Iranian Journal of Materials Forming 7 (1) (2020) 46-53

Online ISSN: 2383-0042

IJMF

Iranian Journal of Materials Forming

Journal Homepage: http://ijmf.shirazu.ac.ir

A Study on the Laser Tube Bending Process: Effects of the Irradiating Length and the Number of Irradiating Passes

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ARTICLE INFO

Article history:

Received 8 July 2019
Revised 9 October 2019
Accepted 16 October 2019

Keywords:

Laser tube bending
Main bending angle
Lateral bending angle
Ovality
Thickness variation

ABSTRACT

In this paper, the laser bending process of a circular tube made of mild steel has been investigated experimentally. For this purpose, the effects of the irradiating length and the number of irradiating passes on the main bending angle of a laser bent tube are studied. In addition, the main defects of the laser tube bending process such as lateral bending angle, ovality and thickness variation are examined. Hence the effects of irradiating length and number of irradiating passes on the lateral bending angle, ovality and thickness variation of a laser bent tube are investigated. The results show that with an increase in the irradiating length, the main bending angle, the ovality percentage and the thickness variation increase and also the lateral bending angle will decrease. In addition, it is concluded that with an increase in the number of irradiating passes, main and lateral bending angles, ovality percentage and thickness variation increase.

1. Introduction

Tube bending is an important process in the boilers, engines, heat exchangers and air conditioners industries. In the mechanical bending processes, hard tooling is employed to exert forces on the surfaces of the tube. However, the tube at extrados becomes thinner due to tensile stresses. This usually causes some kinds of tensile failure such as neck or fracture occurring at extrados. Laser forming as a spring back-free and non-contact forming technique has been under active investigation over the last decades. Instead of applying external forces with forming tools, laser forming is achieved by the plastic deformation induced by thermal stresses resulted from rapid laser heating and cooling. Although the origins of the laser forming technique can be traced back to the established method of flame bending, laser forming is a much more refined and controllable technique that offers numerous unique application possibilities. The extensive variety of possible applications results from the reasonably high degree of control over the energy transfer, high levels of accuracy and reproducibility, very high degrees of flexibility and the non-contact nature of the technique. In addition, the laser based technique could be employed to form parts in locations where it would otherwise be impossible to use conventional forming methods, such as in outer space.

One application of laser forming is laser tube bending. The tube rotates typically 180° or more while its outer circumference is being heated by a laser beam. The laser beam size is chosen in a way so that it will be

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much greater than the tube thickness. As a result, the scanned region of the tube is heated almost homogeneously in the thickness direction, and undergoes compressive plastic deformation and wall thickening due to the restriction on thermal expansion by the surrounding material. The shortening of the material of the scanned region in the axial direction of the tube subsequently causes the tube to bend towards the laser beam.

Compared to laser sheet bending, relatively less effort has been devoted to studying laser tube bending. Silve et al. [1] investigated procedures for the laser bending of square cross-section tubes made of mild steel. Different scanning sequences were compared experimentally. Kraus [2] conducted a finite element modeling study of the laser bending of square cross-section tubes and investigated the heating sequence. Li and Yao [3] explained the mechanism of laser tube bending by stress analysis. The influence of process parameters on the geometry of the bending component was investigated by experiments and numerical simulations. A closed-form expression for the bending angle was also proposed. Hao and Li [4] proposed an analytical model for identifying the relationships between the bending angle and the processing parameters in the laser tube bending process. In the proposed model, the bending angle was as a function of the energy (laser power, absorption, scanning speed) as well as geometric (tube diameter and wall thickness) and material properties (coefficient of thermal expansion, density, heat capacity, Young’s modulus, yield stress). In another research, Hao and Li [5] presented a thermal-mechanical finite element transient analysis to investigate the developments of stress and strain during the laser tube bending process. The simulation of the moving laser beam during the bending process was realized by using individual load arriving time and a special defined load time function. Hsieh and Lin [6] investigated the buckling mechanism of a thin metal tube during laser forming numerically and experimentally. It was shown that the buckling mechanism of thin metal tubes under laser forming was initiated by a uniform temperature gradient combined with plastic deformation. The latter was dependent upon various operation parameters. Safdar et al. [7] studied the effect of the scanning schemes (alternate circumferential, axial and sequential circumferential) on the laser tube bending process. Based on the presented results, it was proved that the scanning schemes significantly influence laser tube bending. The results showed that for the given process parameters, the axial scanning scheme produces twice the bending angle as compared to the circumferential scanning schemes.

