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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

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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).
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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