UNIVERSITI PUTRA MALAYSIA

PARAMETRIC INVESTIGATION OF HEAT TRANSFER AND FLUID FLOW ON LASER MICRO-WELDING

ASGHAR HOZOORBAKHSH

PARAMETRIC INVESTIGATION OF HEAT TRANSFER AND FLUID FLOW ON LASER MICRO-WELDING

By

ASGHAR HOZOORBAKHSH

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, In Fulfilment of the Requirements for the Degree of Master of Science

July 2015

DEDICATION

I dedicate this thesis to my beloved wife for her love, endless support and encouragement with love

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

PARAMETRIC INVESTIGATION OF HEAT TRANSFER AND FLUID FLOW ON LASER MICRO-WELDING

By

ASGHAR HOZOORBAKHSH

July 2015

Chair: Mohd Idris Shah Ismail, PhD
Faculty: Engineering

The aim of this research is to investigate heat transfer and fluid flow phenomena during laser micro-welding of thin stainless steel sheet. A transient 3-D model is developed using computational fluid dynamics (CFD) method to understand some critical characterisation such as temperature fields and melt pool formation and also the perform parameters on laser micro-welding process. The applications of developed thermal models have demonstrated that the laser parameters, such as laser power, scanning velocity and spot diameter have considerable effect on the peak temperature and resulted weld pool. The heat source model is consisted of surface heat source and adaptive volumetric heat source that could be well represented the real laser welding as the heat penetrates into the material. In the computation of melt dynamics, mass conservation, momentum and energy equations have been considered to count the effects of melt flow and the thermo-fluid energy heat transfer. The three-dimensional governing equations from the Navier-Stokes for Newtonian fluid are used to estimate the melt flow that influences the rate of heat transfer and the distribution of temperature in a 3-D domain.

Melt penetration is produced by the use of high power density distribution that results in rapid evaporation, which is expected to generate recoil pressure in the weld pool. Assuming that atmospheric and vaporised material pressure are balanced at the front of the laser beam, the evaporation of the melt leads to significant pressure that drills down the melt to the opposite side of the base material when it is heated over the boiling point. Furthermore, the surface tension of the molten material is also highly responsible for widening the melt pool. The melt surface layer is often influenced by contractive forces of the molten material to minimize its surface free energy. Minimization of the energy has a substantial effect on the melt surface to stretch out its extent towards the non-melted solid region.

The simulation results have been compared with two sets of experimental research to predict the weld bead geometry and solidification pattern which laser welds are made on stainless steel (SUS304). The shape comparison describes those parameters relevant to any changes in the melt dynamics and temperatures are of great importance in the formation of weld pool and heat distribution during laser micro-welding. The fair agreement between simulated and experimental results has been achieved.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Master Sains

KAJIAN PARAMETRIK PEMINDAHAN HABA DAN ALIRAN BENDALIR PADA MIKRO-KIMPALAN LASER

Oleh

ASGHAR HOZOORBAKHSH

Julai 2015

Pengerusi: Mohd Idris Shah Ismail, PhD
Fakulti: Kejuruteraan

Matlamat penyelidikan ini adalah untuk mengkaji pemindahan haba dan fenomena aliran bendalir bagi mikro-kimpalan laser untuk kepingan keluli tahan karat yang nipis. Satu model transien tiga dimensi dibangunkan secara berangka dengan menggunakan kaedah pengiraan dinamik bendalir (CFD) untuk memahami beberapa kriteria kritikal seperti medan suhu dan pembentukan kolam leburan dan kesan parameter kimpalan kepada mikro-kimpalan laser. Model terma yang dibangunkan menunjukkan bahawa parameter laser, seperti kuasa laser, kelajuan pengimbasan dan diameter tompok mempunyai kesan yang besar pada suhu puncak dan menghasilkan kolam kimpalan. Model sumber haba adalah terdiri daripada sumber haba permukaan dan sumber haba isipadu adaptif yang boleh mengambarkan kimpalan laser sebenar sebagai haba yang menembusi ke dalam bahan. Dalam pengiraan dinamik leburan, pengabadian jisim, momentum dan persamaan tenaga telah dipertimbangkan untuk mengira kesan aliran leburan dan pemindahan tenaga haba termo-bendalir. Persamaan tiga dimensi dari Navier-Stokes bagi bendalir Newtonian adalah untuk menganggarkan aliran leburan yang mempengaruhi kadar pemindahan haba dan pengagihan suhu dalam 3-D domain.