Guan et al. [8] developed a 3D thermomechanical finite element analysis model for laser tube bending based on the software MSC/Marc. Their results showed that the gradient and development of the temperature between the laser scanning side and the non-scanning side leads to a complex evolution of the stress and strain. Consequently, the length of the laser scanning side becomes shorter than that of the non-scanning side after cooling. The length difference between both sides makes the tube produce the bending angle. Wang et al. [9] proposed a bending method based on geometric curvatures along the tube curves in which a curved tube in a two- and three-dimension space is formed from a straight tube. The three-dimension scanning path plane was obtained by combining the data in the two-dimension planes. Besides, an experimental verification was carried out to bend straight tubes into a two-dimension sinusoidal and a three-dimension helical tube/coil-shaped. The results showed that the scanning path planning proposed in this paper was effective and feasible. Jamil et al. [10] carried out an experimental and numerical investigation of the laser bending of nickel micro-tubes. From the results, it was evident that the bending angle of the tube increased considerably when a compression was imposed on the tube’s free end during the heating period. There was minimal thinning at extrados which was beneficial in the case of thin-walled micro tube bending in order to avoid cracking or fracture of the thin wall. Imhan et al. [11] studied the laser tube bending process analytically and experimentally. Moreover, they investigated the material properties changes during the process due to the temperature rise. They concluded that the bending angle increases directly by increasing the average laser power under any condition. In another research, Imhan et al. [12] improved the bending angle in the laser tube bending process by enhancing the absorption coefficient of the material and the mechanical formability using laser softening heat treatment. They showed that the output bending angle increases to 1.9° with an increment of 70% after the laser softening heat treatment. Li et al. [13]

studied the influence of processing parameters (including laser power, scanning speed, spot diameter, and scanning times) on the bending angle in the laser tube bending process. They showed that the bending angle increases with an increase in the laser power and spot diameter, and a decrease in the scanning speed.

It should be noted that in the laser tube bending process, in addition to the main bending angle, a lateral bending angle is also created in the deformed tube. The lateral bending angle is an undesirable phenomenon that reduces the dimensional accuracy of the laser bent tube. To the author's knowledge and based on literature review, the lateral bending phenomenon has not been investigated by the researchers in the previous reports. However, the most important innovation of the present paper is to investigate the lateral bending angle in the laser bent tubes experimentally. For this purpose, the effects of irradiating length and number of irradiating passes on the lateral bending angle are studied. In addition to the lateral bending angle, the main bending angle is investigated. The effects of irradiating length and number of irradiating passes on two other main defects such as ovality and thickness variation of laser bent tube are also examined.

2. Experimental Work

Laser tube bending experiments are carried out with an AMADA continuous CO_2 laser with the maximum power of 2000 W. In these experiments, the laser output power, laser beam diameter and laser scanning speed are 1000 Watts, 6 mm and 15 mm/min, respectively. The length, outer diameter and thickness of the initial tube are 144, 18 and 1 mm, respectively. The samples are made of mild steel. To increase the absorptivity of the specimens, the outer surface of the tube is darkened with graphite coatings. Main and lateral bending angles, ovality and thickness variation of the samples are measured using a coordinate measuring machine (CMM). In Fig. 1, a bent tube with a continuous CO_2 laser in the experiments is shown. As it is seen, the tube has been formed successfully with the laser beam. It should be noted that in the experiments, the tubes have been clamped from one edge. No external forces or constraints have been used in the laser forming process and the tubes can deform freely after the laser irradiating step.

Fig. 1. A bent tube with a continuous CO_2 laser in the experiments.

In the following, some of the main defects in the laser tube bending process are explained.

