UNIVERSITI PUTRA MALAYSIA

LASER TUBE BENDING PROCESS FOR STAINLESS STEEL 304

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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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May 2017

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° 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
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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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I certify that a Thesis Examination Committee has met on 24 May 2017 to conduct the final examination of Khalil Ibraheem Imhan on his thesis entitled "Laser Tube Bending Process for Stainless Steel 304" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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Declaration by graduate student

I hereby confirm that:

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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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Signature: ______________________________
Name of Member of Supervisory Committee: Professor Dr. Ahmad Kamal Ahmad

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LIST OF ABBREVIATIONS

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.

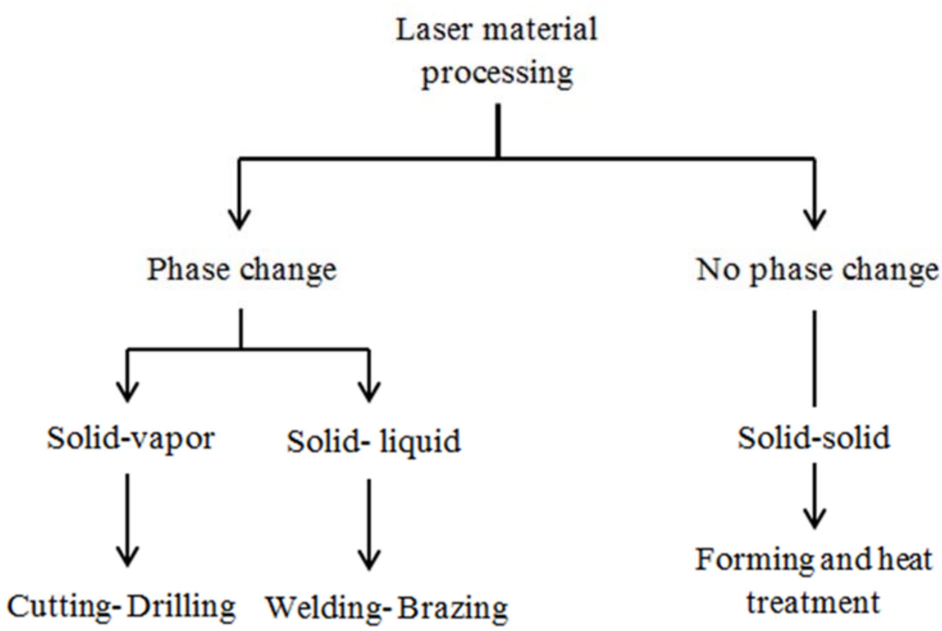
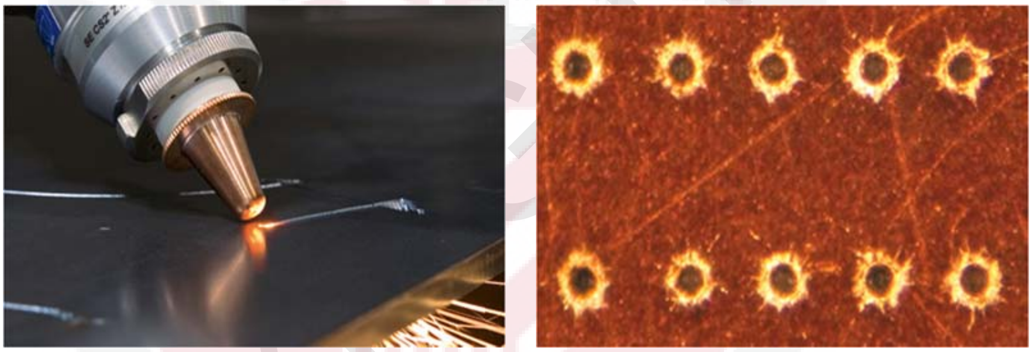


Figure 1.1 : Simple classification of laser material processing
(Majumdar & Manna, 2003)

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)

