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ORIGINAL RESEARCH PAPER

A Study on Main and Lateral Bending Angles in Laser Tube Bending Process

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Abstract

Laser bending process of a circular tube made of mild steel was investigated with experimental tests and finite element simulations. The effects of main process parameters such as laser output power, laser scanning speed, and laser beam diameter on the main and lateral bending angles of laser-bent tube were studied. The experimental tests were performed with a continuous CO_2 laser. The numerical simulations were carried out with Abaqus/Standard technique. The finite element simulations were compared with experimental measurements by adjusting the absorption and heat transfer coefficients of the heat flux in the numerical simulations and comparing the obtained temperature profiles with experimental results. The accuracy of numerical simulations was proved by comparing the numerical results with experimental measurements. The obtained experimental and numerical results showed that increase in the laser output power leads to an increase in the main and lateral bending angles. Moreover, the results proved that the main and lateral bending angles increased with decreasing the laser scanning speed and laser beam diameter.

1. Introduction

The application of laser technology in materials processing such as welding, cutting, hardening, coating, and forming is increasing rapidly [1-3]. Forming with a laser beam has been widely used in last decade because of its ability to fabricate complicated shapes [4-7]. One of the recent applications of laser beam in forming processes is Laser Tube Bending Process (LTBP). Compared to mechanical tube bending with hard tools which leads to tensile failures at the extrados of the tube, in the laser tube bending process, the bending in the tube occurs by plastic deformations induced by thermal stresses, and therefore, the thinning in the extrados of the tube is much less than mechanical bending and as a result, less defects occur in the laser-bent tube. Recently, the researches have focused on the tube bending and forming with laser beam. Hao [8] suggested an equation for prediction of bending angle and validated the equation by experimental measurements. He concluded that the bending angle of a laser-bent tube is related to laser power, angular speed of laser and material properties. A thermo-mechanical analysis was used for finite element simulation of LTBP by Hsieh and Lin [9] with an uncoupled procedure between thermal and mechanical analysis. Zhang et al. [10] studied the numerical simulation of LTBP based on the various linear and circumferential irradiating schemes. He concluded that the irradiating scheme has an important impact in the LTBP. Silve et al. [11] investigated the scanning sequences in LTBP with square cross-sections experimentally. In another study, Kraus [12] studied the numerical simulation of laser bending process for tubes with square cross-section and stud-

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ied the effect of sequence of heating steps. Li and Yao [13] investigated the laser tube bending process experimentally and numerically and studied the relations between geometry of laser-formed tube and the process parameters. Guan et al. [14] studied the LTBP numerically by developing a thermal-mechanical analysis by MSC/Marc software. They concluded that there was a complexity in stress and strain fields of laser-bent tubes because of different temperatures in scanning side and non-scanning side of the tube. The strategy of irradiating schemes for laser tube bending process based of evaluating the curvatures of the tubes was conducted by Wang et al. [15]. In their work, first, the 2D planes were obtained by projecting the 3D shape of the tube and then the process parameters were calculated. The LTBP of micro-tubes made of Nickel alloy was conducted experimentally and numerically by Jamil et al. [16]. They concluded that the bending angle of laser-bent tube noticeably increased by imposing a constraint at the free end of the tube in heating step. Imhan et al. [17] investigated the laser tube bending process based on the experimental tests and analytical approaches. They studied the changes of material characterizations of laser-bent tube because of temperature rising. Their results showed that the bending angle increased by high laser powers in all of conditions. Safari [18] investigated the changes in ovality, thickness variation, and bending angles with the length of irradiation path and the number of irradiations. He concluded that larger irradiation lengths lead to increase in the main and decrease in the lateral bending angles, respectively. Furthermore, more irradiation passes increase the main and lateral bending angles. Khandehdel et al. [19] proposed a new cooling strategy in laser tube bending process with different irradiating schemes such as axial and circumferential patterns experimentally. They concluded that using the proposed cooling strategy, the bending angle of laser-bent tube considerably increased up to 1.5 times. In another work, Khandehdel et al. [20] proposed two irradiating schemes such as step-by-step and reverse patterns for laser tube forming process in order to extract the irradiating paths for 2D and 3D shapes.

