameter during interaction with the material, focal position and scanning speed are 11.95, 0.85 mm, 190 mm and 300 mm/min respectively. Also, the polarization of laser beam in our CO_2 laser machine is circular polarization. As it is seen in Fig. 1a, the proposed pattern in this paper is a continuous pattern and therefore, process parameters are not changed in the translation stage from an irradiating line to its adjacent irradiating line.

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 the following formula based on Gaussian distribution [14]:

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

where η is the absorption coefficient of the irradiated surface, P is the laser power, R is the effective radius of laser that irradiated to the surface of the sheet metal, and x and z are the distances of a point away from the center of the laser. 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 W m^{-2} due to convection is [15]:

$$q_c = h_c(T_s - T_a) \quad (2)$$

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 W m^{-2} due to radiation is [15]:

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

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. 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 [14].

All simulations have been done in two steps. In the first step, the plate has been irradiated with laser and in the second one the plate has been cooled to the ambient temperature and the same convection coefficient has been used in both heating and cooling steps. Obviously, the same mesh is used for both thermal and mechanical calculations. As it was mentioned above, in the laser forming of cylindrical surfaces parallel irradiating lines are used. However, in each irradiating line, dense meshes have been used near the heat source to obtain more accurate results and also coarse meshes far from the heat source to reduce the run time. In Fig. 2, a cylindrical surface obtained from numerical simulations with the proposed analytical method is shown.

Table 1 Thermal properties of mild steel.

Temperature (°C)	Thermal conductivity (W/mm/°C)	Specific heat (kJ/kg/°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

4. Results and discussion

In simulations of laser forming, the mesh size is important. Using coarse elements reduces the accuracy of simulations and very fine elements will increase simulations time without improving the accuracy of results. In order to find an optimum mesh size, a sample point at one of irradiating paths is selected and temperature at this node is calculated at the end of irradiating for various numbers of elements. From Fig. 3, it is concluded that optimum number of elements for these simulations is about 40,000 elements.

Also, 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 made from mild steel with 60 mm (length) × 50 mm (width) and 1 mm thickness. Also, in a case study laser output power, beam diameter and scan velocity are adjusted as 120 W, 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 are measured using two thermocouples (type K) stuck at these locations. In Fig. 4 experimental setup of this test is shown.

In the numerical simulations (with power of 120 W, 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) 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. 5. As it is seen in this figure, by adjustment of heat flux parameters in the simulation, a good agreement between experimental and numerical measurements can 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, these results indicate that experimental and numerical temperature fields are in an acceptable close range.

In the proposed pattern for laser forming of a cylindrical surface (Fig. 1a), laser output power, laser scanning speed, laser beam diameter and number of parallel irradiating lines are process parameters that can affect the radius of curvature of the obtained cylindrical surface. As it was mentioned, laser output power, laser scanning speed and laser beam diameter are selected according to the laser machine characteristics and also maximum allowable temperature in the irradiated area of the sheet. The limit in the maximum allowable temperature of irradiated area of the sheet is melting temperature. Obviously, the maximum temperature of the upper surface of the sheet should be less than its melting temperature. Therefore, combination of laser output power, laser scanning speed and laser beam diameter must lead to a temperature in the upper surface of the sheet that is less than its melting temperature. According to this limitation, the laser output power, laser scanning speed and laser beam diameter are adjusted as 120 W, 50 mm/min and 1 mm respectively. As the laser output power, laser scanning speed and laser beam diameter were selected according to mentioned limitations, it is concluded that key parameter that directly affects the radius of curvature

Table 2 Mechanical properties of mild steel.

