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Scanning path planning for laser bending of straight tube into curve tube

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ABSTRACT

A bending method is presented based on geometric curvatures along the tube curves in which a scanning path planning for laser bending of a straight tube into a curve tube in a two- and three-dimension space. In two-dimensional (plane) bending, there are several segments divided on the curve tube according to extreme point and inflection point of the expected shape of the tube. It is taking the extreme point as the initial place of the path planning, using different scanning spaces for every subsection in order to identify the scanning paths. In three-dimensional bending, a projection decomposition method is used, where the three-dimension is decomposed into two two-dimension planes, and respective scanning path planning and process parameters are thus acquired. Then, the three-dimension scanning path plane was obtained by combining the data in the two-dimension planes. Finally, an experimental verification is carried out to bend straight tubes into a two-dimension sinusoidal and a three-dimension helical tube/coil-shaped. The results show that the scanning path planning proposed in this paper is effective and feasible.

1. Introduction

Tube bending is a process for manufacturing parts found in industry such as, gas/liquid pipe, pressure vessel, automotive, heat exchanger, hydraulic system, and boiler [1,2]. In tube bending process traditionally, many kinds of molds and dies are needed according to the expected shape of workpieces, which costs lots of time and funds. Hence, it is of great significance to develop a flexible bending technique without mold and die so as to cut down the cost and time on developing a new product. Compared with other thermal sources, taking plasma arc for example, laser beam can be controlled more precisely. In laser bending area, tube bending is an important application with bending technology in industry. Laser tube bending utilizes the thermal stresses generated in laser scanning to achieve the expected bends. The wide application of the tube bending process makes the researches in this area very demanding and significant [2,3]. Thermal stresses generated during laser scanning are strongly dependent upon laser beam geometry and scanning direction. It is difficult to isolate the contribution made by these two variables. Laser bending belongs to the latter category and is a relatively new free-bending technology. It is a highly flexible, heat-bending process suitable for low-volume production of various component shapes. Laser bending is particularly suitable for high hardness and brittle materials, such as titanium–nickel alloy, ceramics and cast iron. As laser bending does not require external pressure, there are no rebound and wrinkling phenomena associated with the process so that high bending quality is relatively achieved [4–6].

Laser tube bending is a flexible technology due to delivery of laser beam through fiber optic and the numerical control systems. Literature review shows both the research's achievements and challenges. Silve et al. [6] investigated laser bending of square cross-section tubes. Kraus [7] used the finite element model (FEM) to study basic processes in laser bending of extrusion using the upsetting mechanism. Hao and Li [8] also investigated laser tube bending of circular cross-section using FEM and analytical techniques. They found a linear relationship between bending angle and laser power and a non-linear relationship between bending angle and number of laser passes. Zhang et al. [9] recently studied the effects of scanning plans on laser tube bending and found that axial scan produced greater bending angle as compared to circumferential scan. However the comparison between the scanning schemes involved dissimilar laser beam geometries. Circular beam was used for circumferential scanning whereas axial scan was carried out by a rectangular beam. Thermal stresses generated during laser scanning are strongly dependent upon laser beam geometry and scanning direction; therefore it was difficult to isolate the contributions made by the two variations (i.e., varying scanning scheme and varying laser beam geometry). Thus, it is of great importance to know how different scanning schemes affect laser tube bending. At present there is not much literature present on the subject.

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Nomenclature

A	thermal absorption coefficient of stainless steel
x	distance from beginning path to scanning path (mm)
z	point position/curve function along z direction (mm)
P	laser power (W)
S	scanning speed (mm/min)
L	focal defocusing value (mm)
θ	scanning wrap angle (deg)
T	temperature of scanning zone (K)
x, y, z	three mutually perpendicular directions
a	thermal diffusivity ($cm^2\,S^{-1}$)

The effects of different scanning schemes in laser tube bending are a demanding task, mainly due to the complex geometries, boundary conditions and material properties. The general analytical expressions found in literature for tube bending are mostly for circumferential scanning schemes assuming a two-dimension temperature distribution and temperature independent material properties. Moreover, assumptions required for an analytical solution may be too compromising for a realistic estimation of thermal and mechanical results.