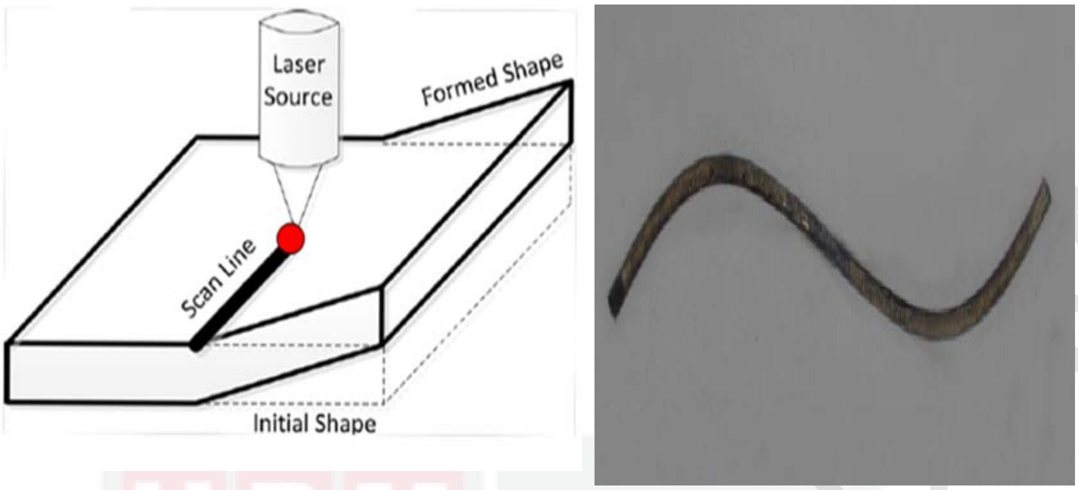
1.1.2 Laser Welding

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.

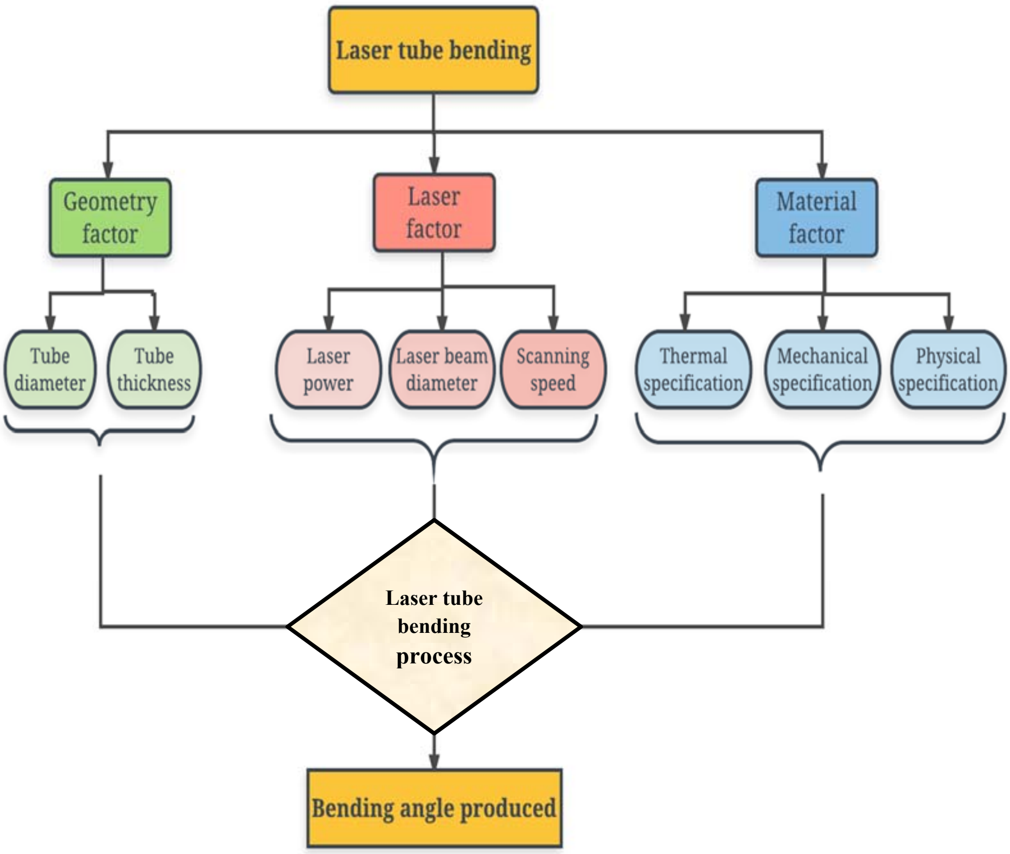


Figure 1.5 : The diagram illustrate the narrowing down of research scope

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.

