**UNIVERSITI PUTRA MALAYSIA**

# *LASER TUBE BENDING PROCESS FOR STAINLESS STEEL 304*

**KHALIL IBRAHEEM IMHAN**

# LASER TUBE BENDING PROCESS FOR STAINLESS STEEL 304

By

**KHALIL IBRAHEEM IMHAN**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy**

**May 2017**

**DEDICATION**

To my father, My Allah SWT blesses his soul and put him in Jannah, and my beloved mother, Allah bless her.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

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**Chairman : Associate Professor B.T. Hang Tuah Bin Baharudin, PhD**
**Faculty : Engineering**

The invention of the laser light in the mid-last-century has opened a wide spectrum of laser material processing due to being unique, coherent and monochromatic. Moreover, the laser forming process of materials has a potential feature to produce new shapes of sheets or tubes that cannot be achieved through conventional methods. In this study, the focus is placed on the laser tube bending process because of its importance in large-term applications. Molds and dies are not currently in use; thus, no external forces that can cause tube bending defects such as wrinkling, wall thinning, springback and cross-section distortion. In addition, the process is flexible and can be controlled by laser parameters, either individually or in combination with other processes. An analytical model is used to study the effect of the average laser power, angular scanning speed, laser beam diameter, and specimen geometry during the laser tube bending process. The material specification impacts on the process behavior are analytically investigated for different material such as Copper, Aluminum, Nickel and Stainless Steel 304. To verify the analytical results, a high-power pulsed Neodymium-doped Yttrium Aluminium Garnet (Nd-YAG) laser of the maximum laser power of 300 (W) emitted at 1064 nm with a fibre-coupled head is used to irradiate stainless steel 304 tubes with a 12.7 mm diameter, 0.6 mm thickness. A motorized rotational stage with computerized control is used to hold and rotate the specimen tube $180^{\circ}$ for one semi-circle scanning, with a maximum angular scanning speed of 40 deg/sec. The deflection of the tube directly was measured to determine the bending angle, which it was 1.33 degrees when the average laser power is 200 W and the angular scanning speed is 30 deg/sec. The study also discovered that the laser softening heat treatment on the tube specimens can enhance the material absorption of the laser light and the mechanical formability; hence, the bending angle produced is increased by 70%. The experimental results become higher than the analytical results as the average laser power exceeds 100 W in both cases, with and without the laser softening heat treatment. Thus, due to the rise of the specimen's temperature, hence, the analytical model is modified and developed to involve the changes of material specifications by adding a factor to the model once the laser power becomes more than 100 W. This behavior may be due to the temperature rise of the tube material from the heat

generated by the laser. The modified model has been tested and optimized by using particle swarm optimization (PSO) to find the perfect specifications of the material affecting the laser tube bending process such as thermal expansion coefficient, specific heat, yield stress, and absorption coefficient. The analytical and experimental results are in the same trend but with different slopes; the bending angle determined is directly proportional to the average laser power, and inversely proportional to the angular scanning speed. Meanwhile, increasing the tube diameter and thickness reduces the value of the bending angle produced. In addition, the material specifications of the bent tube have significant effects on the process, especially the expansion coefficient which is directly proportional to the bending angle and the density as well as the specific heat which are inversely proportional with the bending angle.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