Penembusan leburan dijalankan dengan menggunakan taburan kuasa kepadatan tinggi yang menyebabkan penyejatan pantas, iaitu dijangka menjana tekanan anjalan dalam kolam kimpalan. Dengan mengandaikan bahawa tekanan atmosfera dan bahan mengewap adalah seimbang di hadapan pancaran laser, penyejatan leburan membawa kepada tekanan ketara yang mengerudi turun leburan ke bahagian bertentangan bahan asas apabila ia dipanaskan lebih daripada takat didih. Tambahan pula, tekanan permukaan bahan yang lebur juga sangat bertanggungjawab bagi memperluaskan kolam leburan. Lapisan permukaan leburan sering dipengaruhi oleh kuasa pengecutan bahan lebur untuk mengurangkan permukaan tenaga bebas. Pengurangan tenaga yang mempunyai kesan yang besar pada permukaan leburan untuk meregangkan ke arah kawasan pepejal yang tidak lebur.

Keputusan simulasi telah dibandingkan dua set penyelidikan eksperimen untuk meramal geometri kimpalan manik dan corak pemejalan yang kimpalan laser lakukan pada keluli tahan karat (SUS304). Perbandingan bentuk menerangkan parameter yang berkaitan dengan sebarang perubahan dalam dinamik leburan dan taburan suhu adalah sangat penting pada pembentukan kolam kimpalan dan pemindahan haba semasa mikro-kimpalan laser. Pengesahan yang wajar di antara keputusan simulasi dan eksperimen telah dicapai.

ACKNOWLEDGEMENTS

With the completion of this thesis, I wish to express my extreme gratitude to my supervisor Dr. Mohd Idris Shah Ismail for encouragement, guidance, critics and friendship, as well as providing experimental results of this research. I would like to thank my co-supervisor; Associate Prof. Dr. Nuraini Binti Abdul Aziz for her valuable advice and help during this project.

I owe my loving thanks to my wife Azadeh Bahadoran and my cute daughter Aynaz, my parents and other family members for their continuous support while completing this project.

I certify that a Thesis Examination Committee has met on 09 July 2015 to conduct the final examination of Asghar Hozoorbakhsh on his thesis entitled "Parametric Investigation of Heat Transfer and Fluid Flow on Laser Micro-Welding" 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 Master of Science.

Members of the Thesis Examination Committee were as follows:

B.T. Hang Tuah Bin Baharudin, PhD
Associate Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Nor Mariah Binti Adam, PhD
Associate Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Abdul Aziz Bin Jaafar, PhD
Associate Professor
Faculty of Manufacturing Engineering
Universiti Malaysia Pahang
Malaysia
(External Examiner)

ZULKARNAIN ZAINAL, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 22 September 2015

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

Mohd Idris Shah Bin Ismail, PhD
Senior lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Nuraini Binti Abdul Aziz, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

BUJANG KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ________________________ Date: ________________________

Name and Matric No.: ____

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) are adhered to.

Signature: ________________________
Name of Chairman of Supervisory Committee: _______________________

Signature: ________________________
Name of Member of Supervisory Committee: _______________________

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Ar	Archimedes Number
B	Bottom
BL	Bead Length
BW	Bead Width
CAE	Computer-Aided Engineering
CFD	Computational Fluid Dynamics
CW	Continues Wave
DE	Differential Evolution
DOP	Depth of Penetration
E	East
FE	Finite Element
FEM	Finite Element Method
FVM	Finite Volume Method
Gr	Grashof Number
HAZ	Heat Affected Zone
K	Kelvin
LASER	Light Amplification by Stimulated Emission of Radiation
LATIG	Laser–TIG Hybrid Welding
LBM	Laser Beam Melting
LBW	Laser Beam Welding

N	North
Nd:YAG	Neodymium-doped Yttrium Aluminium Garnet
PDEs	Partial Differential Equations
Pe	Péclet Number
Pr	Prandtl Number
QUICK	Quadratic Upstream Interpolation for Convective Kinematics
Re	Reynolds Number
S	South
SIMPLE	Semi-Implicit Method for Pressure Linked Equations
STC	Super Thermal Conductive
T	Top
TIG	Tungsten Inert Gas Welding
UDF	User-Defined Functions
UV	Ultraviolet
VOF	Volume-of-Fluid
W	West
2-D	Two-Dimensional
3-D	Three-Dimensional

CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

LASER abbreviation stands for Light Amplification by Stimulated Emission of Radiation. Maiman (1960) showed the world's first laser using a crystal of ruby. It is characterized as a convergent, coherent, and monochromatic beam of electromagnetic radiation which has a wavelength range from ultraviolet to infrared. Nowadays, lasers have many applications in different fields of engineering, electronics and medicine (Dahotre & Harimkar, 2008).