REFERENCES

Afrozi, M. N., Aghdam, M. H., Naebi, A., & Aghdam, S. H. (2011). *Simulation and Optimization of asynchronous AC motor control by Particle Swarm Optimization (PSO) and Emperor Algorithm.* Paper presented at the Computer Modeling and Simulation (EMS), 2011 Fifth UKSim European Symposium on.

Akinlabi, E. T., Shukla, M., & Akinlabi, S. A. (2012). *Laser Forming of Titanium and Its Alloys-An Overview.* Paper presented at the Proceedings of World Academy of Science, Engineering and Technology.

Akinlabi, S. A., & Akinlabi, E. T. (2013). Experimental Investigation of Laser beam forming of Titanium and Statistical Analysis of the Effects of Parameters on Curvature.

Ali, J. A., Hannan, M., & Mohamed, A. (2014). *PSO algorithm for three phase induction motor drive with SVPWM switching and V/f control.* Paper presented at the Power and Energy (PECon), 2014 IEEE International Conference on.

Ali, J. A., Hannan, M., Mohamed, A., & Abdolrasol, M. G. (2016). Fuzzy logic speed controller optimization approach for induction motor drive using backtracking search algorithm. *Measurement, 78*, 49-62.

Antsiferov, V. V. e., & Smirnov, G. I. (2005). *Physics of solid-state lasers*: Cambridge International Science Publishing.

Bachmann, F. (2003). Industrial applications of high power diode lasers in materials processing. *Applied Surface Science, 208*, 125-136.

Basting, D. (2005). *Excimer laser technology*: Springer Science & Business Media.

Bayoumi, E. H., Awadallah, M., & Soliman, H. (2011). Deadbeat performance of vector-controlled induction motor drives using particle swarm optimization and adaptive neuro-fuzzy inference systems. *Electromotion Scientific Journal, 18*(4), 231-242.

Brown, M. S., & Arnold, C. B. (2010). Fundamentals of laser-material interaction and application to multiscale surface modification *Laser precision microfabrication* (pp. 91-120): Springer.

Carlone, P., Palazzo, G. S., & Pasquino, R. (2008). Inverse analysis of the laser forming process by computational modelling and methods. *Computers & Mathematics with Applications, 55*(9), 2018-2032.

Carson, Y., & Maria, A. (1997). *Simulation optimization: methods and applications.* Paper presented at the Proceedings of the 29th conference on Winter simulation.

Chen, G., & Xu, X. (2001). Experimental and 3D finite element studies of CW laser forming of thin stainless steel sheets. *Journal of manufacturing science and engineering, 123*(1), 66-73.

Cheng, J., & Yao, Y. L. (2001). Cooling effects in multiscan laser forming. *Journal of Manufacturing Processes, 3*(1), 60-72.

Cheng, P., Fan, Y., Zhang, J., Yao, Y. L., Mika, D. P., Zhang, W., . . . Jones, M. (2006). Laser forming of varying thickness plate—Part I: Process analysis. *Journal of manufacturing science and engineering, 128*(3), 634-641.

Cheng, P., & Lin, S. (2001). An analytical model to estimate angle formed by laser. *Journal of Materials Processing Technology, 108*(3), 314-319.

Cheng, P., Yao, Y. L., Liu, C., Pratt, D., & Fan, Y. (2005). Analysis and prediction of size effect on laser forming of sheet metal. *Journal of Manufacturing Processes, 7*(1), 28-41.

Chow, W. W., & Koch, S. W. (2013). *Semiconductor-laser fundamentals: physics of the gain materials*: Springer Science & Business Media.

Cross, F. (1993). Laser Weapons. The dawn of a new military age. *Lasers in Medical Science, 8*(4), 309-309.