Temperature (°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		

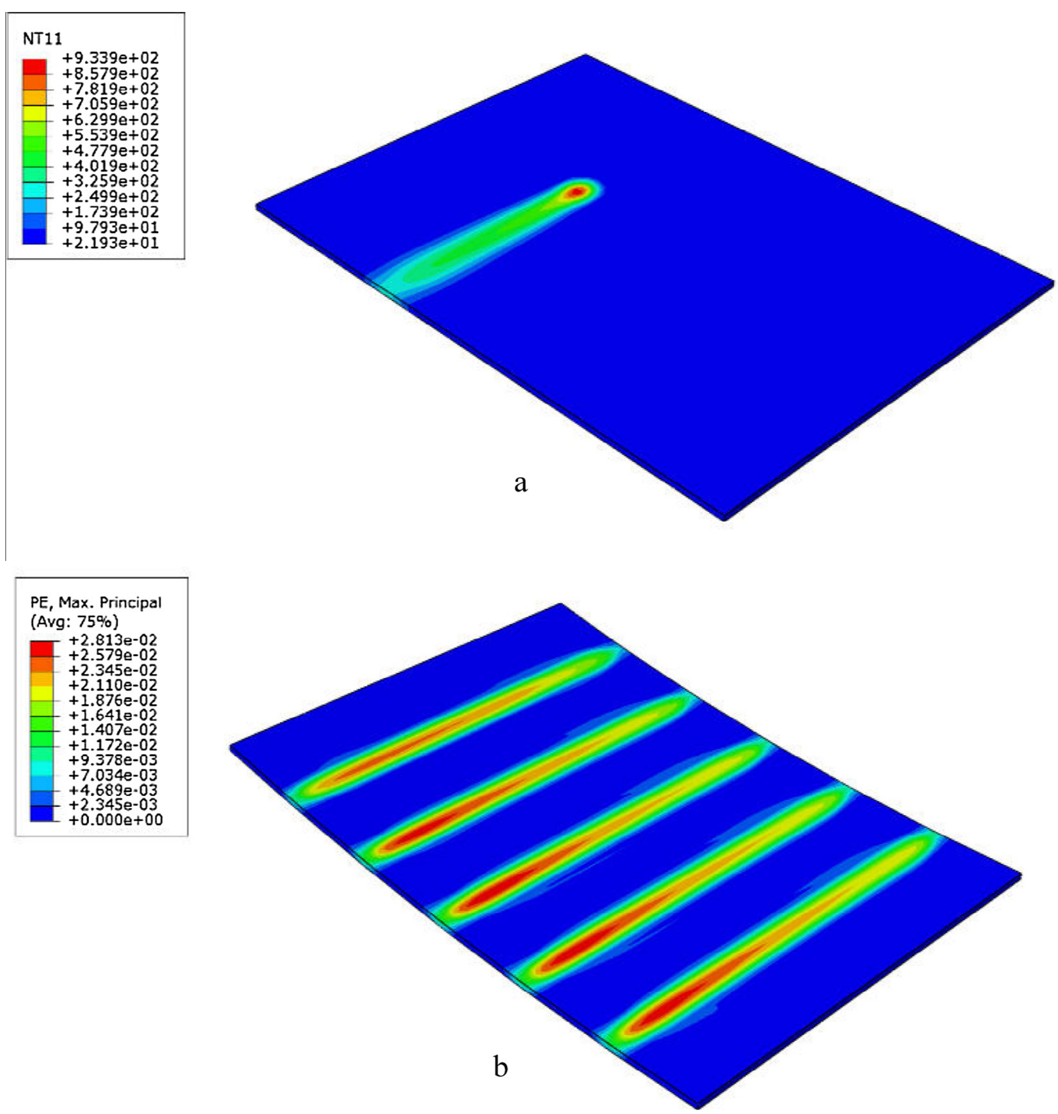

Figure 2 A cylindrical surface obtained from numerical simulations with the proposed analytical method, (a) thermal result; (b) mechanical result.

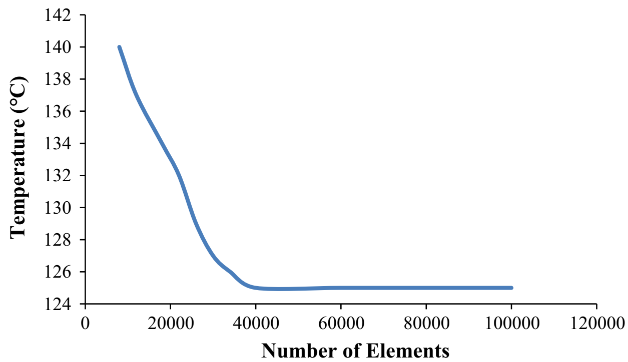

Figure 3 Finding the optimum mesh in the numerical simulations, temperature of a sample point at one of irradiating paths versus number of elements at the end of irradiating.