The evolution of numerical techniques and their uses in high-speed computers has enabled complicated calculations to be performed in relatively short periods of times with acceptable accuracy. Finite-element analysis has been used in the past to model laser bending process [10]. However many numerical models [11] found in several papers have treated the material as elastic or perfectly plastic, which may not be the true reflection of material behavior.

The control of tube bending process depends on the correct planning and selection of a number of process parameters. Different combinations of scanning paths and process parameters yield different bending results and different levels of deformation, and are properly selected according to the expected bending shape as well as the tube geometry and material properties. For example, to bend a straight tube into a V shape, the influencing factors include laser energy parameters (e.g. laser power, scanning speed, beam energy distribution, the absorption of laser materials) and the starting and final geometric parameters of the tube. By contrast, in a three-dimension bending, additional factors such as scanning path, distance and sequence of scan lines, or scan-lines distances from hold end to free end of the tube are important scanning path parameters that influence the final shape formed. As a flexible metal bending process, laser bending has been widely studied for bending V and other simple shaped tubes [12,13] through single or multiple scans. In practice, bending of three-dimension curved tubes is often required which shows a study in laser bending of these tubes shaped complexes.

Latest literature review shows that the researchers focus their work on modeling and optimization for the new bending method based on YAG lasers [14–16]. A strategy of scanning path planning is proposed based on an understanding of the laser tube bending in this project. As other tapes of lasers, such as fiber laser, diode laser, are applied in industry, the method of scanning pass plans will have the same or nearly the same relationships [15–18]. The strategy involves a method for calculating the geometric curvature of the curved tubes. Both plane bending and three-dimension bending are investigated. The experiments are finally carried out to verify the strategy of scanning path planning.

2. The principle of laser bending of a tube and experimental conditions

Laser bending of a tube deals with the temperature gradient mechanism. TGM is basically operative in conditions where temperature gradients are developed in the tube and hence induces high stresses and strains. The scanning zone is exposed to both thermal expansion and shrinkage, which induces a bending angle in the direction of the laser beam.

The material of the tube is AISI304L stainless. Its chemical composition is shown in Table 1. The diameter of tube outside is 6 mm with wall thickness 1 mm. Experimental equipment used is an LMT-5040 precision CNC laser machine and JK701H Nd:YAG laser. Its working mode is a mode of welding output, laser wavelength is 1.06 μm, and output power is from 0 to 650 W. CCD surveillance systems were used to measure the bending angle. Schematic diagram of the experimental system is shown in Fig. 1.

The bending profile can be effectively controlled if the influence of the various factors is comprehensively understood. In the condition of geometric parameters defined, tube bending shape mainly relates to laser power, scanning speed and the diameter of the spot. For the bending parameters determination, bending angle is calculated according to slope of the midpoint of the two adjacent path distances.

For 2D laser bending, a group of given bending angle, and several combinations of the parameters are then calculated. The consideration of the size of the tube, expected shape, and bending accuracy, and the scanning pass plans are shown in Table 2. Laser

Table 1
Chemical composition of 304L stainless steel.

C	Si	Mn	Cr	Ni	S	P
≤0.03	≤1.00	≤2.00	18–22	9–13	≤0.03	≤0.045

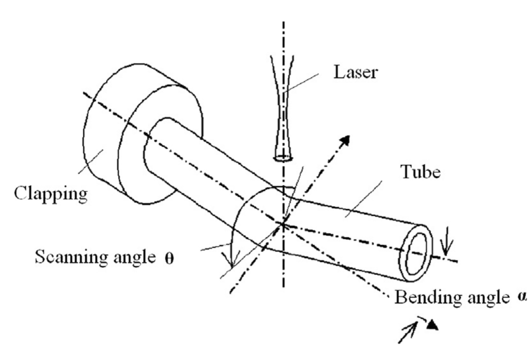

Fig. 1. Schematic of laser tube bending.

Table 2
Bending angle required for every scanning path.

Scanning path no.	1	2	3	4	5
Distance from free end (mm)	9.39	17.57	25.61	33.64	41.82
Bending angle (deg)	5.1	6.4	4.9	6.4	5.1
Scanning path no.	6	7	8	9	10
Distance from free end (mm)	60.60	68.79	76.82	84.85	93.03
Bending angle (deg)	5.1	6.4	4.9	6.4	5.1