Dearden, G., & Edwardson, S. (2003). Laser assisted forming for ship building. *SAIL, Williamsburg, VA*, 2-4.

Dowden, J. (2009). *The Theory of Laser Materials Processing: Heat and Mass Transfer in Modern Technology* (Vol. 119): Springer Science & Business Media.

Duley, W. (2012). *CO2 lasers effects and applications*: Elsevier.

Duley, W., Semple, D., Morency, J.-P., & Gravel, M. (1979). Coupling coefficient for cw CO 2 laser radiation on stainless steel. *Optics & Laser Technology, 11*(6), 313-316.

Dumitras, D. C. (2012). *_CO2_Laser_-_Optimisation_and_Applica(BookZZ.org).pdf*. Janeza Trdine 9, 51000 Rijeka, Croatia

Escudero, M., & Bello, J. (1992). Laser surface treatment and corrosion behaviour of martensitic stainless AISI 420 steel. *Materials Science and Engineering: A, 158*(2), 227-233.

Ganeev, R. (2002). Low-power laser hardening of steels. *Journal of Materials Processing Technology, 121*(2), 414-419.

Geiger, M. (1994). Synergy of laser material processing and metal forming. *CIRP Annals-Manufacturing Technology, 43*(2), 563-570.

Geiger, M., Merklein, M., & Pitz, M. (2004). Laser and forming technology—an idea and the way of implementation. *Journal of Materials Processing Technology, 151*(1), 3-11.

Ghany, K. A., & Newishy, M. (2005). Cutting of 1.2 mm thick austenitic stainless steel sheet using pulsed and CW Nd: YAG laser. *Journal of Materials Processing Technology, 168*(3), 438-447.

Gollo, M. H., Naeini, H. M., & Arab, N. M. (2011). Experimental and numerical investigation on laser bending process. *Journal of Computational and Applied Research in Mechanical Engineering, 1*(1), 45-52.

Goupy, J., & Creighton, L. (2007). *Introduction to design of experiments with JMP examples*: SAS Publishing.

Gregson, V. G. (1983). Laser heat treatment. *Laser Materials Processing*, 201-233.

Griffiths, J. D. (2012). *Modelling of laser forming at macro and micro scales.* University of Liverpool Liverpool.

Guan, Y., Sun, S., Zhao, G., & Luan, Y. (2005). Influence of material properties on the laser-forming process of sheet metals. *Journal of Materials Processing Technology, 167*(1), 124-131.

Guan, Y., Yuan, G., Sun, S., & Zhao, G. (2013). Process simulation and optimization of laser tube bending. *The International Journal of Advanced Manufacturing Technology, 65*(1-4), 333-342.

H. Moslemi Naeini , H. L. V. P., S. Mazdak , H. Mousavi Hondori (2007). TGM Laser Forming Process for Sheet Metals Using Experimental and FEM

Analysis Approach. *4th International Conference and Exhibition on Design and Production of MACHINES and DIES/MOLDS.*

Hao, N. (2010). *On the process parameter of laser tube bending.* Paper presented at the Mechanic Automation and Control Engineering (MACE), 2010 International Conference on.

Hao, N., & Li, L. (2003a). An analytical model for laser tube bending. *Applied Surface Science, 208*, 432-436.

Hao, N., & Li, L. (2003b). Finite element analysis of laser tube bending process. *Applied Surface Science, 208*, 437-441.

Hennige, T., Holzer, S., Vollertsen, F., & Geiger, M. (1997). On the working accuracy of laser bending. *Journal of Materials Processing Technology, 71*(3), 422-432.

Hitz, C. B., Ewing, J. J., & Hecht, J. (2012). *Introduction to laser technology*: John Wiley & Sons.

Hong, I., & Koo, C. H. (2005). Antibacterial properties, corrosion resistance and mechanical properties of Cu-modified SUS 304 stainless steel. *Materials Science and Engineering: A, 393*(1), 213-222.

Hsieh, H.-S., & Lin, J. (2005a). Study of the buckling mechanism in laser tube forming. *Optics & Laser Technology, 37*(5), 402-409.