Developments of Laser end up affordable and easy to maintain systems. The highlighted advantages of laser micro-welding are including the energy deposition control in the joining area accurately, the heat affected zone (HAZ) minimization, complex welds and bond geometries, single-step process, selective joining, low mechanical and thermal of the components load and short cycle times (Guo, 2009).

Laser welding is one of the earliest and the most important recorded applications of laser material processing, which is still considered a major field of the useful application of laser. The principle reason for this popularity is the fact that heating by laser irradiation is possible for all kinds of engineering materials irrespective of the state, chemistry, size, bonding or geometry. This contactless direct heating is a big advantage that causes to join a component with the same or different type by using laser just as a clean heating source without the risk of any chemical reaction or change of the irradiated material. Obviously, steels and alloys joining constitute the consequential request for laser welding.

Micro fabrication progresses have established opportunities to manufacture of the micro-scales structures. These opportunities are useful to create the optical, electronic, biological and magnetic devices which are ranging from sensors to computation and control systems. Micro-welding is an effective technique for manufacturing process in cases that the attributes of macro-machining can be reduced in size to the micro-scales. In addition, laser beam joining techniques has the highest rating in the microsystems technology besides macro-range industrial manufacturing processes.

Very sensitive response has been shown to heat input in weld bead by thin metal sheets, and the geometry of weld bead has a significant role in the strength of joining. Conventional techniques face some difficulties in thin metal sheet welding, for example, some blow holes can be created in the weld bead because of extreme heat input. The distortion risk in micro-welding in the small thickness of thin metal sheets is another problem. Thus, heat input minimization to thin metal sheet is important economically and technically. From the economic point of view, less heat input needs lower laser power which results in low running cost and minor equipment investment. Technically, smaller heat input ends up less HAZ, less distortion and finally low material loss due to evaporation (Ismail, 2012).

Heat transfer and fluid flow are the major interest fields to scientific researchers and engineering, as well as developers, manufacturers and designers. Significant efforts have been considered for traditional applications research, such as energy devices, chemical processing and general manufacturing, containing high performance gas turbines, heat exchangers and general power systems.

From the above requirement and difficulties with the present industrial applications, the laser micro-welding technology has been increasingly interested. Furthermore, the production technologies with short processing time, high reproducibility and high accuracy are required. Laser micro-welding which is characterized as a high beam quality is a promising technology within this application field.

1.2 Computational Fluid Dynamics (CFD)

Computational fluid dynamics (CFD) involve analysis of heat transfer, fluid flow by using of computer-based simulation. In addition, some related phenomena such as chemical reactions can be analysed by this technique. CFD is characterised as a very powerful technique which has a wide range of application areas such as aerodynamics, hydrodynamics, power plant, turbo-machinery, chemical process engineering, electrical and electronic engineering, marine engineering, internal and external environment of buildings, biomedical and meteorology engineering, environmental engineering, hydrology and oceanography.

The conclusive purpose of the CFD developments is to provide a competency comparable with other computer-aided engineering (CAE) tools such as stress analysis codes. CFD has entered into the wider industrial community since the 1990s. Recent upsurge of interest for CFD owe the availability of affordable high-performance computing hardware and user-friendly interfaces.

CFD defined as a part of computational mechanics, which in turn can be part of simulation techniques. Simulation is an effective method, which is used by physicists and engineers to predict or reconstruct the physical situation or engineering product behaviour under assumed boundary conditions (Versteeg & Malalasekera, 2007).

1.3 Problem statement

As a conventional joining technique, if the attributes of macro-machining can be reduced in size to the micro scales, laser micro-welding is a technique that has the potential to become a successful manufacturing process. The laser micro-welding is a complex process which includes some phenomena such as thermal convection and conduction in a multi-phase system, fluid flow, plasma effects and gas dynamics. However, there are some unique problems in scale reduction from macro to micro such as creation of a stable welding structure, effect elimination of welding parameters and overcoming the size effect, also an appropriate heat control as critical aspect of research in weld geometries must be elaborated (Guo, 2009).