**PROSES LENTURAN TIUB MENGGUNAKAN LASER UNTUK STAINLESS STEEL 304**


Oleh

**KHALIL IBRAHEEM IMHAN**


**Mei 2017**


**Pengerusi : Profesor Madya B.T. Hang Tuah Bin Baharudin, PhD**
**Fakulti : Kejuruteraan**



Ciptaan cahaya laser dipertengahan akhir abad yang lalu telah membuka ruang luas kepada bidang pemprosesan bahan disebabkan oleh kerana sifatnya yang unik; koheren, dan monokromatik.Tambahan pula, proses pembentukan bahan menggunakan laser mempunyai potensi untuk menghasilkan bentuk lembaran atau tiub yang tidak dapat dicapai menerusi kaedah konvensional. Dalam kajian ini, fokus diberikan kepada pembengkokan tiub proses kerana ia penting dalam aplikasi yang luas. Acuan tidak lagi digunakan, oleh itu tiada daya luaran yang boleh menyebabkan kecacatan pembengkokan tiub seperti kedutan, penipisan dinding, bidasan dan perencatan keratan rentas. Selain itu, proses ini fleksibel dan boleh dikawal dengan menggunakan parameter laser, sama ada secara individu atau gabungan dengan lain-lain proses. Model analitikal digunakan untuk mengkaji kesan kuasa laser, kelajuan pengimbasan sudut, diameter alur laser dan geometri specimen semasa prosess pembengkokan tiub dengan laser. Kesan daripada spesifikasi bahan terhadap perlakuan prosess dikaji secara analitikal seperti tembaga, Aluminium, Nikel dan keluli tahan karat 304 . Untuk mengesahkan keputusan analitik, laser denyut berkuasa tinggi Magnet-didopkan Yttrium aluminium Garnet Nd-YAG dengan purata kuasa laser maksimum setinggi 300 (W) dipancarkan pada gelombang 1064 nm dengan menggunakan kepala gandingan-fiber untuk menyinari tiub keluli tahan karat 304 dengan dimensi 12.7 mm diameter, 0.6 mm ketebalan dan 70 mm panjang. Pentas putaran bermotor dengan kawalan komputer digunakan untuk memegang dan memutar tiub specimen 180° untuk imbasan separa-bulatan, dengan kelajuan maksimum imbasan sudut 40 darjah/saat. Pesongan tiub serta secara terus telah diukur untuk menentukan sudut pembengkokan, iaitu 1.33 darjah apabila purata kuasa laser adalah 200 W dan kelajuan imbasan sudut adalah 30 darjah/saat. Kajian turut menemukan bahawa rawatan haba pelembutan laser keatas specimen tiub berupaya meningkatkan penyerapan bahan terhadap cahaya laser dan keboleh-bentukan mekanikal; oleh itu, pembengkokan sudut terhasil meningkat sebanyak 70%. Hasil experiment menjadi lebih tinggi daripada hasil analitikal apabila kuasa laser purata melebihi 100 W untuk kedua-dua kes, dengan dan tanpa rawatan haba pelembutan laser. Oleh kerana peningkatan suhu specimen, model analitikal diubah-suai dan

dibangunkan untuk melibatkan perubahan spesifikasi bahan dengan menambah faktor kepada model apabila kuasa laser melebihi 100 W. Model yang diubah-suai ini telah diuji dan dioptimumkan dengan menggunakan pengoptimuman kumpulan zarah (PSO) untuk mencari spefisikasi sempurna dari bahan yang mempengaruhi process laser pembengkokan tiub seperti pekali pengembangan haba, haba tentu, tegasan alah, dan pekali penyerapan. Hasil analitikal dan experimental menunjukkan trend yang sama tetapi dengan cerun berbeza; sudut pembengkokan yang dibentuk adalah berkadar terus dengan kuasa purata laser, dan berkadar songsang terhadap kelajuan imbasan sudut. Sementara itu, peningkatan diameter dan ketebalan tiub mengurangkan nilai sudut pembengkokan terhasil. Tambahan lagi, spesifikasi bahan tiub bengkok mempunyai kesan signifikan terhadap prosess, terutamaya pekali pengembangan dimana ia adalah berkadar terus terhadap sudut pembengkokan dan ketumpatan serta haba yang tertentu adalah berkadar songsang dengan sudut lentur.