Hsieh, H.-S., & Lin, J. (2005b). Study of the buckling mechanism in laser tube forming with axial preloads. *International Journal of Machine Tools and Manufacture, 45*(12), 1368-1374.

Hu, Z., Kovacevic, R., & Labudovic, M. (2002). Experimental and numerical modeling of buckling instability of laser sheet forming. *International Journal of Machine Tools and Manufacture, 42*(13), 1427-1439.

Hu, Z., Labudovic, M., Wang, H., & Kovacevic, R. (2001). Computer simulation and experimental investigation of sheet metal bending using laser beam scanning. *International Journal of Machine Tools and Manufacture, 41*(4), 589-607.

Jacobs, S. F. (1975). Dye Lasers, edited by FP Schäfer. Reviewer. *Review of Scientific Instruments, 46*(8), 1133-1133.

Jamil, M. C., Fauzi, E. I., Juinn, C., & Sheikh, M. (2015). Laser bending of pre-stressed thin-walled nickel micro-tubes. *Optics & Laser Technology, 73*, 105-117.

Jamil, M. C., Sheikh, M., & Li, L. (2011). A study of the effect of laser beam geometries on laser bending of sheet metal by buckling mechanism. *Optics & Laser Technology, 43*(1), 183-193.

Jamil, M. C., Sheikh, M., & Li, L. (2012). A Finite Element Study of Buckling and Upsetting Mechanisms in Laser Forming of Plates and Tubes. *Dynamic Methods and Process Advancements in Mechanical, Manufacturing, and Materials Engineering*, 140.

Jha, G. C., Nath, A., & Roy, S. (2008). Study of edge effect and multi-curvature in laser bending of AISI 304 stainless steel. *Journal of Materials Processing Technology, 197*(1), 434-438.

Kannatey-Asibu Jr, E. (2009). *Principles of laser materials processing* (Vol. 4): John Wiley & Sons.

Katayama, S., Kawahito, Y., & Mizutani, M. (2010). Elucidation of laser welding phenomena and factors affecting weld penetration and welding defects. *Physics procedia, 5*, 9-17.

Khan, O. U., & Yilbas, B. (2004). Laser heating of sheet metal and thermal stress development. *Journal of Materials Processing Technology, 155*, 2045-2050.

Koechner, W. (1999). Properties of solid-state laser materials *Solid-State Laser Engineering* (pp. 28-87): Springer.

Kratky, A. (2006). *Laser assisted forming techniques.* Paper presented at the XVI International Symposium on Gas Flow, Chemical Lasers, and High-Power Lasers.

Kuang, J. H., Hung, T. P., Lai, K., Hsu, C. M., & Lin, A. D. (2012). *The Surface Absorption Coefficient of S304L Stainless Steel by Nd: YAG Micro-Pulse Laser.* Paper presented at the Advanced Materials Research.

Kusinski, J., Kac, S., Kopia, A., Radziszewska, A., Rozmus-Górnikowska, M., Major, B., . . . Lisiecki, A. (2012). Laser modification of the materials surface layer–a review paper. *Bulletin of the Polish Academy of Sciences: Technical Sciences, 60*(4), 711-728.

Kyrsanidi, A. K., Kermanidis, T. B., & Pantelakis, S. G. (1999). Numerical and experimental investigation of the laser forming process. *Journal of Materials Processing Technology, 87*(1), 281-290.

Kyrsanidi, A. K., Kermanidis, T. B., & Pantelakis, S. G. (2000). An analytical model for the prediction of distortions caused by the laser forming process. *Journal of Materials Processing Technology, 104*(1), 94-102.

Lambrechts, W., & Sinha, S. (2017). Electronic Warfare Laser Driver Principles: High-Powered Directed Energy Beam Generation *SiGe-based Re-engineering of Electronic Warfare Subsystems* (pp. 67-100): Springer.

Lawrence, J., Schmidt, M. J., & Li, L. (2001). The forming of mild steel plates with a 2.5 kW high power diode laser. *International Journal of Machine Tools and Manufacture, 41*(7), 967-977.

Lawrence, J. R. (2010). *Advances in laser materials processing: Technology, research and application*: Elsevier.