3. Lateral Bending Angle

In the laser bending process of a tube, in addition to the main bending angle, a lateral bending angle is created that is an undesirable effect. This undesirable phenomenon reduces the dimensional accuracy of the laser bent tube. In Fig. 2, a schematic of the main and lateral bending angles in the laser tube bending process are shown. In the following, the reason for creating the lateral bending angle is discussed. In Fig. 3, variations of the maximum temperature for the tube from the start point of the irradiating path up to its end point for a 180° circular arc is shown. The temperatures have been measured using an infrared laser thermometer (UNI-T: UT305C). It should be noted that the maximum temperature at each point located on the laser irradiating path is calculated and plotted in Fig. 3. At the end point of the irradiating path, the temperature is a combination of the laser irradiated heat and conducted heat from the previous irradiating area. Hence the maximum temperature of the end point is more than that of the start point in case of the irradiating path with only the laser irradiated heat. This means that more plastic strains are caused at the end point of the irradiating path, and consequently, a lateral bending angle occurs. It should be noted that to investigate the effect of the laser irradiating length, 9 tubes were irradiated by a laser in each set of the experiments. Further, 30 tubes were irradiated by a laser beam in each set of the experiments in order to investigate the effect of the number of irradiating passes.

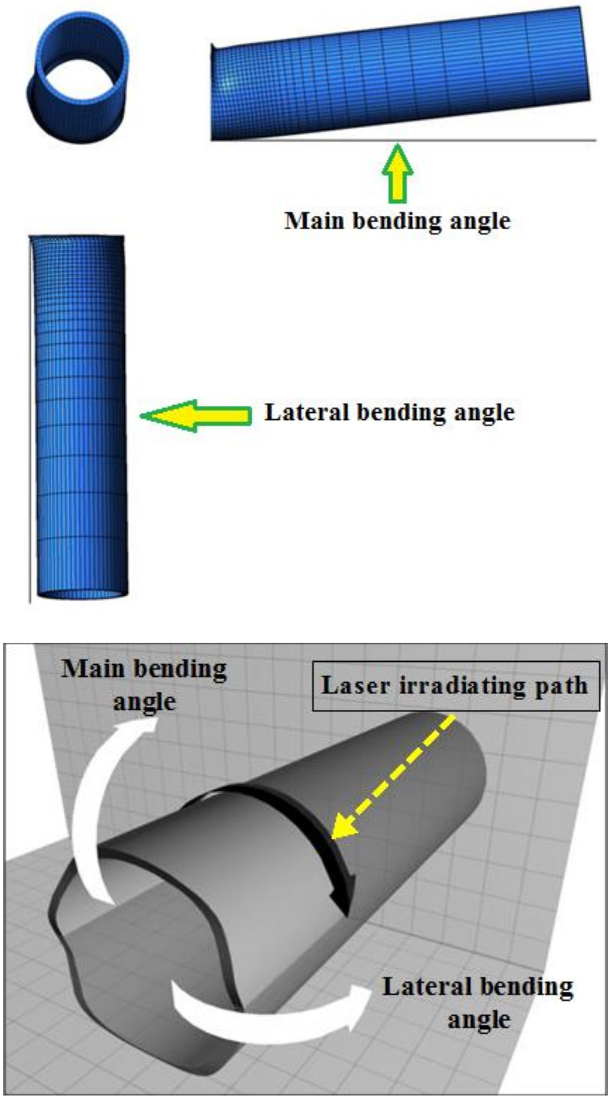

Fig. 2. Schematic of the main and lateral bending angles in the laser tube bending process.

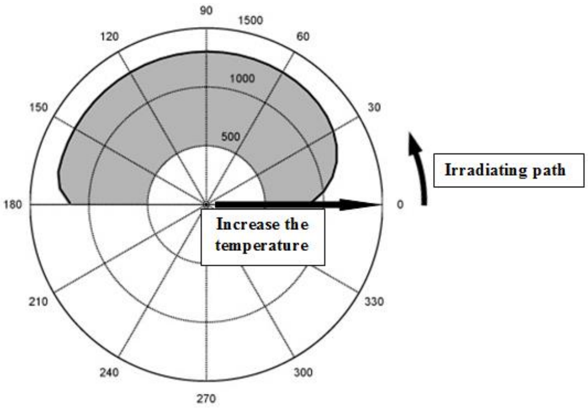

Fig. 3. Graph of maximum temperatures obtained for the points located on the laser irradiating path for the laser tube bending process of a 180° circular arc.