There are several important points in micro beam welding which are essential in the welding process control, including size of beam, beam characterization, interaction of the beam-material, the integration of image processing, temperature measurement and numerical simulation. In the most of mentioned parameters scaling effects can be realized which strictly influence the quality of welding such as the cooling rate/solidification structure, fluid flow stability, distortion and surface tension. In addition, laser micro-welding is affected by some important variables in laser such as beam diameter, power of laser, travel speed, beam configuration, condition of the substrate, workpiece thermophysical properties and the alloy composition (Majumdar & Manna, 2011).

The laser welding process has been numerically and analytically modelled for a particular range of conditions for one or a few phenomena, but unfortunately, as can be observed in chapter two (literature review) of this dissertation, there is not much attention for the fluid flow and heat transfer on laser micro-welds. For instance, the heat source and the material interaction which results in rapid heating, melting, and also molten metal circulation in the weld pool assisted by surface tension gradient, buoyancy forces and recoil pressure in relation to evaporation. Furthermore, the resulting structure and properties of the welds and the temperature variations with time, i.e., the thermal cycles, can be determined by the resulting of liquid metal flow and heat transfer. The weld pool small size, inadequate time for measurement, and high heating and cooling rates create some difficulties in experimental measurements of the velocity and temperature fields during laser micro-welding process. In addition, downscaling of the geometrical dimensions of the welding zone is cause to occur the physical phenomena difficulties.

Thus, there is a strong need for heat transfer measurements and related flow studies, particularly in situations which the definition of fairly straightforward mathematical calculation cannot be completely done. This is including, amongst other things, multi-phase flow and various flow conditions. Accurate predictions in the heat transport process modelling are still not refined in particular in flows which need more studies and measurements. Thus, some flow and thermal measurements must be applied to refine the models and to extend numerical methods to compute of temperature, velocity, and also measurement of real material property which gives rise to have reliable and accurate data.

1.4 Hypothesis of the study

- It is expected to design an advanced numerical model of laser micro-welding to develop a broader range of conditions and mutual interactions among the heat transfer and fluid flow phenomena using a commercial CFD code, ANSYS® FLUENT software.

- A great deal of calculation is requested for the modelling; supposed to computer technology developments is capable to make possible much more time-consuming calculations and complicated models.

- To verify and validate the reliability of the computed results, it is expected; the model can well estimates the weld characteristics in various laser parameters and welding conditions, and the simulated and experimental results illustrate an acceptable prediction.

1.5 Research objective

In this research work, a modelling of heat transfer and fluid flow of laser micro-welding based on computational fluid dynamics (CFD) method is developed and the results are discussed in detail. The simulation is validated by comparing the experimental results with the same emulated laser parameters and welding conditions from another researcher's published work; as highlighted in the acknowledgment.

The specific objectives of the research are summarized and listed as follows:

i. To characterize the thermal phenomena characterisation of heat transfer in laser micro-welding process by considering the heat source and the material interaction leads to rapid heating, melting and thermal cycles in the heating zone.

ii. To conduct computational investigation on fluid dynamics in laser micro-welding and more notice of the issues of molten metal circulation in the weld pool assisted by the recoil pressure, surface tension and buoyancy forces.

iii. To evaluate the velocity and temperature fields due to unusual and infinitesimal weld pool size and time duration in laser micro-welding process using computational fluid dynamics method (CFD).

1.6 Scope and limitation

It is clear; the laser's potential understanding completely is associated with a comprehensive realizing of the physical phenomena in the micro-welding process. As the laser micro-welding is pushed to its limits in new and unique applications, the present modelling approach investigates just the fundamental aspects of laser micro-welding process and the anatomy of micro-welding, particularly heat transfer and fluid flow upon the thin stainless-steel sheet by applying the method of computational fluid dynamics (CFD).

1.7 Thesis Outline

This thesis consists of five chapters and the contents of each chapter are described briefly as follows:

Chapter one is divided into seven subheadings. First one introduces the research background and motivation, second one describes the computational fluid dynamics (CFD) succinctly. This chapter also is included the problem statement, objectives of the research, hypothesis of the study, scope and limitation and thesis outline as third, fourth, fifth, sixth and seventh subheadings respectively.