Lee, K.-L., Pan, W.-F., & Kuo, J.-N. (2001). The influence of the diameter-to-thickness ratio on the stability of circular tubes under cyclic bending. *International Journal of Solids and Structures, 38*(14), 2401-2413.

Li, L., Chen, Y., Wang, X., & Lin, S. (2009). FEM simulation for laser forming processing. *Acta Metallurgica Sinica (English Letters), 17*(3), 317-322.

Li, W., & Yao, Y. (2000). *Numerical and experimental investigation of laser induced tube bending.* Paper presented at the ICALEO 2000: Laser Materials Processing Conference.

Li, W., & Yao, Y. L. (2000). *Buckling based laser forming process: concave or convex.* Paper presented at the ICALEO 2000: Laser Materials Processing Conference.

Li, W., & Yao, Y. L. (2000). Numerical and experimental study of strain rate effects in laser forming. *TRANSACTIONS-AMERICAN SOCIETY OF MECHANICAL ENGINEERS JOURNAL OF MANUFACTURING SCIENCE AND ENGINEERING, 122*(3), 445-451.

Li, W., & Yao, Y. L. (2001). Laser bending of tubes: mechanism, analysis, and prediction. *Journal of manufacturing science and engineering, 123*(4), 674-681.

Lim, G., & Steen, W. (1982). Measurement of the temporal and spatial power distribution of a high-power CO2 laser beam. *Optics & Laser Technology, 14*(3), 149-153.

Liu, S., Fang, X., & FAN, X.-r. (2004). Experiment investigation on rules of laser tube bending. *Laser Technology, 4*, 001.

Lok, M. A., Aoyama, H., Rajaraman, R., Dobson, I., Sarlashkar, J. V., Sorin, D., . . . Sorin, D. J. (2013). An analytical model for calculating the temperature distribution and determining the laser forming mechanism: ICOMM.

Low, D., Li, L., & Corfe, A. (2000). The influence of assist gas on the mechanism of material ejection and removal during laser percussion drilling. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 214*(7), 521-527.

Shayan dehghan, a. M., ''. (2014). Numerical investigation on effect of power variation in laser forming of sheet metas. *indian j.sci.res.1(2), 2*(2250-0138), 844-850.

Magee, J., Watkins, K., & Steen, W. (1998). Advances in laser forming. *Journal of Laser Applications, 10*(6), 235-246.

Majed, A., Ahmadi, F., & Farzin, M. (2009). *Experiment and finite element simulation of laser bending of tubes.* Paper presented at the Proceedings of the Iran Conference Manufacturing Engineering, Birjand, Iran.

Majumdar, J. D., & Manna, I. (2003). Laser processing of materials. *Sadhana, 28*(3-4), 495-562.

Majumdar, J. D., & Manna, I. (2012). *Laser-assisted fabrication of materials* (Vol. 161): Springer Science & Business Media.

Marya, M., & Edwards, G. (2001). A study on the laser forming of near-alpha and metastable beta titanium alloy sheets. *Journal of Materials Processing Technology, 108*(3), 376-383.

Mroziewicz, B., Bugajski, M., & Nakwaski, W. (2013). *Physics of semiconductor lasers*: Elsevier.

Mucha, Z., Hoffman, J., Kalita, W., & Mucha, S. (1997). Laser forming of thick free plates. *Laser Assisted Net Shape Engineering, Proceedings of the LANE'97*, 383-392.

Palanker, D. (2016). Evolution of Concepts and Technologies in Ophthalmic Laser Therapy. *Annual Review of Vision Science, 2*(1).

Pantsar, H., & Kujanpää, V. (2006). Effect of oxide layer growth on diode laser beam transformation hardening of steels. *Surface and Coatings Technology, 200*(8), 2627-2633.

Parsopoulos, K. E., & Vrahatis, M. N. (2002). Particle swarm optimization method for constrained optimization problems. *Intelligent Technologies–Theory and Application: New Trends in Intelligent Technologies, 76*(1), 214-220.

Poli, R. (2008). Analysis of the publications on the applications of particle swarm optimisation. *Journal of Artificial Evolution and Applications, 2008*, 3.

