INVESTIGATION OF THE ARGON SHIELDING GAS ON THE LASER WELDING IN TITANIUM

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Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

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วิทยานิพนธ์นี้ได้ศึกษาการใช้แก๊สอาร์กอนช่วยปกคลุมการเชื่อมโลหะไททาเนียมด้วยเลเซอร์ โดยตัวแปรที่ใช้คือค่ากำลังของเลเซอร์และอัตราการไหลของอาร์กอน โดยค่ากำลังที่ใช้คือ 2.0 2.8 และ 3.5 กิโลวัตต์ อัตราการไหลที่ใช้คือ 0 5 10 และ 15 ลิตรต่อนาที โดยผลการวิจัยที่ได้แสดงให้เห็นว่าแก๊สอาร์กอนปกป้องรอยเชื่อมจากกระบวนการออกซิเดชันซึ่งทำให้ไททาเนียมไม่เกิดการแตกหัก จากการปรับเปลี่ยนค่าการไหลของแก๊สอาร์กอนที่เหมาะสมทำให้คุณภาพรอยเชื่อมเพิ่มขึ้นทั้งรูปลักษณ์และค่าความแข็งแรงเชิงกลเนื่องจากการกำจัดพลาสมา ที่ระดับกำลัง 2.0 กิโลวัตต์โดยไม่มีแก๊สอาร์กอนปกคลุม เกิดโหมดการเชื่อมแบบคอนดักชัน และเมื่อใช้แก๊สอาร์กอนปกคลุมจะทำให้เกิดการเปลี่ยนโหมดของการเชื่อมไปเป็นคีย์โฮล นอกเหนือจากนี้ค่าความแข็งแรงเพิ่มขึ้นตามอัตราการไหลของแก๊สปกคลุมแต่จะอิ่มตัวในที่สุด อย่างไรก็ตามอัตราการไหลของแก๊สปกคลุมที่มากเกินไปจะทำให้ความแข็งแรงเชิงกลมีค่าลดลงเนื่องจากการเชื่อมที่ไม่สมบูรณ์ ที่ระดับพลังงานมากเกินไป 3.5 กิโลวัตต์และอัตราการไหลของแก๊สที่มากเกินไปทำให้เกิดการกระเด็นและการหายไปของโลหะ

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RATCHANIKORN KOOMRAM : INVESTIGATION OF THE ARGON SHIELDING GAS ON THE LASER WELDING IN TITANIUM. THESIS ADVISOR: SUKANYA TACHATRAIPHOP, Ph.D. 68 PP.

LASER WELDING/TITANIUM/ARGON SHIELDING GAS

A laser welding of the commercial pure (CP) titanium was investigated by varying the argon shielding gas flow rate and the laser energy. The powers were 2.0, 2.8 and 3.5 kW. The flow rates of argon were 0, 5, 10 and 15 liter(s)/min. The results showed that the argon gas prevented an oxidation process; therefore, there was no cracking. With an appropriated argon flow rate, the weld qualities were improved both appearance and mechanical strength due to the plasma suppression. When the laser power was low, 2.0 kW, the laser welding provided the conduction mode in the no shielding gas condition. The conduction mode became the keyhole mode with the presenting of the shielding gas. Moreover, the tensile strength was improved and reached a saturated level when an argon flow rate was increased. However, an excessive argon shielding gas decreased the tensile strength by created incomplete weld. The excessive laser power, 3.5 kW, and the excessive gas flow rate caused a weld splatter and metal loss.

School of Laser Technology and Photonics Student’s signature__________

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CHAPTER I

INTRODUCTION

1.1 BACKGROUND

1.1.1 Laser welding

In welding process, two pieces of material are joined together. First, the material absorbs an applied energy. Then, the material is melt. It is transferred back to the solid phase shortly after the applied energy end. During the welding process, the quality and appearance of the weld are formed. In general, good weld qualities have a sufficient penetration, no crack, no distortion, no material splatter, no porosity, acceptable mechanical strength, and etc. There have been several experiments showed that laser welding provides a good weld quality and mechanical strength (Yamagishi, 1993, Qi et al., 2000, Liu et al., 2002 and Watanabe, 2006).

