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# Improve the material absorption of light and enhance the laser tube bending process utilizing laser softening heat treatment

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ABSTRACT

Laser forming is a flexible control process that has a wide spectrum of applications; particularly, laser tube bending. It offers the perfect solution for many industrial fields, such as aerospace, engines, heat exchangers, and air conditioners. A high power pulsed Nd-YAG laser with a maximum average power of 300 W emitting at 1064 nm and fiber-coupled is used to irradiate stainless steel 304 (SS304) tubes of 12.7 mm diameter, 0.6 mm thickness and 70 mm length. Moreover, a motorized rotation stage with a computer controller is employed to hold and rotate the tube. In this paper, an experimental investigation is carried out to improve the laser tube bending process by enhancing the absorption coefficient of the material and the mechanical formability using laser softening heat treatment. The material surface is coated with an oxidization layer; hence, the material absorption of laser light is increased and the temperature rapidly rises. The processing speed is enhanced and the output bending angle is increased to 1.9° with an increment of 70% after the laser softening heat treatment.



## 1. Introduction

The laser forming process has been established in recent years, and demonstrated to be the key to solving numerous industrial issues which cannot be made by ordinary techniques. This process is used to bend or form both plates and tubes. Laser tube bending is extremely importance in wider applications of manufacturing such as in aerospace, engines, heat exchangers and air conditioners. Laser tube bending is used to overcome the defects of conventional bending methods such as wrinkling, wall thinning, springbuck and cross-sectional distortions [1]. It is similar to the heat treatment process; whereby, the surface temperature of the material must be less than the melting point. There are numerous nonlinear phenomena which accompany this process such as temperature, microstructure, and stress field changes; all of which are significantly interrelated [2]. The heated area suffers from wall thickening and compressive plastic deformation due to the limitation of thermal expansion by the unheated material. When the laser source is switched off, a rapid cooling occurs which prompts material shrinkage in the heated surface. As a result, the shortening of the irradiated material in the axial direction of the tube forces it to bend towards the laser source. During the bending process, heat is generated because of the strain energy, however, it is very small compared to the input laser beam energy so it can be neglected [3]; as shown in Fig. 1.

At the point when light incident on the material surface, some is reflected and the remaining will be absorbed by the material layers. If the light incident regularly on a flat surface, the reflected portion $R$, as per Fresnel's equation, can be composed as:

$$R = (n_1 - n_2/n_1 + n_2)^2 \tag{1}$$

where $n_1$ and $n_2$ are the refractive index of the atmosphere and material, respectively.

Optically, the reflectivity of any material is dependent on the light wavelength and the dispersion relation of the refractive index. For the absorptivity $\alpha$, the penetrating or the decay of light is through depth z, according to the Beer–Lambert law [4] which is:

$$I(z) = I_o e^{-\alpha z} \tag{2}$$

where $I_o$ is the intensity penetrated inside the surface after taking into account the reflection loss. Absorption by metals is highly dependent

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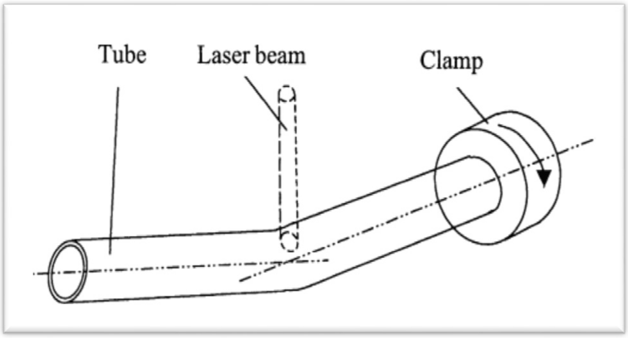


**Fig. 1.** The laser tube bending scheme.

on the wavelength of light, material type, the angle of incidence, and the surface condition [5]. In addition, the material properties change with temperature so the absorptivity can be increased by coating the surface, or supporting the surface oxidized during the process progress. Furthermore, the increase of wavelength leads to a decrease of absorptivity. For instance, the $CO_2$ laser has 10,600 nm wavelengths so the tests revealed that the absorptivity for alloy steel is between 4.5% and 5.3%; while the Nd-YAG laser has 1064 nm wavelength so the absorptivity increased to 28.6% and 30%. For that reason, the trend is to find short wavelength lasers, such as the diode laser [6].