As noted in the review of the references, so far little research has been done on laser tube bending compared to sheets. Additionally, in few studies research is done on the laser tube bending; comprehensive and complete studies on the effect of process parameters on the main and lateral bending angles have not been done. Hence, in this paper a comprehensive study on the effects of process parameters such as laser output power, laser scanning speed and laser beam diameter on the main bending angle of the laser-bent tube as well as its lateral bending angle was performed with both experimental and numerical works. In addition, in the numerical simulations, in order to improve the accuracy of finite element simulations, by adjusting the absorption and heat transfer coefficients and comparing the temperature profile with the experimental measurements, the true heat flux for laser tube bending process was obtained.

2. Experimental Work

The experimental tests of LTBP were performed with a continuous AMADA CO_2 laser. The maximum power of the employed laser was 2000 Watts. The length, thickness, and outer diameter of initial mild steel tubes were 144, 1, and 18mm, respectively. The irradiating path at outer surface of laser-bent tubes was coated with graphite in order to increase the absorption coefficients of the tubes. In the experiments, the focal plane (the laser spot point) was adjusted 2mm above the tube surface. This position for focal plane was fixed in all of experimental tests. The bending angles were measured with a CMM machine. In Fig. 1, a laser-bent tube with the laser beam in the experiments is shown.

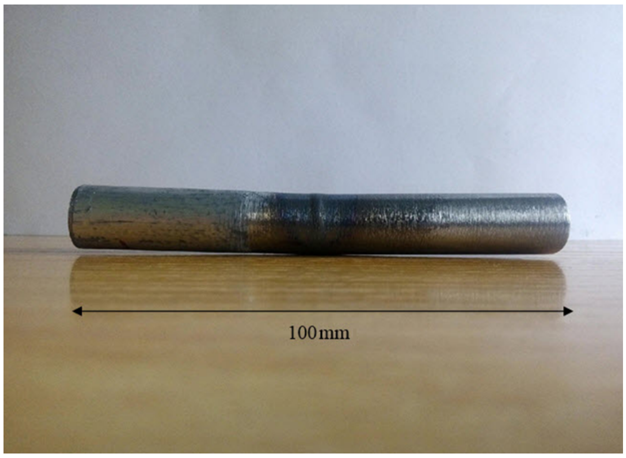

Fig. 1. A laser-bent tube with the laser beam in the experiments.

3. Numerical Simulation

The ABAQUS/ Implicit package was employed for simulating the thermal and mechanical analysis of LTBP. In the bending process with a laser beam, the energy dissipation of plastic deformation is negligible in comparison with energy of laser beam. So, the thermal and mechanical solutions can be performed decoupled. The temperatures, displacements, stress and strain fields can be extracted from finite element simulations. In Fig. 2, a schematic of tube bending process with a laser beam is shown. As same as the experimental tests, the length, thickness, and outer diameter of initial tubes were 144, 1 and 18mm, respectively. In Fig. 3, the temperature field in a laser tube bending simulation is shown. As it is seen, steep temperature gradient occurs in the local heated zone, and therefore, a fine mesh is essential near the laser irradiation path. However, because less accuracy is required in areas farther from the laser irradiation path, coarse mesh was applied in these areas. In Fig. 4, a tube with a suitable mesh pattern for laser tube bending simulations is shown. As it is indicated in Fig. 4, the meshes located at irradiating line are dense in order to increase the accuracy of the results while the meshes located far from the heating line are coarse because of reducing the solution time. In addition, in the finite element simulations, a 360° tube was laser formed but in Fig. 4, in order to better visibility of mesh pattern only $1/4^{th}$ is shown.

The C3D20 and DC3D20 elements were used for mechanical and thermal analyses, respectively. In the finite element simulations, the surface heat flux method was employed for imposing the heat flux into the tube surface and for this purpose, the DFLUX subroutine was utilized in order to describe the surface heat flux in ABAQUS. The applied USER SUBROUTINE DFLUX can describe the density, geometry, and scanning velocity of heat flux. It is computed with the following equation:

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

In Eq. (1), η is the absorption coefficient, P is power of laser, R is beam radius and x and z are the coordinates of a point away from center of laser beam. Heat transfer during the heating and cooling steps of LTBP are modeled by natural heat radiation and convection. In the simulations of LTBP, thermo-mechanical properties of the tubes were used as temperature dependent data and the values at different temperatures were taken from Ref. [21] and are listed in Tables 1 and 2, respectively.