4. Ovality

Ovality is largely associated with the evolution of tensile stresses at extrados and compressive stresses at the intrados in the heat affected zone during the bending operation. In Fig. 4, a schematic of ovality in the heat affected zone of a laser bent tube is shown.

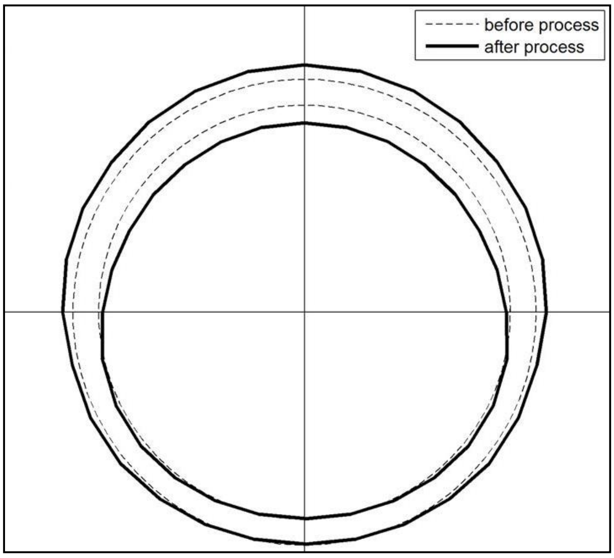

Fig. 4. A schematic of ovality in the heat affected zone of a laser bent tube.

Percentage of ovality is the measure of the cross section distortion of a circular tube in the bending zone. In applications, such distortions could lead to a turbulent flow for any fluid that passes through the tube. The ovalization of the tube's cross- section is defined by the following equation:

$$Ovalization = \frac{D_{max} - D_{min}}{D} \times 100\ (\%) \quad (1)$$

Where D_{max} and D_{min} are the maximum and minimum deformed average diameters respectively, and D is the un-deformed tube diameter.

5. Thickness Variation after the Laser Tube Forming Process

It should be noted that in the laser irradiating step, the thickness of the intrados (laser irradiating zone) decreases due to the thermal expansion phenomenon, while in the cooling step the thickness of the intrados increases due to the presence of compressive stresses. However, due to the evolution of tensile stresses at extrados and compressive stress at the intrados during the bending operation, the thickness variation occurs for a tube after the laser bending process. In Fig. 5, a schematics of the thickness variation in the heat affected zone of a laser bent tube is shown.

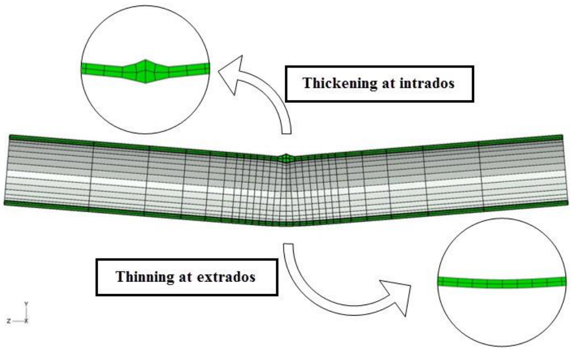

Fig. 5. Schematics of the thickness variation in the heat affected zone of a laser bent tube.

To investigate the thickness variations in the laser tube bending process, according to Fig. 6, the thickness variation ratio (TVR) is defined as:

$$TVR = \frac{Thickness\ at\ highest\ point\ of\ intrados}{Thickness\ at\ lowest\ point\ of\ extrados} \quad (2)$$

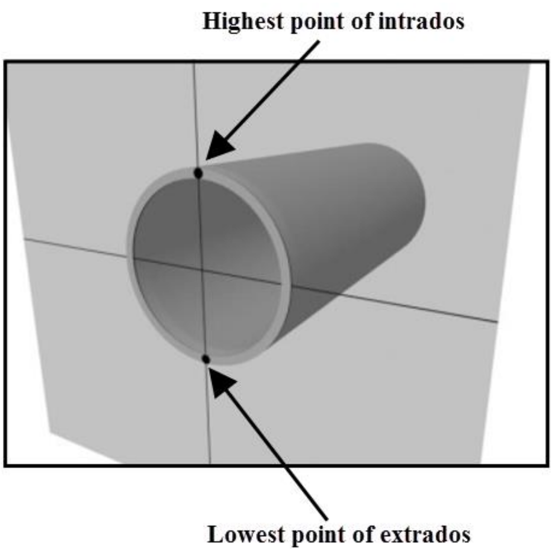

Fig. 6. A schematic view of the highest point of intrados and the lowest point of extrados in the heat affected zone.