With outstanding laser properties, the laser beam welding is greatly utilized (Ion, 2005). The coherent nature of laser allows the laser beam to be focused to a small spot. The typical focus spot diameter of the laser beam ranges from 100 to 1400 µm. Meanwhile, a tips of the torch welding provides a size range from 0.51 to 3.25 mm (Ucellini, www, 2003). A large energy area often damages a piece nearby or creates un-intended weld area. Moreover, it brings a large distortion. Furthermore, the laser coherent nature brings a directionality quality. With both small spot and directionality qualities, a laser provides a good controllable weld area. Because of a small spot size, laser also provides a high energy density. It gives a power density up to 10^5 to 10^7 W/cm^2 (Mazumder, 1997), whereas sun energy power density on the earth is 1.367–1.3675 kW/m^2 (Cowan, 1997).

In addition, laser is inertialess. There is a short time interaction between laser beam and work piece. Start and stop time can occurs in a short period. Then, the high welding speed is possible. Laser beam welding can be significantly improved both speed and precision by launching laser beam through the fiber optic attached to the robot arm.

However, a small focusing spot requires a precise part fit-up. A good alignment is a critical matter in laser beam welding. The misalignment in range of mm can cause a problem in laser welding (Duley, 1999).

Even, nowadays the price of laser system was came down and become affordable. The cost of laser welding system is still more expensive than comparable torch welding system. However, whenever there are needs for a high quality weld, laser beam welding is an attractive welding method. The laser market has seen the growth year after year. "World Laser Machine Tools Markets" in 2005, the world laser machine tools market revenues were $4,205.5 Million and are expected to reach $8,381.6 Million towards 2012 (Virein, Kumar, and Yadlapalli, www, 2006). According to a new report, *Laser 2010,* from market research company, Strategies Unlimited, the global market for lasers is expected to grow by $2.6 billion to $8.8 billion in 2014, representing a growth rate of 9 percent, which is more moderate than the average historical rate of 14 percent. Also, a laser welding has been used for many applications (Notenbloom, 1982, Lutttke, 1987, and Havrillva, 1990). For example the electron guns of the television tubes, razor blades, heart pace maker, optoelectronic transmitters, food mixer whisks the part of the car engine, tailor back of the car and specialist fabrication etc.

1.1.2 Titanium properties

The natural properties of the titanium are low density, excellent high temperature mechanical properties and good corrosion resistance. Those properties lead titanium into various applications, for examples, a partial removal denture, part of aero engine, artificial joint, and etc. All applications significantly require the high quality welded titanium. However, titanium has a low thermal conductivity and high melting point (1680 ^{o}C) (Tagoya and Shinotaki, 1999) which makes it hard to be welded. If the energy is too low, titanium will not melt and welded. Moreover, a welding area can hardly spread to the sides by the help of the low thermal conductivity. On another hand, if the energy is too high, the vicinity area will be melt as well. Therefore, it is hard to weld titanium without damaging the piece nearby and creating the imperfect weld.

Since the laser provides a high energy density with a small spot size, laser beam welding is appropriate for a titanium material (Liu, 2002). Moreover titanium can absorb Nd:YAG laser up to 26% comparing to CO_2 8% laser (Duley, 1999). In general during the welding process titanium has high chemical reactivity with oxygen at high temperature. The oxygen reaction causes hardness increment and brittle in titanium welding (Wang and Welsch, 1995). The simplest solution of this problem is shielding gas during welding process while laser beam welding was utilized. A shielding gas was used to protect the molten area from oxygen and help the suppression of plasma effect. Another word, laser beam welding allows the oxidation control and the plasma suppression process in order to improve the laser welded titanium.