Rassweiler, J. J., & Klein, J. (2016). Re: Update on Lasers in Urology. Current Assessment on Holmium: yttrium-aluminum-garnet (Ho: YAG) Laser Lithotripter Settings and Laser Fibers. *European Urology, 70*(3), 538-539.

Roohi, A. H., Gollo, M. H., & Naeini, H. M. (2012). External force-assisted laser forming process for gaining high bending angles. *Journal of Manufacturing Processes, 14*(3), 269-276.

Roohi, A. H., Moslemi Naeini, H., Hoseinpour Gollo, M., Shahbazi Karami, J., & Shahabad, I. (2016). Effects of temperature gradient magnitude on bending angle in laser forming process of aluminium alloy sheets. *Journal of Computational & Applied Research in Mechanical Engineering (JCARME), 5*(2), 97-109.

Safari, M. (2014). Numerical Investigation of the Effect of Process and Sheet Parameters on Bending Angle in the Laser Bending Process. *World Journal of Mechanics, 2014*.

Safari, M., & Farzin, M. (2014). A study on laser bending of tailor machined blanks with various irradiating schemes. *Journal of Materials Processing Technology, 214*(1), 112-122.

Safdar, S., Li, L., Sheikh, M., & Liu, Z. (2007). Finite element simulation of laser tube bending: Effect of scanning schemes on bending angle, distortions and stress distribution. *Optics & Laser Technology, 39*(6), 1101-1110.

Shen, H., Shi, Y., & Yao, Z. (2006). Numerical simulation of the laser forming of plates using two simultaneous scans. *Computational Materials Science, 37*(3), 239-245.

Shen, H., & Vollertsen, F. (2009). Modelling of laser forming–An review. *Computational Materials Science, 46*(4), 834-840.

Shi, Y., Shen, H., Yao, Z., & Hu, J. (2006). Numerical investigation of straight-line laser forming under the temperature gradient mechanism. *Acta Metallurgica Sinica (English Letters), 19*(2), 144-150.

Shi, Y., Shen, H., Yao, Z., & Hu, J. (2007). Temperature gradient mechanism in laser forming of thin plates. *Optics & Laser Technology, 39*(4), 858-863.

Shroff, A., Malajian, D., Czarnowicki, T., Rose, S., Bernstein, D. M., Singer, G. K., . . . Guttman-Yassky, E. (2016). Use of 308 nm excimer laser for the treatment of chronic hand and foot eczema. *International journal of dermatology*.

Shyy, Y.-H. (1993). Laser range finder: Google Patents.

Smith, T., Michaleris, P., Reutzel, E., & Hall, B. (2012). *Finite element model of pulsed laser forming.* Paper presented at the the 13th International Symposium on Laser Precision Microfabrication.

Soares, O. D., & Perez-Amor, M. (1987). Applied laser tooling *Applied Laser Tooling* (pp. 1-24): Springer.

Luxon, J., & e Parker, D. (1992). *Industrial lasers and their applications, (pbk)*: Prentice-hall.

Takahara, J., Yamagishi, S., Taki, H., Morimoto, A., & Kobayashi, T. (1997). Guiding of a one-dimensional optical beam with nanometer diameter. *Optics letters, 22*(7), 475-477.

Tang, G. (2014). *Nanosecond Pulsed Laser Processing of Metals and Welding of Metal-glass Nanocomposites.* University of Dundee.

Totten, G. E., Funatani, K., & Xie, L. (2004). *Handbook of metallurgical process design*: CRC press.

Vij, D., & Mahesh, K. (2013). *Medical applications of lasers*: Springer Science & Business Media.

Vollertsen, F. (1994). Mechanisms and models for laser forming. *Laser Assisted Net Shape Engineering, Proceedings of the LANE'94, 1*, 345-360.

Vollertsen, F., Sprenger, A., Kraus, J., & Arnet, H. (1999). Extrusion, channel, and profile bending: a review. *Journal of Materials Processing Technology, 87*(1), 1-27.

WANG, X.-y., XU, W.-x., XU, W.-j., HU, Y.-f., LIANG, Y.-d., & WANG, L.-j. (2011). Simulation and prediction in laser bending of silicon sheet. *Transactions of Nonferrous Metals Society of China, 21*, s188-s193.