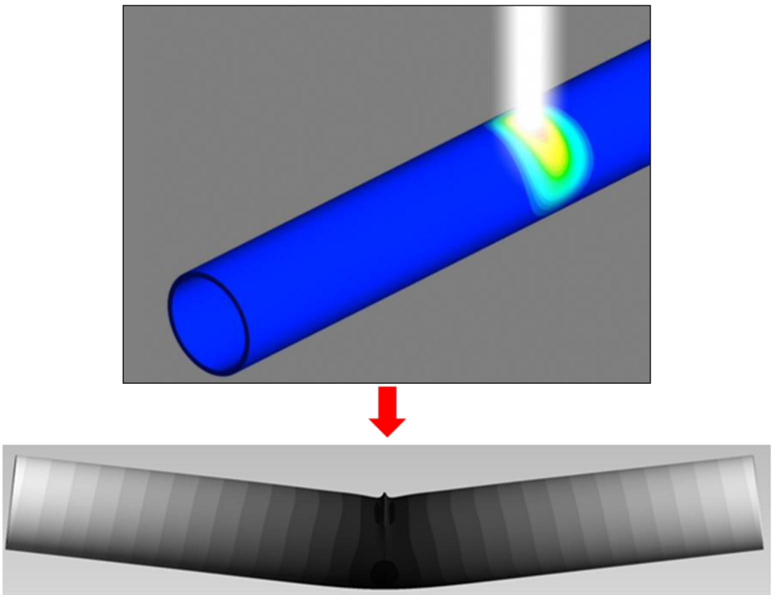

Fig. 2. Schematics of laser tube bending process.

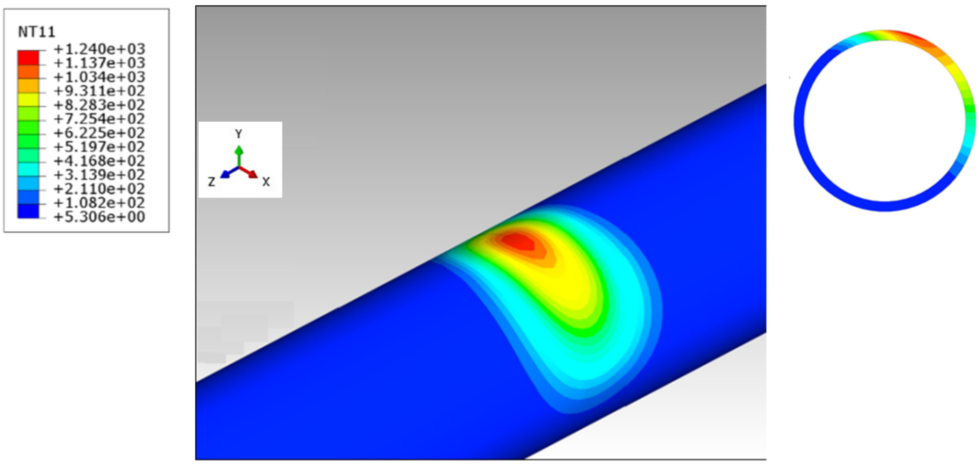

Fig. 3. Temperature field in the laser tube bending simulation.

Table 1
Thermal properties of the tubes made of mild steel [21].

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

Table 2
Mechanical properties of the tubes made of mild steel [21].

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	$0.148E-04$		

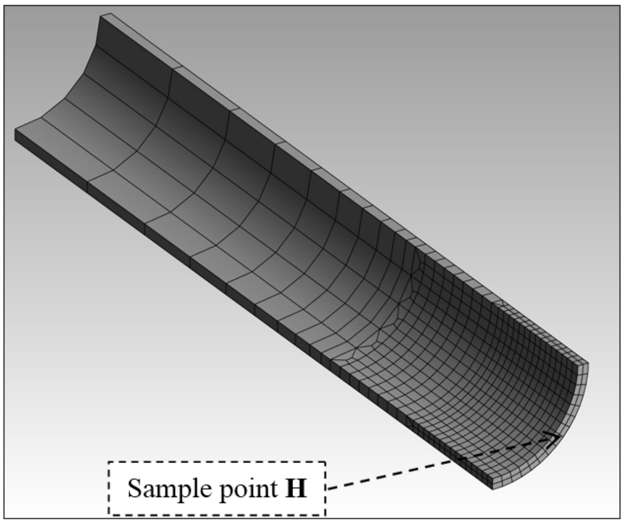

Fig. 4. A tube with a suitable mesh pattern for laser forming simulation.

