# PULSED Nd:YAG LASER MICRO WELDING OF STAINLESS STEEL MATERIAL

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*Dedicated to my beloved parents.*
*Thanks for everything…………*

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## ABSTRACT

In this study, the influence of various operating parameters of pulsed Nd:YAG laser on the welding of stainless steel material is investigated. The effects of laser peak power, pulse duration, focus point position, number of laser pulse shots and angle of incidence on the weld width and weld penetration depth are analyzed. The laser micro welding is performed using a Unitek Miyachi LW10E ultra compact flash lamp pulsed Nd:YAG laser system with a maximum peak power of 3.5kW. The effects of various pulsed Nd:YAG laser welding parameters on weld pool development are studied by making individual spot welds carefully along the prepared specimens. Then, the weld pool is examined by using a Field Emission Scanning Electron Microscopy (FESEM) to characterize its microstructure. The composition of material before and after welding is analyzed by using an Energy Dispersive X-ray (EDX). The weld width and penetration depth are visualized and captured by using an optical microscope equipped with Charge Couple Devices (CCD) video camera, which is interfaced with image processing system. From the captured image, the Matrox Inspector 2.1 software is used to measure the weld width and weld penetration depth. A laser power of 3.5kW with pulse duration of 2.5kW produces weld width and penetration depth of 0.57mm and 1.31mm, respectively. A mathematical model of penetration depth has been developed. The mathematical model is able to describe the effect of laser beam penetration inside stainless steel material. When the laser beam is incident onto the surface of the material, a fraction of the beam is reflected and the remainder is absorbed into the material. For the time independent laser beam penetration, the power decreases according to the first order of the Bessel function along the radius and drops exponentially with the depth. At a depth of 1.00mm, the power reduces to 0.17kW at the central axis of the weld. The tensile strength of the weld joint is measured using an INSTRON Series IX/s Automated Materials Tester System. The measurement is performed for the butt and lap weld joint with crosshead speed of 0.2mm/min. The tensile strength for single spot butt weld joint is 22.96MPa and 6.90MPa for the lap joint. From the outcome, butt joint provides stronger attachment than the lap joint. In conclusion, pulsed Nd:YAG laser spot micro welding produces good welding on stainless steel and this is a promising technique for miniature assemblies technology such as in photonics packaging.

# ABSTRAK

Dalam kajian ini, pengaruh pelbagai parameter operasi kepada laser Nd:YAG denyutan ke atas kimpalan keluli tahan karat telah dikaji. Kesan-kesan kuasa laser, tempoh denyutan, kedudukan titik fokus, bilangan tembakan denyut laser dan sudut tuju ke atas lebar kimpalan dan kedalaman penembusan kimpalan telah dianalisis. Kimpalan mikro laser dilakukan menggunakan sistem laser Nd:YAG denyutan pancaran cahaya tersangat padat Unitek Miyachi LW10E dengan kuasa puncak maksimum 3.5kW. Kesan pelbagai parameter kimpalan laser Nd:YAG denyutan ke atas pembentukan kolam kimpalan dikaji dengan menghasilkan bintik kimpalan individu secara berhati-hati sepanjang spesimen yang disediakan. Kemudian, kolam kimpalan diperiksa dengan menggunakan Mikroskop Imbasan Elektron Medan Pancaran (FESEM) untuk menyatakan struktur mikronya. Komposisi bahan sebelum dan selepas kimpalan dianalisis dengan menggunakan Sebaran Tenaga Sinaran-X (EDX). Lebar dan kedalaman penembusan kimpalan dilihat dan dirakam dengan menggunakan mikroskop optik yang dilengkapkan dengan kamera video Peranti Gandingan Cas (CCD), yang diantaramuka dengan sistem pemprosesan imej. Daripada imej yang dirakam, perisian Matrox Inspector 2.1 digunakan untuk mengukur lebar kimpalan dan kedalaman penembusan kimpalan. Kuasa laser 3.5kW dan tempoh denyutan 2.5kW menghasilkan lebar kimpalan dan kedalaman penembusan masing-masing 1.31mm dan 0.57mm. Model matematik kuasa penembusan kimpalan telah dibangunkan. Model matematik ini berupaya untuk menggambarkan kesan-kesan penembusan sinaran laser di dalam bahan keluli tahan karat. Apabila pancaran laser ditujukan keatas permukaan bahan, sebahagian daripada pancaran dipantulkan dan selebihnya diserap kedalam bahan. Untuk tembusan laser tidak bergantung dengan masa, kuasa berkurang berdasarkan aturan pertama fungsi Bessel sepanjang jejari dan jatuh secara exponen dengan kedalaman. Pada kedalaman 1.00mm, kuasa berkurang kepada 0.17kW pada paksi tengah kimpalan. Kekuatan tegangan kimpalan diukur menggunakan Sistem Ujian Automatik Bahan-bahan INSTRON Siri IX/s. Pengukuran dibuat untuk sambungan kimpalan pangkal dan bertindih dengan halaju silang 0.2mm/min. Kekuatan tegangan untuk kimpalan bintik tunggal pangkal ialah 22.96MPa dan 6.90MPa untuk sambungan bertindih. Daripada keputusan, sambungan kimpalan pangkal adalah lebih kuat daripada sambungan kimpalan bertindih. Kesimpulannya, kimpalan bintik mikro laser Nd:YAG denyutan menghasilkan kimpalan yang baik pada keluli tahan karat dan ini merupakan teknik yang baik digunakan pada teknologi pemasangan perkakas kecil seperti dalam pempakejan fotonik.