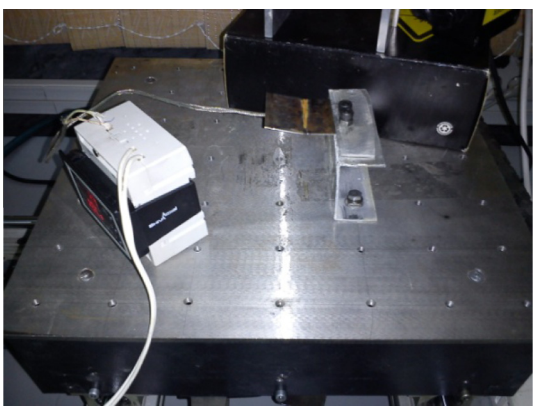

Figure 4 Experimental setup for measuring of temperature profiles on the bottom surface under the heat line and on the top surface with 1 mm distance from the center of heat line with thermocouple.

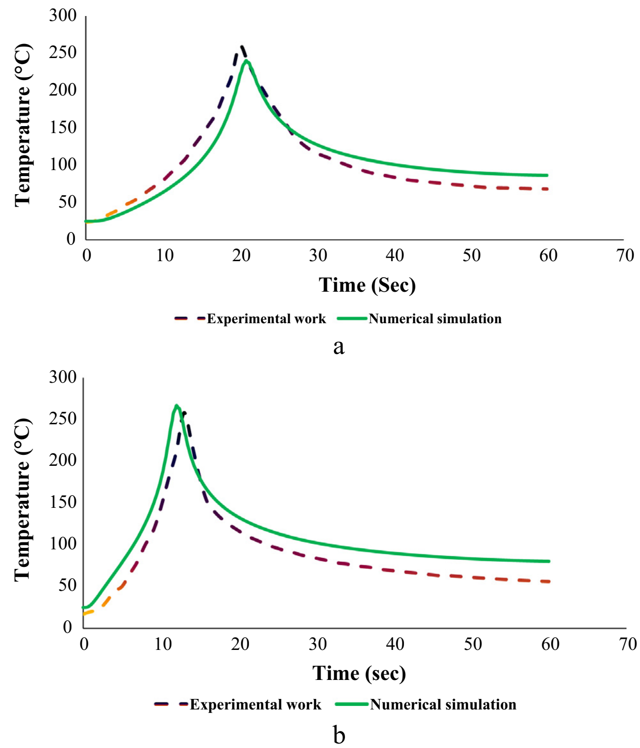

Figure 5 Temperature profiles obtained from experimental and numerical works for two sample points of the plate at the end of heating step: (a) on the top surface with 1 mm distance from the heat line, (b) on the bottom surface under the heat line.

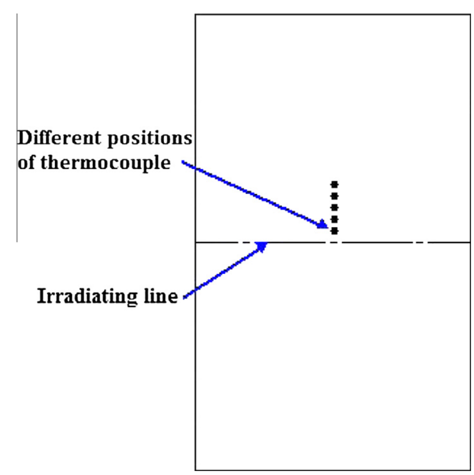

Figure 6 Schematic of experimental tests and numerical simulations for obtaining temperature profiles in various displacements of an irradiating line.

of the laser formed cylindrical surface is the number of irradiating lines in other words the distance between neighbor irradiating lines. Hence, in this paper, the proposed analytical method suggests the required number of irradiating lines for laser forming of a cylindrical surface with a certain radius of curvature. In the following, this analytical method is explained.