Chapter two presents the detailed literature review associated with laser micro-welding and its future developments, mechanism of laser welding and material interaction and laser processing of materials. Furthermore, the transient heat transfer and fluid flow analysis in three categories; numerical modelling based on mathematical calculation, simulation based on finite element method (FEM) and simulation based on finite volume method (FVM) have been reviewed separately.

Chapter three describes the methodology involved in this research work. The problem identification with CFD and the fluid flow and heat transfer governing equations (mass conservation, momentum and energy equations) in three dimensions; state and Navier–Stokes equations for a Newtonian fluid are investigated sequentially. In continuing, the modelling of heat source equations that imported in the simulation by writing a proper and specific coding, known as UDF (User-Defined Functions) has been pursued. Then, considered assumptions and developed computational approaches used in the analytical model (ANSYS® FLUENT software) in five main steps (geometry model, mesh model, material model, cell zone and boundary conditions and solution) are described.

Chapter four is results and discussion and detailed results of the numerical simulation are interpreted and discussed. The main core of this chapter is heat transfer and fluid flow analysis that investigated from point views of dimensionless numbers, fluid dynamics, weld pool shapes and weld thermal cycles. Comparison between experimental and simulation results in weld bead geometry and solidification pattern is also illustrated to validate the model.

Chapter five is exhibited the conclusion of the research by summarizing this study principal results and present suggestions for further research efforts.

REFERENCES

Abderrazak, K., Bannour, S., Mhiri, H., Lepalec, G., & Autric, M. (2009). Numerical and experimental study of molten pool formation during continuous laser welding of AZ91 magnesium alloy. *Computational Materials Science, 44*(3), 858-866.

Akbari, M., Saedodin, S., Toghraie, D., Shoja-Razavi, R., & Kowsari, F. (2014). Experimental and numerical investigation of temperature distribution and melt pool geometry during pulsed laser welding of Ti6Al4V alloy. *Optics & Laser Technology, 59*, 52-59.

ANSYS Fluent 15.0 User's Manual. ANSYS Documentation>Fluent>User's Guide & Theory Guide – Release 15.0: ANSYS Inc.

Bag, S., & De, A. (2010). Computational modelling of conduction mode laser welding process. In S. Xiaodong Na (Ed.): Sciyo (InTech).

Bag, S., Trivedi, A., & De, A. (2009). Development of a finite element based heat transfer model for conduction mode laser spot welding process using an adaptive volumetric heat source. *International Journal of Thermal Sciences, 48*(10), 1923-1931.

Belhadj, A., Bessrour, J., Masse, J.-E., Bouhafs, M., & Barrallier, L. (2010). Finite element simulation of magnesium alloys laser beam welding. *Journal of Materials Processing Technology, 210*(9), 1131-1137.

Berretta, J. R., de Rossi, W., David Martins das Neves, M., Alves de Almeida, I., & Dias Vieira Junior, N. (2007). Pulsed Nd: YAG laser welding of AISI 304 to AISI 420 stainless steels. *Optics and Lasers in Engineering, 45*(9), 960-966.

Beyer, E., Mahrle, A., Lütke, M., Standfuss, J., & Brückner, F. (2012). *Innovations in high power fiber laser applications.* Paper presented at the SPIE LASE.
Bramson, M. A. (1968). *Infrared radiation. A handbook for applications* (Vol. 1).

Brown, C., & Banas, C. (1971). *Deep penetration laser welding.* Paper presented at the AWS 52nd Annual Meeting, San Francisco, California.

Clancy, L. (1975). Aerodynamics, Chapter 3. *Topics on pressure fields*, 22-59.

Courtois, M., Carin, M., Le Masson, P., Gaied, S., & Balabane, M. (2013). A new approach to compute multi-reflections of laser beam in a keyhole for heat transfer and fluid flow modelling in laser welding. *Journal of Physics D: Applied Physics, 46*(50), 505305.

Dahotre, N. B., & Harimkar, S. P. (2008). *Laser fabrication and machining of materials*. New York, N.Y.: Springer.

Duley, W. W. (1976). CO2 lasers: Effects and applications. *NASA STI/Recon Technical Report A, 77*, 15811.

Duley, W. W. (1999). *Laser welding*: Wiley New York.