Wang, X., & Li, D. (2002). Mechanical and electrochemical behavior of nanocrystalline surface of 304 stainless steel. *Electrochimica Acta, 47*(24), 3939-3947.

Wang, X., Wang, J., Xu, W., & Guo, D. (2014). Scanning path planning for laser bending of straight tube into curve tube. *Optics & Laser Technology, 56*, 43-51.

Watkins, K., Edwardson, S., Magee, J., Dearden, G., French, P., Cooke, R., . . . Calder, N. (2001). Laser forming of aerospace alloys: SAE Technical Paper.

Watson, S., Viola, S., Giuliano, G., Najda, S., Perlin, P., Suski, T., . . . Czernecki, R. (2016). *High speed visible light communication using blue GaN laser diodes.* Paper presented at the SPIE Security+ Defence.

Weber, M. J. (1999). Handbook of Laser Wavelength: CRC Press, Boca Raton, US, 784p.

Wee, L. M., & Li, L. (2005). An analytical model for striation formation in laser cutting. *Applied Surface Science, 247*(1), 277-284.

Yan, J., Gao, M., & Zeng, X. (2010). Study on microstructure and mechanical properties of 304 stainless steel joints by TIG, laser and laser-TIG hybrid welding. *Optics and Lasers in Engineering, 48*(4), 512-517.

Yang, Liu, Z., Xue, B., Liao, Z., Wang, J., & Li, J. (2016). *Visible light communication and lighting using laser diodes.* Paper presented at the Numerical Simulation of Optoelectronic Devices (NUSOD), 2016 International Conference on.

Yang, L., Tang, J., Wang, M., Wang, Y., & Chen, Y. (2010). Surface characteristic of stainless steel sheet after pulsed laser forming. *Applied Surface Science, 256*(23), 7018-7026.

Yau, C., Chan, K., & Lee, W. (1997). *A new analytical model for laser bending.* Paper presented at the Laser assisted net shape engineering 2, Proceedings of LANE,vol. 2, 1997, pp. 357-392.

Zhang, J., Cheng, P., Zhang, W., Graham, M., Jones, J., Jones, M., & Yao, Y. L. (2006). Effects of scanning schemes on laser tube bending. *Journal of manufacturing science and engineering, 128*(1), 20-33.

Zhang, P., & Liu, H. (2010). *Thermal deformation behaviors of laser rectangular tube bending.* Paper presented at the Computer, Mechatronics, Control and Electronic Engineering (CMCE), 2010 International Conference on.

Zhang, W., Jones, M., Graham, M., Farrell, B., Azer, M., Zhang, J., & Yao, Y. (2005). *Large diameter and thin wall laser tube bending.* Paper presented at the 24th International Congress on Applications of Lasers and Electro-Optics, ICALEO.

Internet citation:

[1] Laser Cutting. (2017) from http://www.messer-cs.com/us/processes/laser-cutting/

[2] Drilling. July 18, 2016 https://lightmachinery.com/laserapplications/drilling/

[3] Oroin LZR Combo 200. 2017 from http://orionwelders.com/product/lzr-combo-200/

[4] A Story of Invention: the Laser. March 11, 2013 from http://www.intellectualventureslab.com/invent/a-story-of-invention-the-laser

[5] List of laser types. May 2007 from https://en.wikipedia.org/wiki/List_of_laser_type

[6] Slideshare uses cookies to improve functionality. 2017 from https://www.slideshare.net/roberteshun/chapter-8-masers-and-lasers

[7] Properties of laser light. November 01, 2016 from http://www.daenotes.com/electronics/microwave-radar/laser-light-properties

[8] Laser rangefinder. 2014 from http://saab.com/land/weapon-systems/laser-rangefinder/g-tor/

[9] CO_2 Laser Surgery. FEBRUARY 5, 2011 from http://drpaulose.com);

[10] Experimental and Therapeutic Medicine. August 24, 2015 from https://www.spandidos-publications.com/etm/10/4/1467

[11] Thermal properties of metal. 2017 from https://www.engineersedge.com/properties_of_metals.htm