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Investigation of material specifications changes during laser tube bending and its influence on the modification and optimization of analytical modeling

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ABSTRACT

Nowadays, laser tube bending process has become commonly used in laser material processing and fabrication fields because of its ability to produce such forms and shapes that cannot be achieved by normal mechanical bending tools. The process can avoid and overcome most of bending defects like wall thinning, wrinkling, spring back and ovalization. This investigation focused on the experimental, analytical modeling, and numerical simulation to give more understanding of the process. In this work a high power pulsed Nd-Yag laser of maximum average power laser 300 (W) emitting at 1064 nm and fiber coupled has been used to irradiate stainless steel 304 tubes of diameter 12.7 mm, 0.6 mm thickness and 60 mm in length. An analytical model has been used to determine the bending angle by using Matlab program software. The changes of material specification during the laser tube bending process due to the temperature rise has been studied and the analytical model has been modified and enhanced. Particle Swarm Optimization (PSO) was used to optimize the analytical and experimental results and reduce the mean absolute error.

1. Introduction

Laser tube bending has become one of the basic parts of laser metal forming because of its extraordinary capability for the creation and overcomes the troubles that confronting the tube bending technique. Moreover, tube bending is an attractive application in many high-technological industries such as aerospace, aviation, automobile, shipbuilding, energy and health care [1]. The bending process occurs based on the non-uniform distribution of temperatures on specimen surface which generate different thermal stress between the irradiated area and the cold side of the tube. The majorities of researchers focused their efforts to understand the laser tube bending process and study the behavior of affecting parameters such as laser specifications and beam delivery conditions, the geometry of specimen and material properties. The mechanism used in laser tube bending is Buckling mechanism where the diameter of the laser beam is chosen to be much bigger than the tube thickness as seen in Fig. 1. Hence the inner side of the tube which faced the laser beam is homogenized heated in thickness direction caused material expansion. The expansion is restricted by unheated material which leads to plastic compression. Due to the cooling, the material suffers shrinkage and shortening in axial direction forced the tube to bend towards of laser beam, that what is Li and Yao [2] were mentioned in their work, they studied the mechanism of laser tube bending with deep concentration by numerical and experimental analysis. Jamil et al. [3] carried out the effects of laser power, beam diameter and plate our tube thickness. A numerical study has been conducted on a stainless steel plate and tube where the plate bending verified experimentally and the tube numerical results compared with the published papers results. Hsieh and Lin [4] thin metal tube of stainless steel 304 has been irradiated by CO_2 laser. Numerical and experimental investigation has conducted with considering of buckling mechanism. Li and Yao [5] examined the mechanism process for better understanding the behavior of parameters and

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the expected results. A finite element is used to simulate the process and validated experimentally. Safdar et al. [6] used an axial scanning for tube bending instead of common circumferential scan. The thermal stress generated due to laser tube bending depend externally on laser beam geometry and scanning type or direction. The parameters analysis numerically and verified experimentally by using fiber-coupled diode laser. Zhang et al. [7] used four scanning schemes for laser tube bending, involve pulsed line-source axial procession, line-source axial scanning without and with water cooling, and point-source circumferential scanning. The finite element method was used to find the coupled thermo-mechanical model and it is validated experimentally. Hao and Gai [8] studied the effects of parameters on the process of thin wall tube by using finite element methods and experiments. The conclusion was that the tube thickness increased the process will be difficult and effect on the final shape of the tube bending as well as the laser beam diameter. Guan et al. [9] analyzed numerically the process of single and multiscan depend on the gradient temperature between the scanned laser of the tube and the unscanned side to produce stress and strain caused the tube bending. Optimization of different parameters to find the maximum bending angle was carried out. Jamil et al. [10] carried out a comprehensive experimental and numerical study the laser tube bending of Nickle micro-tubes. Pre-stressed has supplied on laser scanning region to assist the tube bending and the produced bending angle result was much greater. In this paper, attention is paid to study the laser tube bending process analytically by Hao, N. and L. Li analytical model and validated experimentally. The effects of material specifications changes during laser tube bending due to the temperature rise are taken into account to modify and enhance Hao and Li analytical model by using Particle Swarm Optimization (PSO) to optimize the analytical and experimental results and to reduce the mean absolute error.