6. Results and Discussion

6.1. Effect of the irradiating length

In this paper, the irradiating length is expressed in the form of an arc at the upper semicircular of the tube. As it is seen in Fig. 7, the maximum irradiating length is an arc from 0° up to 180°. As it is seen in this figure, other irradiating lengths are symmetrical circular arcs in the upper half of the circle. In Fig. 7, the effect of the irradiating length on the main and lateral bending angles are shown.

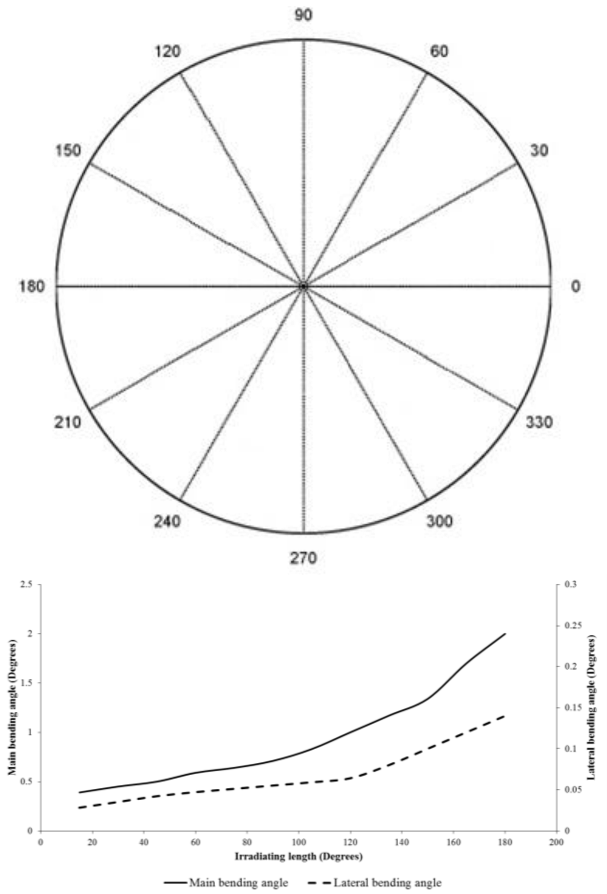

Fig. 7. Effect of the irradiating length on the main and lateral bending angles of a laser bent tube.

As it is seen in Fig. 7, with an increase in the irradiating length, the main bending angle increases. The reason is that by increasing the irradiating length, the plastic deformation areas, and consequently, the main bending angle increase. Furthermore, it is concluded from Fig. 7 that by increasing the irradiating length, the lateral bending angle of the laser bent tube increases. The reason is that by increasing the irradiating length, due to the increase in the plastic deformation area of the tube, bending stiffness of the tube increases, and consequently, the lateral bending angle increases as well. In addition, in Fig. 8, the effect of the irradiating length on the ovality percentage of the laser bent tube is shown. As it is seen in this figure, the percentage of ovality increases by increasing the irradiating length. The reason is that with an increase in the irradiating length, the difference between tensile stresses at extrados and compressive stresses at intrados increases due to the increase in the heat affected zone.

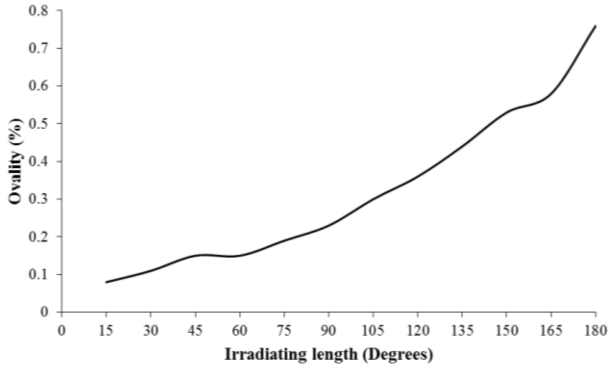

Fig. 8. Effect of the irradiating length on the ovality percentage of the laser bent tube.