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Date:

**Declaration by Members of Supervisory Committee**

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

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| | |
|---|---|
| TGM | Temperature Gradient Mechanism |
| BM | Buckling Mechanism |
| UM | Upsetting Mechanism |
| CMM | Coordinate Measuring Machin |
| FEA | Finite Element Analysis |
| Nd-YAQ | Neodymium-Doped Yttrium Aluminum Garnet |
| SS304 | Stainless Steel 304 |
| CNC | Computer Numerical Control |
| LSHT | Laser Softening Heat Treatment |
| SEM | Scan Electronic Microscopic |
| PSO | Particle Swarm Optimization |
| MAE | Mean Absolute Error |
| RMSE | Root Mean Square Error |
| MSE | Mean Square Error |

# CHAPTER 1

# INTRODUCTION

## 1.1 Laser Material Processing

The laser is one of the greatest innovations of the 20th century. It has become an important part for many applications such as medical, military, communications, manufacturing, and more. Moreover, the demands for laser material processing have increased due to the laser beam's capability to interact with metals and non-metals. In addition, it is a non-contact form of processing, has reduced processing cost, completes the operation, improves product quality and produces minimum heat-affected zones (Majumdar & Manna, 2003). At the point when light incidents on the material surface, some of it is reflected, while the remainder will be absorbed by material layers. Optically, the reflectivity of any material is dependent on the light wavelength and material specifications, including surface roughness (Brown & Arnold, 2010). The absorbed power begins to heat the surface of the material according to thermal rules and properly penetrates to a limited depth within the material. Hence, the bulk material temperature rapidly increases depending on laser and material parameters. This increase in temperature leads to phase changes, as in the cases of evaporation and melting. Simply heating the material with a weak laser power will result in no phase changes. On the other hand, the increase of material temperature is further identified by the laser material's processing types; for example, the cutting, hole drilling, welding or heat treatment, as shown in Figure 1.1.

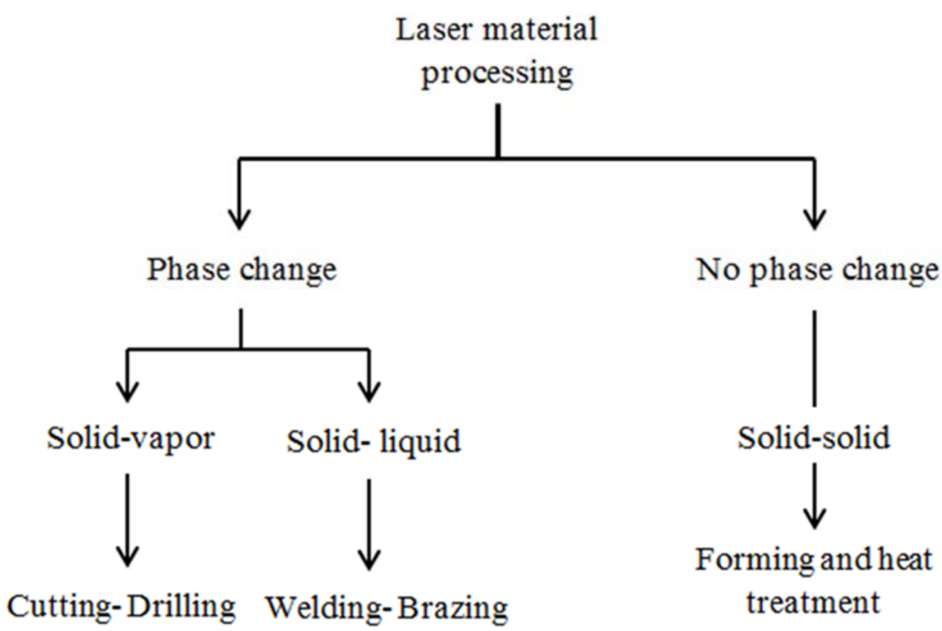
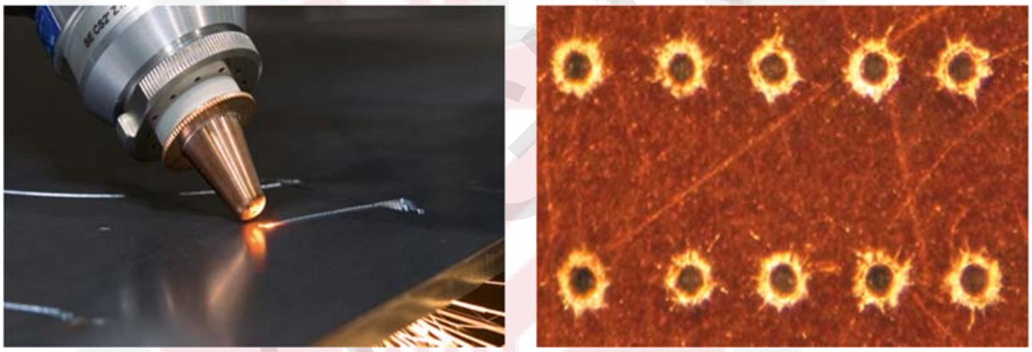