In the proposed analytical method, an important condition is assumed for laser forming of a cylindrical surface with certain radius of curvature. This fundamental assumption is that each irradiating line is not affected with the transferred heat during laser irradiating of neighbor heat line. In other words, the distance between neighbor heat lines is sufficiently large and the generated heat flux in each irradiating line is only due to itself laser irradiating. For investigating the minimum distance between neighbor irradiating lines (minimum distance that each irradiating line is not affected with the heat transfer of neighbor heating line) experimental tests and numerical simulations are performed. For this purpose, as it is shown schematically in Fig. 6, an experimental setup is prepared. In this experimental test, a thermocouple (type K) is positioned in points with various distances from a heating line and temperature profiles are extracted for these points and compared together. In this experimental test, laser output power, laser scanning speed and laser beam diameter are adjusted in which maximum heat flux is imported into the plate and their values are selected as 120 W, 50 mm/min and 1 mm respectively. In the numerical simulation, a similar procedure is performed and temperature profiles in the points with various distances from irradiating line are extracted. In Fig. 7 experimental and numerical results of temperature profiles for points with various distances from irradiating line are shown. As it is seen

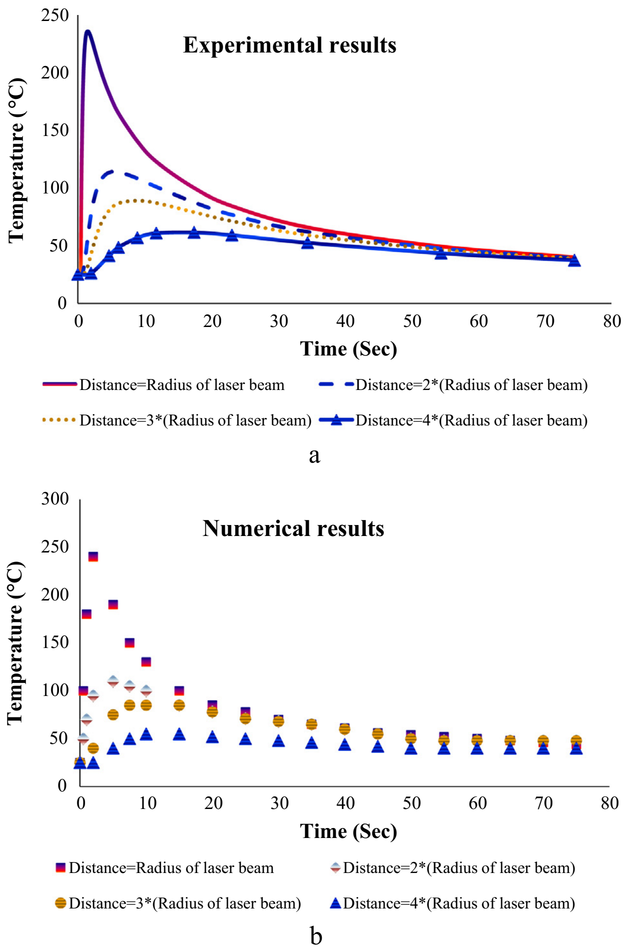

Figure 7 The results of temperature profiles for points with various distances from an irradiating line in order to finding minimum allowable distance between neighbor irradiating lines; (a) experimental results, (b) numerical results.

in this figure there is a good agreement between experimental observations and numerical simulations. Also, as it is seen in this figure, a parametric investigation on the distance of thermocouple from irradiating line is performed and the effects of various distances from irradiating line on the temperature profiles are investigated. The distance from irradiating line is defined with respect to laser beam radius. As it is seen from Fig. 7, it is concluded from experimental and numerical results that with increasing the distance thermocouple from irradiating line, the effect of heat transfer of irradiating line is decreased. It is noted that for a distance equal to 4 × radius of laser beam, the thermocouple has minimum effectiveness of heat transfer of irradiating line and minimum values of temperatures are extracted with the thermocouple. Therefore, it is concluded that in the laser forming of cylindrical surface, the distance between neighbor irradiating lines should be adjusted equal to 4 × radius of laser beam.

As the distance between neighbor irradiating lines was determined, in the following the analytical method for laser forming of a cylindrical surface with arbitrary radius of curvature is explained. First step is laser forming of a cylindrical surface with maximum achievable deformation. For this purpose, laser parameters such as laser output power, laser scanning velocity and laser beam diameter should be adjusted in a way that maximum heat flux is induced into the plate and also with this limitation that in this state, the temperature of top surface of the plate should be less than melting point of the plate. Also, with the allowable distance between neighbor irradiating lines equal to 4 × radius of laser beam, number of irradiating lines is evaluated.