2. Principle of laser tube bending

Laser tube bending is similar to the heat treatment process and the surface temperature of the material has to be less than the melting point. There is a lot of nonlinear phenomena accompany this process like the temperature, microstructure, and stress field changes, all are significantly interrelated [11]. Hao and Li [12] established a new analytical model to determine the bending angle and studied the effects of significant parameters. Circular tube with circumferential scanning was used as shown in Fig. 2; the tube rotates on its axial axis around 180°, where the laser light is defocused on the tube surface with laser beam diameter much bigger than tube thickness. The heated area suffered wall thickening and compressive plastic deformation because of the thermal expansion limitation by the unheated material. When the laser source is turning off a rapid cooling occur, with material shrinkable on the heated surface. As a result, the shortening of irradiated material in the axial of the tube direction forced it to bend towards of laser source [12]. During bending process heat is generated because of strain energy, but it is very small compared to input laser beam energy so it can be neglected. In same direction Cheng and Lin [13] established an analytical model to estimate the produced angle with more accurate compared to other models and verified it experimentally.

3. Hao and Li's analytical model

Basically, there are two analytical models controlling the laser tube bending, the thermal model and the mechanical model which involve stress and then converted to plastic strain action to produce the bending angle. In addition, there are other aspects of

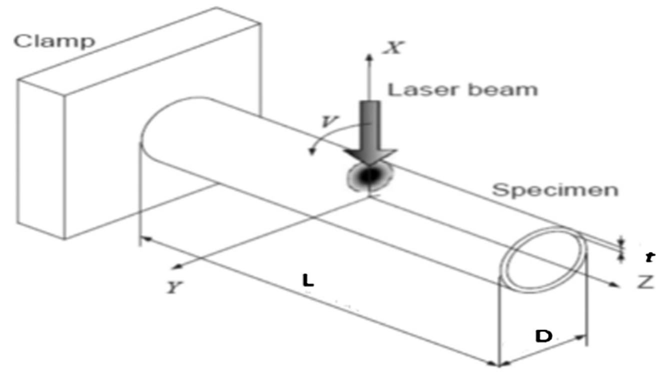

Fig. 1. laser tube bending circumferential scanning scheme.

thermal model related to the temperature field caused by a laser beam, assuming uniform thermal conductivity and the temperature of the heat source acting in the quasi- steady method. Hence, the temperature can be determined from the below Eq. [14]:

$$T(z,t') = (2(1-R)F/k)(St'/\pi)^{1/2})ierfc(z/2(kt')^{1/2}) \quad (1)$$

where k is thermal conductivity, F is the heat flux at the spot center, ierfc the integral complementary error function, R reflectivity and t' the heating time. To find the temperature on the material surface when z = 0 then Eq. (1) will become

$$T(0,t') = (2(1-R)F/k)(St'/\pi)^{1/2} \quad (2)$$

where R is Reflectivity, k is the thermal conductivity coefficient; S is the thermal diffusivity coefficient.

Laser intensity $F = P/A$ where P is the laser power and A is the laser beam area and can be written as:

$A = \pi l^2/4$ where l is the laser beam diameter. The heat loss from the specimen per unit area W/m^2 is either a result of convection as

$$q_c = h_c(T_s - T_a) \quad (3)$$

where h_c is the coefficient of convection heat transfer, T_s is tube surface temperature and T_a air temperature.

Or radiation which expressed by

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

where ε is the surface Emissivity [15].

The laser is heating the material surface and induced plastic compressive strain, from Fig.3 there are two forces F exerts inversely to each other between the heated and unheated material where the laser scanning is only on the upper portion of the tube circumference and in the axial direction.

Strain on scanning area is:

$$\varepsilon_s = -\Delta T\alpha/2 + F/SE \quad (5)$$

where S is the area of the section of half tube. E is the Yong's modulus of the material.

The strain of unscanned portion is

$$\varepsilon_{us} = -F/SE \quad (6)$$

The angle bend can be found from the below:

$$\theta = (\pi\ l/4D)[\Delta T\alpha - 2(\sqrt{2}-1)\sigma_y/E] \quad (7)$$

where l is the length of heated region and can be considered the laser beam diameter, D is a tube diameter, and σ_y is a yield stress of the material.

The heat energy generated by laser for bending is:

$$Q = P\eta\upsilon t' \quad (8)$$