Edwards, S. A. (2008). *The nanotech pioneers: where are they taking us*: John Wiley & Sons.

Falkovich, G. (2011). *Fluid mechanics: A short course for physicists*: Cambridge University Press.

Fortunato, A., Ascari, A., Orazi, L., Cuccolini, G., Campana, G., & Tani, G. (2012). Numerical simulation of nanosecond pulsed laser welding of eutectoid steel components. *Optics & Laser Technology, 44*(7), 1999-2003.

Guo, K. W. (2009). A review of micro/nano welding and its future developments. *Recent patents on nanotechnology, 3*(1), 53-60.

Gürtler, F.-J., Karg, M., Leitz, K.-H., & Schmidt, M. (2013). Simulation of laser beam melting of steel powders using the three-dimensional volume of fluid method. *Physics Procedia, 41*, 881-886.

Hashemzadeh, M., Chen, B., & Soares, C. G. (2014). Comparison between different heat sources types in thin-plate welding simulation. *Hydraulic Engineering II*, 329.

He, X., Elmer, J., & DebRoy, T. (2005). Heat transfer and fluid flow in laser microwelding. *Journal of Applied Physics, 97*(8), 084909.

Ismail, M. I. S. (2012). *Micro-welding of Engineering Materials by High Brightness Lasers.* (Doctoral Course), OKAYAMA UNIVERSITY.

Ismail, M. I. S., Okamoto, Y., & Okada, A. (2012). Micro-Welding of Super Thermal Conductive Composite by Pulsed Nd: YAG Laser. In D. C. Dumitras (Ed.), *Nd YAG Laser*: InTech.

Ismail, M. I. S., Okamoto, Y., Okada, A., Uno, Y., & Ueoka, K. (2012). Direct micro-joining of flexible printed circuit and metal electrode by pulsed Nd: YAG laser. *International Journal of Precision Engineering and Manufacturing, 13*(3), 321-329.

Jackson, M. J. (2007). Laser Micro-and Nanofabrication. *Micro and Nanomanufacturing*, 387-474.

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

Kazemi, K., & Goldak, J. A. (2009). Numerical simulation of laser full penetration welding. *Computational Materials Science, 44*(3), 841-849.

Kim, K., Lee, J., & Cho, H. (2010). Analysis of pulsed Nd: YAG laser welding of AISI 304 steel. *Journal of mechanical science and technology, 24*(11), 2253-2259.

Koo, B. S. (2013). *Simulation of Melt Penetration and Fluid Flow Behavior during Laser Welding.* (Doctor of Philosophy), Lehigh University.

Kuang, J.-H., Hung, T.-P., & Chen, C.-K. (2012). A keyhole volumetric model for weld pool analysis in Nd: YAG pulsed laser welding. *Optics & Laser Technology, 44*(5), 1521-1528.

Li, Z., & Gobbi, S. (1997). Laser welding for lightweight structures. *Journal of materials processing technology, 70*(1), 137-144.

Löhner, R. (2008). *Applied computational fluid dynamics techniques: an introduction based on finite element methods*: John Wiley & Sons.

Maiman, T. H. (1960). Stimulated optical radiation in ruby.

Majumdar, D., & Manna, I. (2011). Laser material processing. *International Materials Reviews, 56*(5-6), 341-388.

Malek Ghaini, F., Hamedi, M., Torkamany, M., & Sabbaghzadeh, J. (2007). Weld metal microstructural characteristics in pulsed Nd: YAG laser welding. *Scripta Materialia, 56*(11), 955-958.

Mazumder, J., & Steen, W. (1980). Heat transfer model for CW laser material processing. *Journal of Applied Physics, 51*(2), 941-947.

Mordike, B., Cahn, R., Haasen, P., & Kramer, E. (1993). Materials Science and Technology. *Processing of Metals and Alloys, 15*, 112.

Okamoto, Y., Gillner, A., Olowinsky, A., Gedicke, J., & Uno, Y. (2008). Fine micro-welding of thin stainless steel sheet by high speed laser scanning. *Journal of Laser Micro Nano Engineering, 3*(2), 95-99.

Pang, S., Chen, L., Zhou, J., Yin, Y., & Chen, T. (2011). A three-dimensional sharp interface model for self-consistent keyhole and weld pool dynamics in deep penetration laser welding. *Journal of Physics D: Applied Physics, 44*(2), 025301.