**Figure 1.1 : Simple classification of laser material processing**
(Majumdar & Manna, 2003)

### 1.1.1 Laser Cutting and Drilling

Nowadays, laser material cutting has become a reliable process and is widely used due to its ability to control parameters; thus, the quality of metal cutting can be accurate with a narrow kerf, smooth edge and short time of operation (Ghany & Newishy, 2005). The cutting occurs when a high laser power is focused on the material so the front surface of the cutting area is evaporated and the surrounding area is melted as shown in Figure 1.2(a) , where the molten material is ejected from the kerf by utilizing a gas jet (Wee & Li, 2005). Hole drilling is another important material process employed in numerous manufacturing applications. The hole's diameter and the finishing are crucial factors in this process, therefore, the laser beam diameter should be properly selected. The material is ejected from the hole through evaporation or by using the inert gas jet (Low et al., 2000), despite the explosive pressure that ejects the molten material out of the hole as illustrated in Figure 1.2(b). Finally, both the cutting and hole drilling are considered as phase changing processes; hence, the latent heat of evaporation and liquid should be taken into account.



(a) (b)

**Figure 1.2 : (a) Laser cutting (b) Laser hole drilling**
(Laser Cutting. (2017) from http://www.messer-cs.com/, (DRILLING July 18, 2016 from https://lightmachinery.com)

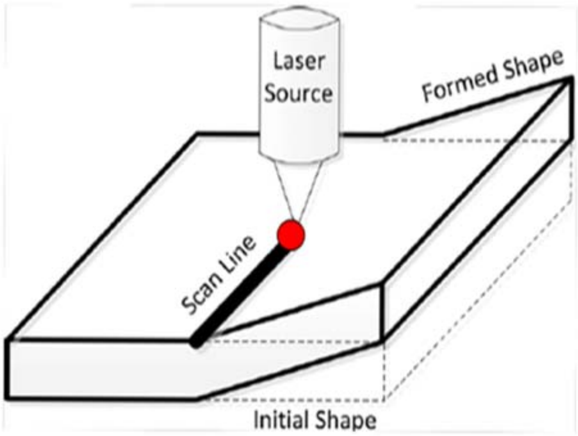
### 1.1.2 Laser Welding

Laser welding has acquired significant consideration as a promising joining innovation with astounding, high exactness, superior, fast and great adaptability with low mishaps or bending. In spite of the acknowledgment of simple and wide applications due to the congeniality of the robot, full computerisation, systematization, generation lines and others are needed. The utilization of laser welding is expanding (Katayama et al., 2010). In addition, the laser welding process is considered a phase changing process, transforming solid to liquid with critical limitations; the welding cannot be achieved without metal melting. Simultaneously, to continue the welding line, the vaporization phase must be avoided. The laser is used in all other welding types, such as brazing and soldering, with suitable flux; as illustrated in Figure 1.3.

**Figure 1.3 : Laser welding machine** (Oroin LZR Combo 200, 2017 from http://orionwelders.com/product/lzr-combo-200/)

### 1.1.3 Laser Forming and heat treatment

The laser forming process was developed in the last couple of years and demonstrated that it is the key to solving numerous industrial issues that cannot be manufactured through ordinary methods. The laser forming process is a technique employed to bend or form both plates and tubes due to their extreme importance in wide applications of manufacturing; such as aerospace, engines, heat exchangers and air conditioners as show in Figure 1.4(a) and (b). To summarize this process, the upper tube thickness is homogeneously heated; hence, the heated area will suffer wall thickening and compressive plastic deformation due to its restriction by the unheated area. During the cooling process, the heated area shrinks and is still restricted by the unheated area which exerts a tensile force (F). Meanwhile, the heated area exerts an inverse force, so if this force is high enough, the tube can be bent (Hao & Li, 2003).