The same patterns for mesh was applied for thermal and mechanical analyses. In the simulations, the tube was irradiated by laser beam in the heating step and then in the cooling step, the tube allows to cool slowly in the ambient temperature. In Fig. 5, a simulated bent tube by laser beam is presented.

4. Lateral Bending Angle

In the LTBP, an undesirable phenomenon appears that is named as lateral bending that reduces the dimensional accuracy of the laser-bent tube. This phenomenon happens due to unbalancing in the temperature distribution along the irradiation path that leads to different plastics strains.

5. Results and Discussion

As it was mentioned in Section 2, due to the importance of mesh size in the accuracy and solution time of laser tube bending simulations, the mesh density was considered to be high in the irradiating path while in areas farther from the irradiation path the mesh density was less required. An appropriate mesh pattern is shown in Fig. 4. For evaluating the optimum mesh size for simulations, a sample point H was selected on the irradiating path (Fig. 4) and the temperature of this point was extracted at the end of heating step for different sizes of the elements. In the Fig. 6, the extracted temperatures based on various element numbers are presented and it is concluded that the optimum element numbers for laser tube bending simulations is approximately 10900 elements.

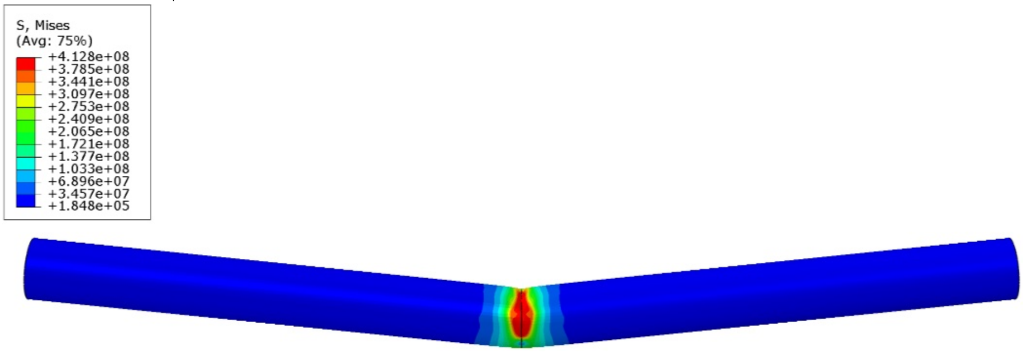

Fig. 5. A simulated bent tube by laser beam.

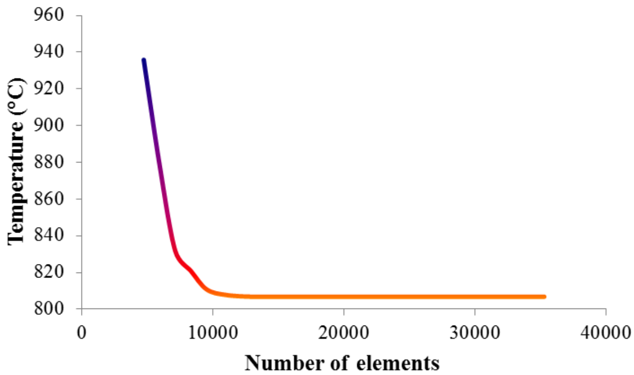

Fig. 6. The extracted temperatures based of various element numbers for sample point H.