In Fig. 9, the effect of the irradiating length on the thickness variation ratio (TVR) is presented. As it is seen, an increase in the irradiating length is followed by a subsequent increase in the TVR. The reason is that by increasing the irradiating length, the main bending angle of the laser bent tube increases and consequently thickening in intrados and thinning in extrados increase as well.

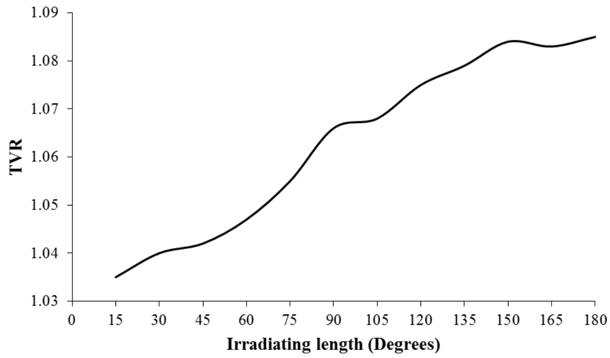

Fig. 9. Effect of the irradiating length on the thickness variation ratio (TVR) of a laser bent tube.

6.2. Effect of the number of irradiating passes

In Fig. 10, the effects of the number of irradiating passes on the main and lateral bending angles are shown. As it is seen, with an increase in the number of irradiating passes, both main and lateral bending angles increase. It should be noted that to investigate the number of irradiating passes' effect, maximum irradiating length that is an arc from 0° up to 180° is selected. As it is seen from Fig. 10, by increasing the number of irradiating passes, the rate of increase in the main and lateral bending angles decreases. This is because of increasing the bending stiffness of the tube due to the thickening of intrados after each pass.

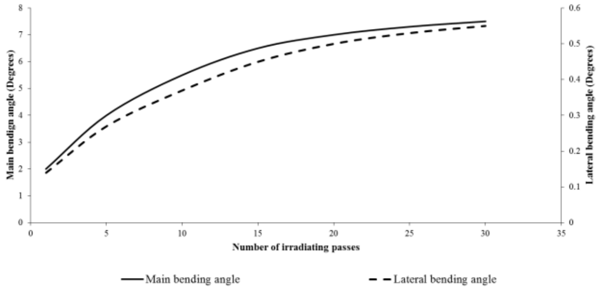

Fig. 10. Effects of the number of irradiating passes on the main and lateral bending angles.

Besides, in Fig. 11, the effect of the number of irradiating passes on the ovality percentage of a laser bent tube is seen. By increasing the number of irradiating passes, the ovality percentage of the laser bent tube increases as well but the rate of the increase in the ovality decreases due to the fact that the bending stiffness of the tube rises, and consequently, the rate of the tube bending angle decreases.

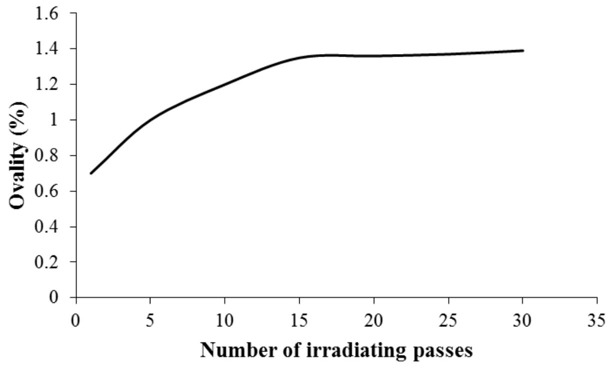

Fig. 11. Effect of number of irradiating passes on ovality percentage of laser bent tube.

In Fig. 12, the effect of the number of irradiating passes on the TVR is seen. As it is shown in this figure, by increasing the number of irradiating passes, the TVR increases but its rate of increase decreases because of the increase in the bending stiffness of the tube which leads to the decrease of the rate of the tube bending angle.