(a)

(b)

**Figure 1.4 : (a) Laser plate forming** (Roohi et al., 2012) **(b) Laser tube bending** (Wang et al., 2014)

## 1.2 Problem statement

Laser tube bending is a new technique that has promising potential to solve or improve many specific industrial problems. In general, laser forming is a complex and nonlinear process, while laser tube bending is a more complicated process since the difficulties are added by the effects of the geometric shape. Many researchers had conducted their studies to understand the laser sheet bending process, however, comparatively fewer efforts were made to investigate laser tube bending. Controlling the process parameters require further investigation to overcome the problems listed in the following:

- The conventional bending methods have many defects such as wrinkling, wall thinning, springbuck and cross-section distortions (Hitz et al., 2012).
- The mechanical method is unable to bend large tube diameters of more than 50 mm due to the difficulties of producing the templates, along with the high cost. Hence, the extrados portion suffers from stretching and the intrados portion suffers from wrinkling rather than the distortion of the cross section (Hitz et al., 2012). The laser light can do such tasks and bend large tube diameters of 150 mm (Zhang et al., 2005).
- The analytical, numerical and experimental modelling are still unable to cover all aspects of the process for a complete industrial application.
- There is a lack of information regarding the impact of overall process parameters and the effect of each parameter on the other (Hao & Li, 2003) .
- Both the bending angle and its direction cannot be easily predicted in either tube or thin sheet bending (Jamil et al., 2012) .
- The bending process is slow with low efficiency; hence, to produce the desired angle, one must employ multi-passes of irradiation and.

- The analytical models do not consider the temperature dependency of the material specifications (Hao & Li, 2003).

The proposed work can be considered as a contribution to fill the gap concerning the parameters' behaviors in laser tube bending studies. The laser tube bending research is crucial to develop or modify a new model for the enhanced comprehension of each significant parameter. According to a recent review, no published report had analyzed the increase of the bending angle by using single scanning in the laser tube bending process. The temperature rise effect on the material specification was not taken into account in the analytical modeling.

## 1.3 Objectives and esearch questions

### Objectives

In order to address the problems, the objectives were as follows:

- To model the effect of the material properties and specimen geometry on the laser tube bending process.
- To analysis the effect of the average laser power, angular scanning speed and laser beam diameter on the laser tube bending process.
- To enhance the laser tube bending process and increase the amount of the bending angle produced by the single laser scan.
- To optimize the modified model of the laser tube bending process.

As previously mentioned, the target of this research is to determine the effect of the process parameters on the process speed and to determine suitable methods for increasing the processing speed.

### The Main Question

At the end of this study, the main question of this investigation was answered:

"How can understanding the behavior of the process parameters, along with the modification of the analytical model, increase the process speed and bending angle?"

## 1.4 Significant of study

The significance of assessing the laser tube bending process may be summarized as the following:

i. Understanding the effect of the process parameters on the processing speed and the bending angle produced.

ii. Enhancing the efficiency of the laser tube bending process by changing and controlling effective parameters.
iii. Modifying the analytical model to be more compatible with laser tube bending.

## 1.5 Scope and the limitation of the study

This study was conducted between the years of 2014-2017, in conformity with following the scopes and limitations illustrated in Figure 1.5.

1. The research basically concentrated on the laser tube bending process of Stainless Steel 304 tubes with the same length, but with various diameters and thicknesses.
2. The process was executed by using a high-powered pulse Nd-YAG laser machine (JK300HPS), with a fiber coupled head, and a maximum average laser power of 300 W that emits wavelength 1064 nm in Gaussian mode.
3. The specimen was held and rotated from 180° to 360° during the motorized rotational stage, with computerized controlling, for one circumferential scanning.
4. A motorized rotational stage with computerized controlling was employed to hold and rotate the specimen tube 180° for one circumferential scanning with a maximum angular scanning speed of 40 deg/sec.