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| | |
|---|---|
| $a$ | Aperture of a lens |
| $\alpha$ | Thermal diffusivity |
| $A$ | Applied laser power |
| $A_{ls}$ | Laser spot area |
| $c$ | Specific heat |
| $D$ | Depth of heat penetration |
| $f$ | Focal length |
| $I_0$ | Power density |
| $J_0$ | First order of Bessel function |
| $k$ | Wave number |
| $K$ | Thermal conductivity |
| $L_m$ | Latent heat of fusion |
| $l$ | Weld penetration depth |
| $n$ | Medium refractive index |
| $P$ | Laser beam peak power |
| $p_{parallel}$ | Reflectivity for parallel-polarized light |
| $p_{perpendicular}$ | Reflectivity for perpendicular-polarized light |
| $p$ | Reflectivity average value for unpolarized light |
| $\rho$ | Material density |
| $r$ | Laser beam radius |
| $T$ | Temperature |
| $T_m$ | Melting temperature |
| $T_0$ | Room temperature |
| $t$ | Pulse duration |
| $R$ | Material reflectivity |
| $\mu$ | Material absorption coefficient |
| $w_0$ | Beam waist |
| $Y_0$ | Second order of Bessel function |
| $\lambda$ | Wavelength |
| $z$ | Direction of depth |
| $z_0$ | Rayleigh range |

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

Lasers have been widely used in the manufacturing industry especially in the fabrication of small components for electronics, photonics, aerospace, biomedical, micro-electro-mechanical systems (MEMS), micro-electro-optomechanical systems (MEOMS) over the last three decades (Ready, 1997, Fadhali, 2008; Mousavi, 2008; Kazemi, 2009). The state-of-the art laser material processing includes the pulsed Nd:YAG laser spot welding for photonic devices packaging (Marley, 2002), which utilizes the laser for high precision joining and alignment. The laser beam is focused on the material surface and is partly absorbed. The laser beam absorption is an important physical process in laser micromachining (Fadhali, 2008). Laser material processing provides rapid, precise, clean, flexible, and an efficient process (Steen, 2003).

Laser welding is a liquid-phase fusion welding process for joining metals by melting their interfaces. Laser welding is a high energy density, low heat-input process with specific advantages over conventional fusion welding processes. These includes high welding speed, narrow heat-affected zone (HAZ) and low distortion, ease of automation, single-pass thick section capability and enhanced design flexibility. One of the key features of laser welding is the ability to weld without filler materials and it offers distinct advantages (Ming Pang, 2008).

Pulsed laser welding is characterized by intermittent laser beam powers that allows melting and solidification to take place consecutively. After each and every pulse the weld pool solidifies and depending on the process parameters, various points in the weld zone may experience different thermal events (Ghaini, 2007).

Laser spot welding is a very attractive process. It produces small, precise welds with a high-aspect ratio defined as the penetration depth over weld width and with very little thermal distortion. The pulsed Nd:YAG laser has been demonstrated to be an ideal candidate for spot welding because of its high peak power intensity, short pulse time, and resultant low-heat input (Liu, 1993).