Moreover, in the numerical simulations of laser bending, applying a true distribution of heat flux can directly affect the accuracy of the obtained results and noticeably increases the reliability of simulations. For this aim, in an experimental test, a sample plate was prepared from the mild steel tube. The prepared sheet was then irradiated with laser beam and the temperature profile of the bottom surface of the sheet in the laser irradiating path was measured by a type K thermocouple. In the finite element simulations, the same process with similar dimensions and material properties for the plate and similar process parameters for the laser bending process was considered and the temperature profile for the point corresponding to the experimental tests was extracted. However, by adjusting the parameters of heat flux such as laser absorption coefficient and coefficients of convection and radiation heat transfers, the best distribution of heat flux distribution for laser tube bending process was evaluated.

5.1. Effect of Laser Output Power

In Fig. 7, the effect of changes in the laser power on main and lateral bending angles are presented based of experimental measurements and numerical results. As it is seen, high values of power leads to more main and lateral bending angles. With high values of power, the heat flux entering the tube increased and followed by plastic deformation in the irradiated areas and consequently main bending angle. In addition, higher values of the main angle increase the bending stiffness and lateral bending angle.

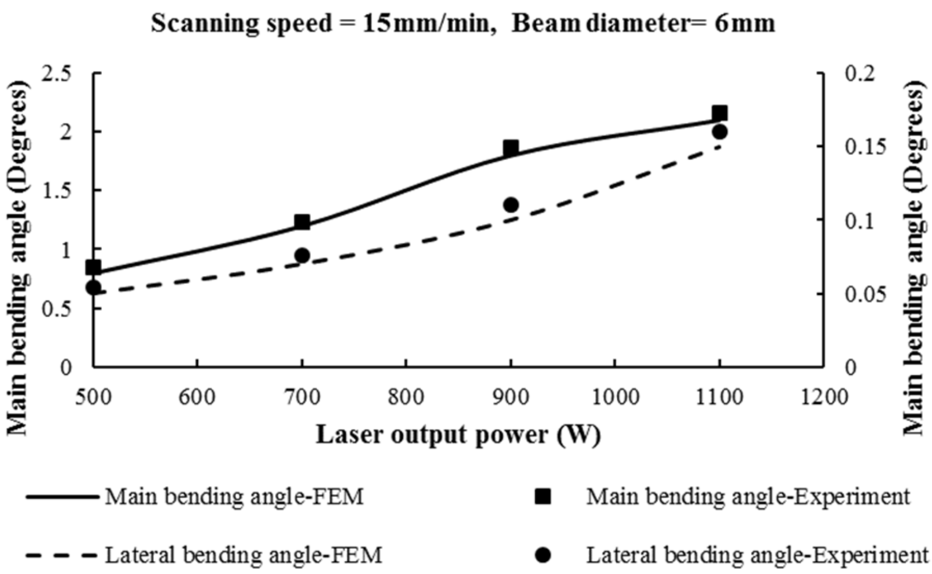

Fig. 7. Effect of laser output power on main and lateral bending angles of laser bent tube.

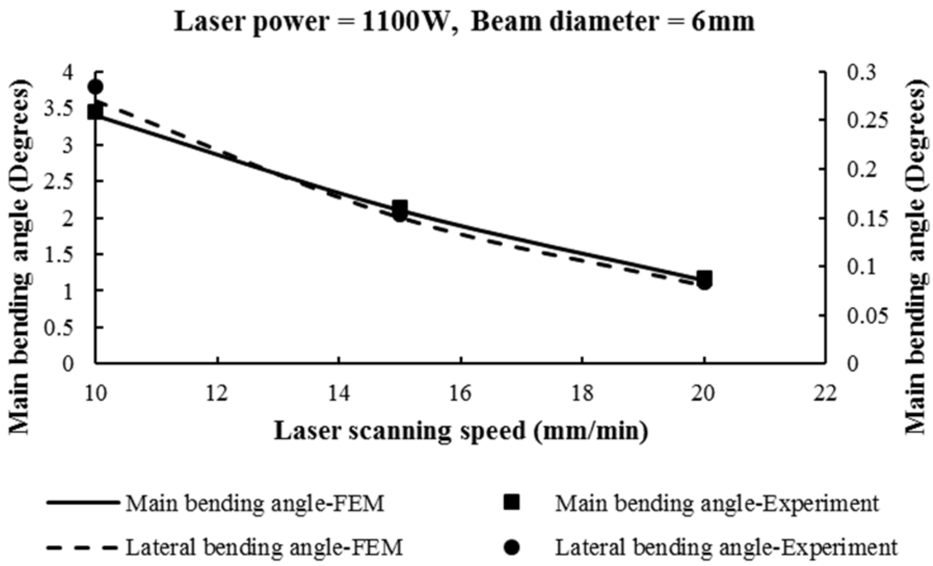

Fig. 8. The effects of laser scanning speed on main and lateral bending angles in laser tube bending process.