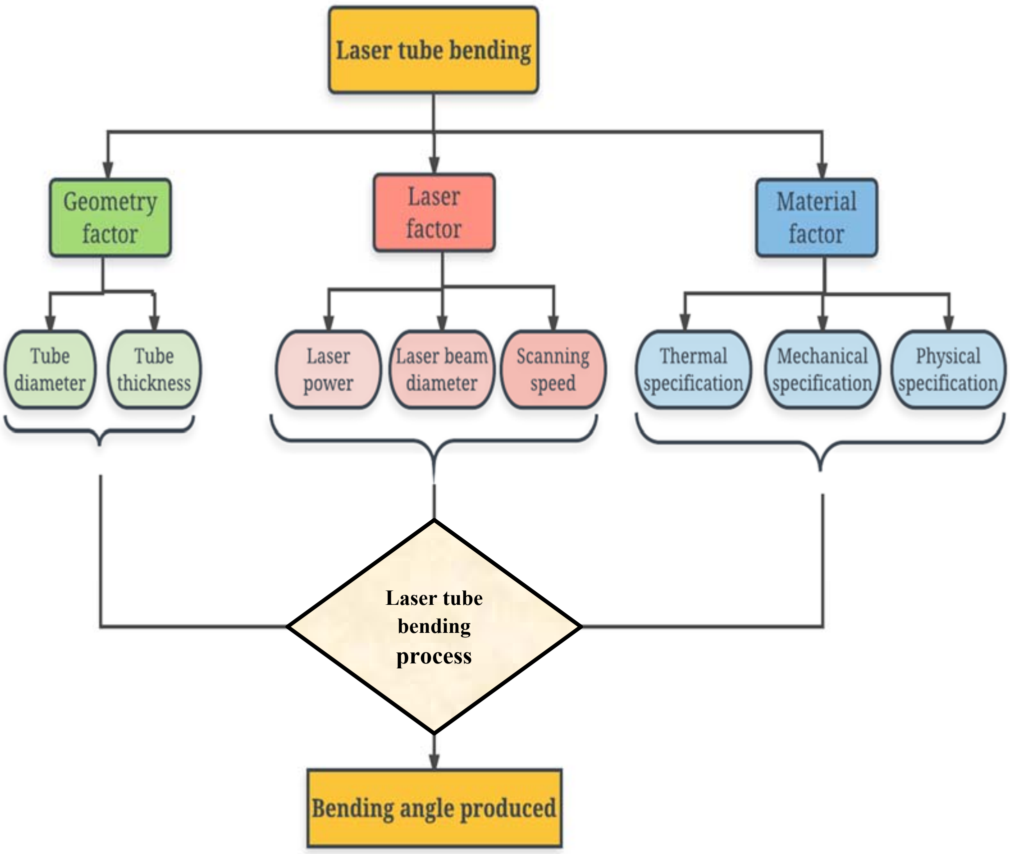



**Figure 1.5 : The diagram illustrate the narrowing down of research scope**

## 1.6 Thesis organization

This thesis was divided into five chapters. Chapter 1 provided a brief note on the laser material process and laser tube bending. The problem statement was identified, and the hypothesis questions and objectives, the significance of the study, as well as, the scope and limitation were subsequently listed. Chapter 2 consisted of the literature review which analyzed the aspects of the laser tube bending process.

Chapter 3 discussed the methodology and design of the experiment, while Chapter 4 focused on collecting data and analyzing the results by comparing the analytical and experimental results to obtain the best bending angle value. The analytical model modification and testing were also taken into account. Finally, Chapter 5 concluded the thesis, and the main contributions were reviewed. The limitations of the laser tube bending process were acknowledged, and additional suggestions for future works were provided.

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