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Laser bending of pre-stressed thin-walled nickel micro-tubes

M.S. Che Jamil [a,*], E.R. Imam Fauzi [a], C.S. Juinn [a], M.A. Sheikh [b]

[a] Manufacturing Engineering Group, School of Mechanical Engineering, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia
[b] Laser Processing Research Centre (LPRC), School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester M60 1QD, United Kingdom

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ABSTRACT

Laser forming is an innovative technique of producing bending, spatial forming and alignment of both metallic and non-metallic parts by introducing thermal stresses into a work piece with a laser beam. It involves a complex interaction of process parameters to mechanical and thermal characteristics of materials. This paper presents a comprehensive experimental and numerical study of laser bending process of thin-walled micro-tubes. The effect of input parameters, namely laser power, pulse length and pre-stress constraint, on the process and the final product characteristics are investigated. Results of the analysis show that the bending angle of the tube increases considerably when a constraint is imposed at the tube's free end during the heating period. The introduction of compressive pre-stresses (from mechanical bending) in the irradiated region increases the final deformation which varies almost linearly with the amount of pre-stress. Due to high thermal conductivity and thin-walled structure of the tube, the heat dissipates quickly from the irradiated region to its surrounding material. Therefore, a combination of short pulse duration and high power is preferable to generate a higher thermal gradient and induce plastic strain. Design of experiment and regression analysis are implemented to develop an empirical model based on simulation results. Sensitivity analysis is also performed to determine the influence of independent variables on output response. It is evident that initial displacement and pulse length have a stronger positive effect on the output response as compared to laser power.

1. Introduction

Laser forming has become a viable process for shaping both metallic and nonmetallic components and offers many advantages of process flexibility in comparison to conventional forming methods. This technique involves passing a focused or partially focused laser beam over the surface of work piece, thereby inducing rapid localized heating, followed by cooling as heat is dissipated to the neighboring material. In the manufacturing of boilers, engines and pipes for small-batch production, laser tube bending is much more suitable due to the minimal cost of required tooling. It is also easier to automate considering the flexibility of the laser beam delivery and numerical control system. Despite these advantages, there are issues related to the conventional tube bending process such as wrinkling instability, over thinning, and cross-section deformation. In certain cases where an elastic strain component remains in the material after completion of plastic deformation, a significant spring back may occur and affects both geometrical and shape accuracy [1].

To date, considerable efforts have been made in tube bending technologies. Numerical and experimental studies have been conducted to understand the mechanisms and the effect of control parameters on the bent tube. The procedures for laser bending of mild steel tubes with square cross section were investigated by Silve et al. [2]. A finite element analysis of laser bending of square cross sectional tubes was performed to study the heating sequence [3]. The analysis suggested that an inhomogeneous plastic zone exists at the beginning of the scanning through the domination of upsetting mechanism. Another analysis was conducted by Li and Yao [4] to investigate the mechanism of laser tube bending using stress analysis. It was found that the bending angle decreases with increasing beam diameter due to the diminished laser intensity. At the same time, the curvature radii of the bent tube increase as the ratio of the tube outer diameter to the wall thickness increases. Hao and Li [5] developed an analytical model to identify the correlation between the bending angle and process parameters. From the analytical and experimental results, it was suggested that the laser induced bending angle increases with the laser power. Zhang et al. [6], numerically investigated different laser scanning schemes for tube bending with and without cooling. It was concluded that axial scan produced greater bending angle as compared to circumferential scan. Safdar et al. [7] studied the effect of

* Corresponding author. Tel.: +60 10 4349035/4 5996368.
E-mail address: mesabrijamil@usm.my (M.S. Che Jamil).

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scanning direction on laser tube bending using finite element analysis. They also studied the effect of beam geometries on various laser processes such as laser transformation hardening, laser surface heating and laser melting. Guglielmotti et al. [8] studied the bending of slotted tubes as well as enlarging of one tube end using a high power diode laser. They found that high power diode lasers are a very efficient laser source for tube forming due to its large laser spot. Guan et al. [9] analyzed a 3D thermomechanical finite element model for laser tube bending. With the integration of genetic algorithm for process optimization, a new analytical model with objective functions of maximum bending angle and fixed bending angle was established. Wang et al. [10] developed a bending method based on geometric curvature of curved subsection divisions in two- and three-dimensional spaces.