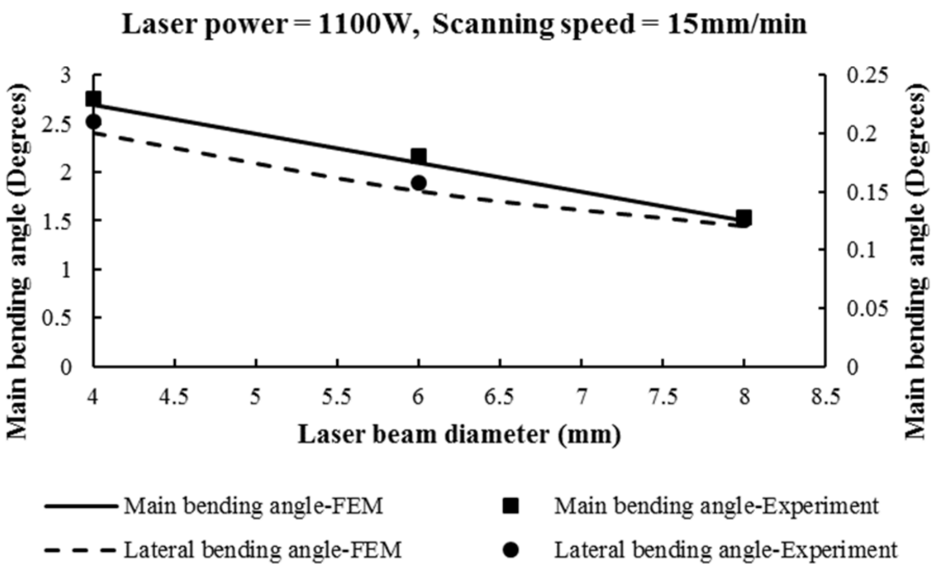

Fig. 9. Changes in the main and lateral bending angles of the laser-bent tube in proportion to the change in the laser beam diameter.

5.2. Effect of Laser Scanning Speed

The effects of laser scanning speed on bending angles in LTBP are indicated in Fig. 8 based of experimental measurements and numerical results. As it is concluded from this figure, decrease in scanning speed leads to higher values of main bending angle due to increase in the irradiated heat flux followed by more plastic deformation areas. Furthermore, lateral bending angle increases because of the effects of bending stiffness.

5.3. Effect of Laser Beam Diameter

Changes in the bending angles of the laser-bent tube in proportion to the change in the laser beam diameter are shown in Fig. 9 based on experimental measurements and numerical results. It is proved from this figure that higher values of beam diameter lead to decrease in the main bending angle because of decrease in the irradiated heat flux into the tube and consequently the lateral bending angle.

6. Conclusions

Laser bending of mild steel tubes was investigated experimentally and numerically. The effects of laser output power, laser scanning speed and laser beam diameter on main and lateral bending angles of laser-bent tubes were studied. The following results were obtained:

1. For evaluating the optimum mesh size for simulations, a sample point H was selected on the irradiation path and its temperature was extracted at the end of heating step for different sizes of the elements.
2. In addition, by adjusting the absorption and heat transfer coefficients and comparing the temperature profile with the experimental measurements, the true heat flux for LTBP was obtained.
3. The results showed that with increasing the power, the main angle increased because of increase in irradiated heat flux and consequently plastic deformation areas. Additionally, the lateral bending angle increased due to increase in bending stiffness.
4. In addition, it was proved that with increasing the scanning speed and beam diameter, the banding angle rised because of increase in entering heat flux and plastic deformations. Moreover, increase in bending stiffness due to decrease in scanning speed and beam diameter led to increase in the lateral bending angle.

Compliance with Ethical Standards

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