Plewa, J., Tanner, E., Mueth, D., Gruber, L., & Bradley, K. (2008). System and method for manipulating and processing materials using holographic optical trapping: Google Patents.

Ready, J. (1971). Effects of High Power Laser Radiation (Academic, New York, 1971). *Chap, 3*, 18.

Rohde, M., Markert, C., & Pfleging, W. (2010). Laser micro-welding of aluminum alloys: experimental studies and numerical modeling. *The International Journal of Advanced Manufacturing Technology, 50*(1-4), 207-215.

Sabbaghzadeh, J., Azizi, M., & Torkamany, M. J. (2008). Numerical and experimental investigation of seam welding with a pulsed laser. *Optics & Laser Technology, 40*(2), 289-296.

Saldi, Z., Kidess, A., Kenjereš, S., Zhao, C., Richardson, I., & Kleijn, C. (2013). Effect of enhanced heat and mass transport and flow reversal during cool down on weld pool shapes in laser spot welding of steel. *International Journal of Heat and Mass Transfer, 66*, 879-888.

Schawartz, M. (1979). Metals Joining Manual Book: McGraw-Hill, New York, USA.

Schlichting, H. (1979). Boundary-Layer Theory (7th, ed.): McGraw-Hill, New York.

Schubert, E., Klassen, M., Zerner, I., Walz, C., & Sepold, G. (2001). Light-weight structures produced by laser beam joining for future applications in automobile and aerospace industry. *Journal of Materials Processing Technology, 115*(1), 2-8.

SHANMUGAM, N. S., BUVANASHEKARAN, G., & SANKARANARAYANASAMY, K. (2012a). Finite Element Simulation of Nd: YAG laser lap welding of AISI 304 Stainless steel sheets.

Shanmugam, N. S., Buvanashekaran, G., & Sankaranarayanasamy, K. (2012b). Some studies on weld bead geometries for laser spot welding process using finite element analysis. *Materials & Design, 34*, 412-426.

Sonti, N., & Amateau, M. (1989). Finite-element modeling of heat flow in deep-penetration laser welds in aluminum alloys. *Numerical heat transfer, 16*(3), 351-370.

Sun, H., Li, R., Chénier, E., & Lauriat, G. (2012). On the modeling of aiding mixed convection in vertical channels. *Heat and Mass Transfer, 48*(7), 1125-1134.

Tan, W., Bailey, N. S., & Shin, Y. C. (2013). Investigation of keyhole plume and molten pool based on a three-dimensional dynamic model with sharp interface formulation. *Journal of Physics D: Applied Physics, 46*(5), 055501.

Ventrella, V. A., Berretta, J. R., & De Rossi, W. (2010). Pulsed Nd: YAG laser seam welding of AISI 316L stainless steel thin foils. *Journal of Materials Processing Technology, 210*(14), 1838-1843.

Versteeg, H. K., & Malalasekera, W. (2007). *An introduction to computational fluid dynamics: the finite volume method*: Pearson Education.

Volpp, J. (2012). Investigation on the influence of different laser beam intensity distributions on keyhole geometry during laser welding. *Physics Procedia, 39*, 17-26.

Wang, R., Lei, Y., & Shi, Y. (2011). Numerical simulation of transient temperature field during laser keyhole welding of 304 stainless steel sheet. *Optics & Laser Technology, 43*(4), 870-873.

White, F. (2006). *Viscous fluid flow* (3rd. ed.). New York: McGraw-Hill.

Wilson, J., & Hawkes, J. (1987). *Lasers: principles and applications*: Prentice Hall London.

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.

Zacharia, T., David, S., Vitek, J., & Debroy, T. (1989a). Heat transfer during Nd: YAG pulsed laser welding and its effect on solidification structure of austenitic stainless steels. *Metallurgical Transactions A, 20*(5), 957-967.

Zacharia, T., David, S., Vitek, J., & DebRoy, T. (1989b). Weld pool development during GTA and laser beam welding of type 304 stainless steel.

Zhao, H., Niu, W., Zhang, B., Lei, Y., Kodama, M., & Ishide, T. (2011). Modelling of keyhole dynamics and porosity formation considering the adaptive keyhole shape and three-phase coupling during deep-penetration laser welding. *Journal of Physics D: Applied Physics, 44*(48), 485302.