Laser bending of 'microtubes' has also received attention from several researchers [11–12] in MEMS applications, medical and other engineering fields. Chandan et al. [11] used a laser for bending hypodermic needles (SS304) with an outer diameter of 1.032 mm and thickness of 0.143 mm. A pulsed beam with 700 μm diameter from a CO_2 laser was used to irradiate the tube. Majed et al. [12] used a pulsed Nd:YAG laser beam to bend a 0.63 mm diameter tube with 0.19 mm thickness. The beam size was kept to 2 mm in diameter. They concluded that the main factors affecting the bending angle using a pulsed laser were pulse energy, duration of heating and beam size. One aspect of laser tube bending that has received more attention recently is the bending of 'thin-walled' tubes. The advantage of laser tube bending is minimal thinning at the intrados. This is the main driver for research on laser tube bending of thin-wall tubes. Hao et al. [13] recently conducted a study on numerical simulation of laser bending of thin-walled tubes. These tubes were made of a low carbon stainless steel (316 L) with 32 mm diameter and 0.48 mm wall thickness. Results related to intrados protrusion in the laser scanned region were obtained.

This paper presents experimental results and a 3D finite element model for simulation of laser micro-tubes bending process. The numerical model was used to study the effect of bending control parameters; laser power, pulse length and initial displacement at the tube's free end on output properties; temperature, bending angle, ovality, and bulging was successfully demonstrated by varying the. A commercial finite element analysis software package ANSYS® was used to develop the model. Temperature-dependent thermal and mechanical properties were considered in the analysis. Transient thermal and non-linear mechanical analyses were sequentially performed. Simulation results were compared with the experimental results. It is shown that these results are well correlated, thereby indicating that the developed model is valid for the prediction of temperature distribution.

2. Laser tube bending

2.1. Laser tube bending with pre-stresses

Most researchers agree that the primary mechanism in tube bending is a combination of upsetting; that is the thickening of the scanned region [3–7], and buckling [14]. In the micro-scale laser forming application, these thermal processes, analogous to the upsetting and buckling mechanism, were used with appropriate scaled process parameters [15,16]. The upsetting mechanism is especially valid for tube bending with scans along the axial direction of the tube, where the shortening and thickening of the heated region in the axial direction causes the tube to bend upwards as schematically illustrated in Fig. 1. During the heating period, the thermally induced compressive stresses are exerted on the region in the axial and circumferential directions. The wall thickening was governed by the significant stress in axial direction, while the vertical component of the circumferential stress is responsible for the displacement outward in radial direction. The buckling mechanism of the thin tubes under laser bending usually was initiated by the combination of a uniform temperature gradient and plastic deformation. Eventually it also depends upon other process parameters such as laser power, heating period, wall thickness and thermal properties [14].

In this work, tubes were made of pure nickel with extremely thin wall (outer diameter $d = 960$ μm, thickness $t = 50$ μm, ratio $d/t = 19.2$) were used. Due to its thickness, the tubes are very difficult to bend mechanically as the tube's thin-wall is prone to buckle easily under compression. Considering the size of tubes, a very small beam diameter could not induce sufficient plastic strain zone to produce significant bending. Prior to this, two types of laser were tried which failed to produce any significant bending of the tube. The first was a Laserval Violino 532 Laser. This laser had power of 7 W and beam size of 55 μm. The second laser used was Spectron CO_2 laser with 100 W maximum power and beam size at focal spot size of 230 μm. A wide range of frequency and speed were tested but either no bending was observed or the heated portion melted and cut the tube. The problem was also modeled using finite element analysis to investigate the reasons for failure. It was established that too small beam size could not create sufficient plastic strain zone in order to produce significant bending. On the other hand, due to high thermal conductivity of nickel, heat from the laser scanned region propagated quickly to other regions of the tube, causing unrestricted thermal expansion. Also, the tube's thin wall meant that it had a low value of second moment of area. Hence it had inadequate counter-moment strength to restrain expansion during heating. Without any external constraint the heated portion expands freely causing the tube's free end to deflect away from laser direction. Consequently, no significant plastic strain is produced as the material in the heated

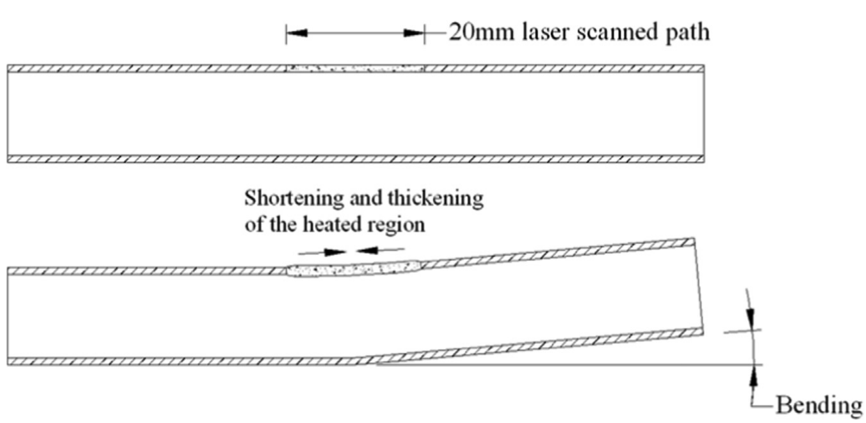

Fig. 1. Schematic illustration of upsetting mechanism for axial scan tube bending.