In a spot welding using a pulsed Nd:YAG laser, the major process variables include the laser pulse energy, pulse time, beam diameter and intensity distribution, focal position, and material-dependent properties, such as absorptivity and thermophysical material properties. The size and shape of a spot weld and the occurrence of various weld defects, such as cratering and porosity, are dependent on these process variables (Liu, 1993).

Despite the industrial importance of pulsed Nd:YAG laser spot welding (Beretta, 2007) and the theoretical understanding provided by the existing models, few experimental studies on the influence of laser welding process parameters on weld pool shapes and defects for different materials have been reported for pulsed Nd:YAG laser spot welds (Fadhali, 2007).

With the demand of defect-free laser welded joints, strong, low porosity and good surface quality, pulsed Nd:YAG laser welding could be the right answer for this dilemma (Kazemi, 2009). This is a very promising technique and could compete in the near future with other methods that are well established and commercially used. Thorough investigations are still needed to comprehend and overcome these welding problems.

## 1.2 Problem statement

Although pulsed Nd:YAG laser micro welding has become widely used in microelectronics and photonics packaging industry, a full understanding of various phenomena involved is still a matter of trials and speculations (Nowakowski, 2005; Fadhali, 2008). Laser micro welding is a very complex process which involves variability in shape and properties of welds. Until today, researchers are still finding ways to produce optimum laser micro welding conditions for specific applications. To facilitate pulse Nd:YAG laser spot weld development, it is a common practice to adjust the laser peak power, pulse duration and laser spot size. These physical parameters need to be optimized numerically and experimentally to obtain the desired weld dimensions and microstructure with minimum defects. A strong weld joint is needed to produce reliable and stable attachment. An accurate understanding of the effect of these parameters on melting, weld appearance and heat input is thus required.

## 1.3 Objectives of study

The objectives of this research work can be summarized as follows.

1. To produce spot welds on stainless steel by using pulsed Nd:YAG laser.

2. To determine experimentally the weld penetration depth and weld width of stainless steel by controlling laser welding parameters.

3. To develop a model for the estimation of weld penetration depth and laser beam penetration for stainless steel.

## 1.4 Scope of study

In order to achieve the objectives of this research, a pulsed Nd:YAG laser source with a wavelength of 1064nm has been used to produce the weld. The laser source generates laser peak power of between 0.5kW and 3.5kW with pulse duration ranging from 0.3ms to 10.0ms respectively. Stainless steel material is used as the welding material. The effects of laser welding parameters such as laser peak power, pulse duration, angle of incidence, laser focus point position and number of pulse shots have been investigated on the spot weld dimensions involving penetration depth and weld width. Good weld possess deep penetration and narrow width (Ready, 1997). The penetration depth and weld width are observed by optical microscopy (OM) and the image of the magnified size is captured by a CCD video camera driven by VideoTest 5.0 software. The captured images are measured by Matrox Inspector 2.1 software to give the actual value of penetration depth and weld width.

A one dimensional heat conduction equation and the energy balance equation at the laser spot are derived to determine the weld penetration depth. The penetration depth is obtained by controlling the laser welding parameters that includes the peak power, pulse duration, laser beam radius and the properties of welding material. Modeling of laser beam penetration in welding material is derived using governing continuity equation based on a cylindrical coordinate. The modeling is performed using the Matlab software.

The reliability and stability of a weld is determined by its strength and microstructure. The strength of a weld joint is measured using an INSTRON Series IX/s Automated Materials Tester System. The defects encountered in laser welding, such as porosity and weld cracking are characterized by Field Emission Scanning Electron Microscopy (FESEM). The element composition of base and welded material is analyzed by Energy Dispersive X-ray (EDX).

## 1.5 Significance of study

This study enabled us to explore the physical process involved and provided better understanding of the laser micro welding processes. With the present demand for high quality welding in miniature assemblies, it is important to determine the desired weld penetration depth and weld width. The desired weld penetration depth and weld width can be obtained by controlling the laser welding parameters such as laser peak power, pulse duration, focus point position, laser spot radius, number of laser pulse shots and angle of incidence. This will also determine which parameter mostly influences the weld penetration depth and weld width.

The mathematical model developed to predict penetration depth would reduce the experimental time and cost associated with the parameters in laser micro welding. Measurement of laser beam penetration inside the material is a difficult task as well as it requires very tiny and sensitive power detector. Hence, mathematical modeling is very important for predicting the laser beam penetration.

This study addresses the weldability of stainless steel material. It has been determine the reliability of stainless steel in laser welding of miniature assemblies such as photonics packaging.