The laser tube bending is studied by experimental means, and simulated by analytical or finite element analysis. However, the experimental results are only true for investigated cases. Moreover, the analytical element analysis can be the more specific case, while the finite element simulation is agreeable with experimental results [7]. The procedure can be influenced by numerous parameters including material parameters, geometric parameters, and laser parameters [8], which can independently or mutually impact the process heading. Material parameters can firstly be classified into thermal parameters (such as thermal expansion coefficient, specific heat and thermal conductivity), secondly, into physical parameters (such as density and absorption coefficient), and finally, into mechanical parameters (such as yield stress and Young's modulus). These parameters are temperature dependent and have an obvious effect on the laser forming process. Hence, it is necessary to understand the effects of these parameters on laser bending angles to specify the optimal process parameters [9]. In this paper, an experimental investigation is presented to improve the laser tube bending process by enhancing the absorption coefficient and the mechanical formability of the material using laser softening heat treatment.

## 2. Experiment and methodology

Heat treatment implies controlling the heating and cooling of the material to improve the physical and mechanical properties without altering the product shape. The laser provides a decent chance to exceptional heat treatment due to its finite size and short time, which facilitates localized heating of the material. So far, the bulk material is cold compared to the irradiated area, and that is an ideal condition for quenching [10]. The surface treatment usually occurs below the melting temperature of the material, and the common treatment is surface hardening, annealing, and tempering or softening. The tempering or softening is employed to increase the ductility of the metal components, where it improves formability before cold forming or laser forming to produce lightweight parts [11]. Steel components are widely employed in the industry, however, they are high-strength and brittle materials; therefore, local laser softening is applied to make them flexible and formable without any defects. On the other hand, the softening treatment by temporary laser heating is used to recrystallize the grain structure to be fully homogeneous in the thickness aspect [12]. Generally, laser forming is a slow process, especially laser tube bending, due to geometric challenges. Lasers can be utilized for locally softening to increase the ductility of metal components, which is crucial for automotive applications, since by increasing the ductility, lightweight automotive body panels are produced. Laser tube bending can produce special shapes that are applied in numerous industrial fields.

A high power pulsed Nd-YAG laser JK300HPS with maximum average power of 300 W emitted at 1064 nm and fiber coupled is used to irradiate stainless steel 304 (SS304) tubes of 12.7 mm diameter, 0.6 mm thickness and 70 mm length. Moreover, a computerized RSA Series Motorized Rotation Stage with its controller (from Zolix Company) is employed for holding and rotating the tube, as illustrated in Fig. 2. Experiments are conducted to choose the best conditions for softening heat treatment by changing the laser average power or the laser beam diameter, as well as the laser scanning speed. The results for the average laser power is 150 W, laser beam diameter (9 mm), and scanning speed (30 deg/s) defocused directly onto the tube surface. Furthermore, the stepper motor of the rotation stage is rotated at an angle of 360°; a 2-min interval time after each heat treatment is applied to allow the material to cool and the oxidation interaction to occur so as to change the shiny color of the stainless steel. Hence, the samples are tested by a spectrophotometer, type UV-3600 SHIMADZU, before and after the Laser Softening Heat Treatment (LSHT) to determine the change in material absorbance. The Scan electronic microscope (SEM), type FEI Inspect S50, is further used to examine the sample and see the oxidization layer. Finally, the best result of the bending angle achieved from this process will be considered from the significant method of LSHT. The tube is irradiated with a 200 W laser beam with a diameter of 7.5 mm, an angular scanning speed of 30 deg/s, and a rotating angle of 180°. The deviation of the tube around the x-axis is measured by a dial gauge to determine the bending angle. It should be mentioned that no surface melting of the SS304 stainless steel has been seen, either during

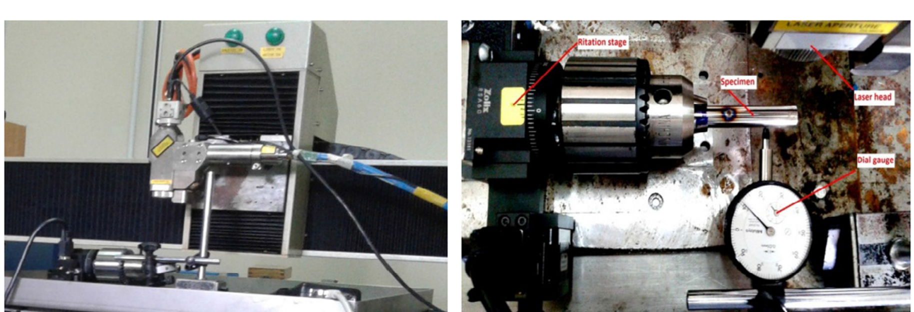


**Fig. 2.** Experiment setup.