However, in the first step, a cylindrical surface with maximum achievable deformation is produced. In Fig. 1a, irradiating pattern for laser forming of a cylindrical surface is shown. As it is seen in this paper, in order to balancing the inputted heat flux into the plate, consecutive irradiating paths are arranged in the opposite directions. In the proposed analytical method, there are two fundamental assumptions. First assumption is in the laser forming of a cylindrical surface, if the allowable distance between neighbor irradiating lines is adjusted equal or larger than 4 × radius of laser beam, achieved bending angle in each irradiating line is constant. With this assumption and according to Fig. 8a, a relation between final bending angle, bending angle in each irradiating line and the number of irradiating lines is extracted as Eq. (4).

As it is seen in Fig. 8a, N, b and a are the number of irradiating lines, final bending angle and bending angle in each irradiating line.

$$b = \frac{1}{2} N \times a \tag{4}$$

Second fundamental assumption is that the produced curvature in the laser formed cylindrical surface is a portion of a circular curvature. With this assumption and according to Fig. 8b, Eq. (5) is extracted. As it is seen in Fig. 8b, Eq. (5) is the relation between central angle of cylindrical surface (c), radius of curvature of cylindrical surface (R) and the final bending angle of plate (b).

$$c = 2 \times b \tag{5}$$

In addition, from Fig. 8b, Eq. (6) can be extracted.

$$L = R \times c \tag{6}$$

In Eq. (6), L is the initial length of the blank. However, from Eqs. (4)–(7) can be extracted.

$$L = R \times N \times a \tag{7}$$

As it is seen from Eq. (7), it is concluded that if the values of initial length of the blank (L) and the bending angle in each irradiating line (a) have been calculated and also the desired radius of curvature of cylindrical surface is specified, therefore number of irradiating lines for laser forming of the cylindrical surface with the desired radius of curvature are obtained from Eq. (7). It should be noted that obviously the dimensions of initial blank such as length, width and thickness and also material of initial blank have been seemed in Eq. (7) and in the determination of parameter a. In other word, analytical formula (Eq. (7)) proposed in this paper, is independent to dimensions and material of initial blank.

For investigating the performance of proposed analytical method, some experimental tests are performed. For this purpose, initial blanks with length of 100 mm, width of 60 mm and thickness of 0.85 mm are prepared. Also, in order to inducing the maximum value of heat flux into the plate, maximum value of power, minimum value of scanning speed and minimum value of laser beam diameter are adjusted as