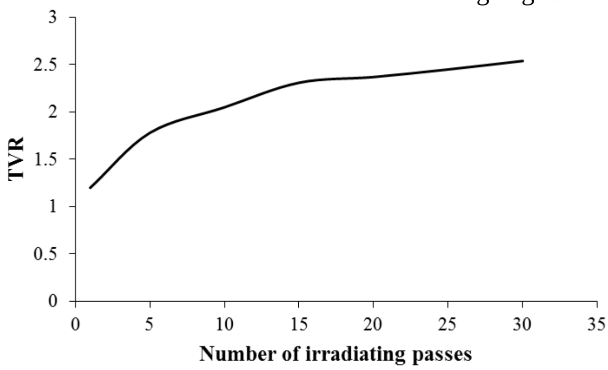

Fig. 12. Effect of the number of irradiating passes on the TVR of the laser bent tube.

7. Conclusions

In this paper, the laser tube bending process of mild steel was investigated experimentally. For this purpose, the effects of the irradiating length and the number of irradiating passes on the main and lateral bending angles, the ovality percentage and thickness variation of laser bent tubes were studied. The following conclusions could be drawn for this work:

1. It was seen that with an increase in the irradiating length, the main bending angle increased due to the rise in the size of the plastically deformed area. Moreover, by increasing the irradiating length, the lateral bending angle of the laser bent tube decreased due to thickened intrados.

2. It was shown that the percentage of ovality increased by increasing the irradiating length. The reason was that with an increase in the irradiating length, the difference between tensile stresses at extrados and compressive stresses at intrados rose.

3. It was concluded that with an increase in the irradiating length, the thickness variation ratio (TVR) increased as well due to the fact that the main bending angle of the laser bent tube rose and consequently the thickening in intrados and thinning in extrados increased.

4. It was obtained that with an increase in the number of irradiating passes, both the main and lateral bending angles increased. However, the rates of increase in the main and lateral bending angles decreased because the bending stiffness of the tube increased as passes went by thickening of intrados after each pass.

5. It was shown that by increasing the number of irradiating passes, the ovality percentage of laser bent tube was increased but the rate of increasing in the ovality was decreased due to raising the bending stiffness of tube and consequently decreasing the rate of tube bending angle.

6. It was seen that by increasing the number of irradiating passes, the TVR increased but its increase rate decreased due to an increase in the bending stiffness of the tube and consequently the rate of the tube bending angle decreased.

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مطالعه‌ای بر فرآیند خمکاری لوله به کمک لیزر: اثرات طول تابش‌دهی و تعداد پاس‌های تابش‌دهی

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چکیـــده

در این مقاله، فرآیند خمکاری به کمک لیزر یک لوله استوانه ای ساخته شده از جنس فولاد کم کربن به صورت تجربی بررسی می شود. بدین منظور، اثرات طول تابش دهی و تعداد پاس های تابش دهی بر زاویه خمش اصلی لوله خم شده به کمک لیزر مطالعه می شود. به علاوه، عیوب مهم فرآیند خمکاری لوله به کمک لیزر شامل زاویه خمش جانبی، بیضوی شدن و تغییرات ضخامت مورد بررسی قرار می گیرند. از این رو، اثرات طول تابش دهی و تعداد پاس های تابش دهی بر زاویه خمش جانبی، بیضوی شدن و تغییرات ضخامت لوله خم شده به کمک لیزر بررسی می شوند. نتایج نشان می دهند که با افزایش طول تابش دهی، زاویه خمش اصلی، درصد بیضوی شدن و تغییرات ضخامت افزایش یافته و همچنین زاویه خمش جانبی کاهش می یابد. به علاوه، نتیجه گرفته می شود که با افزایش تعداد پاس های تابش دهی، زوایای خمش اصلی و جانبی، درصد بیضوی شدن و تغییرات ضخامت افزایش می یابد.

واژه‌های کلیدی: خم‌کاری لوله به کمک لیزر، زاویه خمش اصلی، زاویه خمش جانبی، بیضوی شدن، تغییرات ضخامت