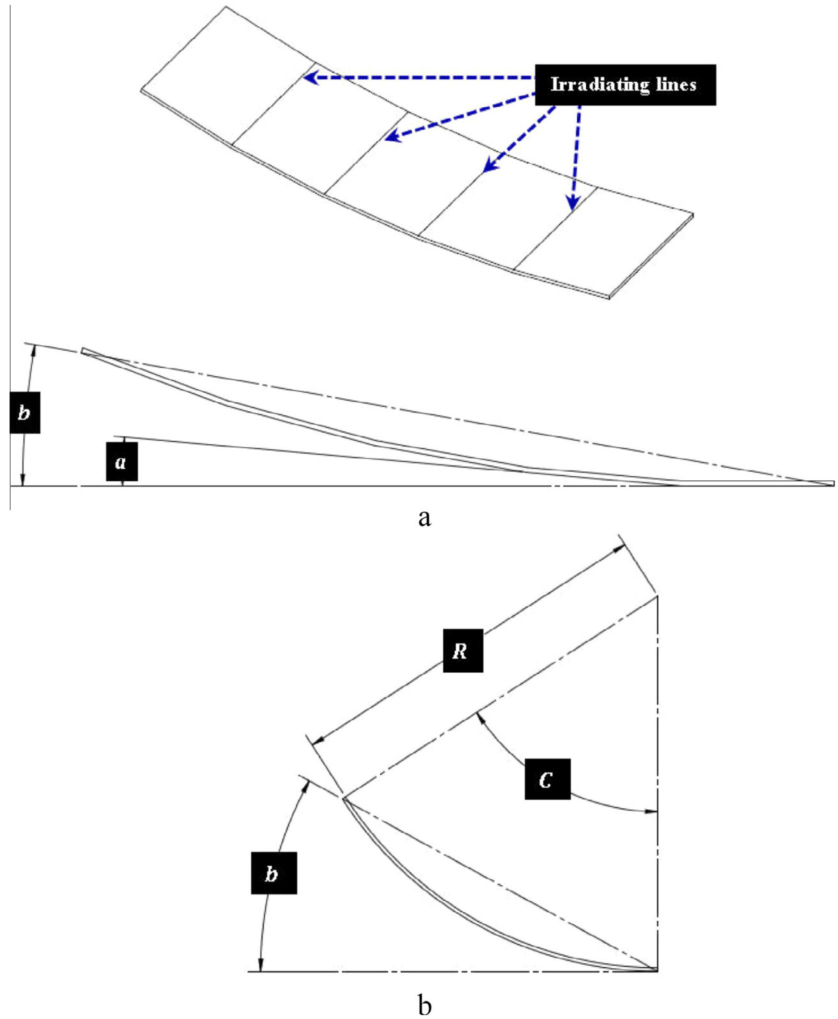

Figure 8 Schematic of a laser formed cylindrical surface with irradiating lines and the relationship between final bending angle, bending angle in each irradiating line and the number of irradiating lines.

Table 3 A comparison between the desired radius of curvature and calculated radius of curvature of the laser formed cylindrical surface for different radius of curvatures.

Radius of curvature of the desired cylindrical surface (mm)	The required number of irradiating lines	The used number of irradiating lines	Radius of curvature of the laser formed cylindrical surface (mm)	Difference between analytical and experimental tests (%)
120	20.42	20	133	9.78
250	9.80	10	241	3.73
330	7.43	7	349	5.44
400	6.13	6	415	3.61
480	5.11	5	491	2.24
570	4.30	4	589	3.22

120 W, 150 mm/min and 1 mm, respectively. Also, as the length of the initial blank is 100 mm and minimum allowable distance between neighbor irradiating lines is 2 mm, maximum number of irradiating lines is 49 lines. In this state, with the selected parameters for laser machine and adjusted process parameters, a cylindrical surface with maximum curvature in other words minimum radius of curvature in one pass is laser formed. Radius of curvature of laser formed cylindrical surface with above conditions is calculated as 50 mm. The bending angle in each irradiating line is calculated from Eq. (7) and its value is 2.34° for each irradiating line. In the following, some experimental tests are performed for laser forming of

cylindrical surfaces with arbitrary radius of curvatures. In Table 3, a comparison between the desired radius of curvature of cylindrical surface and calculated radius of curvature of the laser formed cylindrical surface is presented for different radius of curvatures.

As it is seen in Table 1, there are small differences between analytical and experimental values of radius of curvature and therefore it is concluded that the proposed analytical method is a very good, easy and powerful method for laser forming of cylindrical surfaces with arbitrary radius of curvatures.

5. Conclusion

In this work, laser forming of cylindrical surfaces with arbitrary radius of curvature was investigated experimentally and numerically. A new and comprehensive method was proposed in this paper. This method contained simple linear irradiating lines and using an analytical method, required process parameters for laser forming of a cylindrical surface with a specific radius of curvature was proposed. In the numerical simulations, the optimum number of meshes was obtained. For this purpose, a sample point at one of irradiating paths was selected and temperature at this node was calculated at the end of irradiating for various numbers of elements. Heat flux distribution in the numerical simulations was defined and calibrated with experimental measurements. It was concluded that evaluated heat flux distribution with this procedure was in good agreement with temperature profile obtained from experimental measurements. In addition, it was found that key parameter that directly affects the radius of curvature of the laser formed cylindrical surface was the number of irradiating lines in other words the distance between neighbor irradiating lines. It was concluded that for a distance equal to $4 \times$ radius of laser beam, each irradiating line was not affected with the transferred heat during laser irradiating of neighbor heat line. Performance of the proposed method for production of cylindrical surface with a specific radius of curvature was verified with experimental tests. The results showed that using proposed analytical method, cylindrical surfaces with any radius of curvature could be produced successfully.

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