1.1.3 Relative study

The research of laser welding in titanium was illustrated in the following. In 1995, Zhang Li, et al., introduced the laser welding in titanium alloy and the result showed that the laser welded profile was satisfied by Nd:YAG laser. In 2000, Qi Yunlian, et al., presented that the laser beam welding gave a narrowest weld seam, less deformation and finer microstructure which are good properties for the weld seam. In 2002, Liu published the joint strength of laser welding. The conclusion of the study was the strength of the laser welding titanium could be improved as similar as the non weld by the appropriate condition of welding. The conclusion of all studies confirmed that laser welding is a profitable welding in titanium. In 2007, Hong Wang presented the numerical method of the influence of the gas shielding in welding titanium. The results of the study was the size of argon shielding gas is larger than helium, the effect of the protection was increased when the flux rate was increased and the recommendation of the shielding gas flow rate was more than 7.5 liters/min. Furthermore, the effect of the gas shielding was represented in 2007 by Ming Gao. The topic was the effect of the gas shielding parameters on weld penetration of CO_2 laser-TIG hybrid welding. The result of the study was that the shielding gas is important factor for deeper weld penetration. The relationship of the shielding gas and the penetration concerned with the plasma effect. Other study in the influence of the shielding gas in titanium was reported by B.M. Choi and B.K. Choi. The result was summarized as the maximum flow rates, 25 liters/min, provide the maximum tensile strength comparing others, 15 and 20 liters/min. The studies of the shielding gas influence on the laser welding titanium was summarized that the shielding gas is important parameter of obtaining the good weld quality and mechanical strength.

1.2 Significance of the study

As been discussed, laser welding has been one of the most interesting techniques which have been confirmed by the laser market value in billion dollars business. Other welding methods, for example, flame torch and arc welding are not suitable for titanium because of difficulty and a poor weld quality. However, laser has prominent properties which can provide a good weld quality for a titanium material. Moreover, the shielding gas flow rate was used to suppress the oxidation and plasma process in order to improve and control the weld quality and appearance. The related studies were a simulation of the shielding gas influence on laser welding and the effect of shielding gas on GTAW welding. This research has characterized the experimental influence of the flow rates on laser welding in titanium via metallography and mechanical test.

1.3 Research objective

The influence parameters both laser power density and argon gas flow rate was characterized, the appearance and mechanical property of laser welded titanium were reported. The laser welded titanium was observed via optical microscope, metallography investigation and mechanical test which is tensile test.

1.4 Research hypothesis

As been discussed, argon shielding gas can suppress the plasma plume and resulting in a better welded quality for a titanium. As the gas flow rate change, the weld quality and appearance of the laser welded titanium are subjected to change as well. Thus, a various argon flow rates were investigated. Besides the gas flow rate, the laser energy density influenced on the titanium welding was evidence.

1.5 Scope and limitations of the study

In this research, Commercial pure (CP) titanium Grade 2 was used because of the versatile use and conveniently supply. The CP titanium is welded with two aspects: the different laser power and the gas flow rate. The quality of the welding was investigated via metallography and mechanical property. The appearance is observed by an optical microscope. The mechanical property is measured by a tensile test which the force is applied to the material.

1.6 Organization

This thesis is organized into five chapters which this is the first. Chapter II is a theoretical review of the laser welding and titanium. It starts with the laser beam properties which are utilized into welding materials. The laser welding process and the related parameters including laser powers, shielding gas and joint configuration are also presented. Next topic, titanium which is used in this thesis is. The final topic of Chapter II is the investigation method for characterize the laser welding in titanium. In Chapter III, the experimental set up is described. The results and discussions of the experiment are presented in Chapter IV. Finally, the conclusions of the thesis are presented in Chapter V.

CHAPTER II

THEORETICAL REVIEW

Laser is a short form of “Light Amplification by Stimulated Emission of Radiation”. A stimulated emission is the internal emission of the material. The electron, possess in an upper energy level of the material, was excited by photon. Electron changes the level from upper to lower and emits two photons. The stimulated emission is described in Figure 2.1.

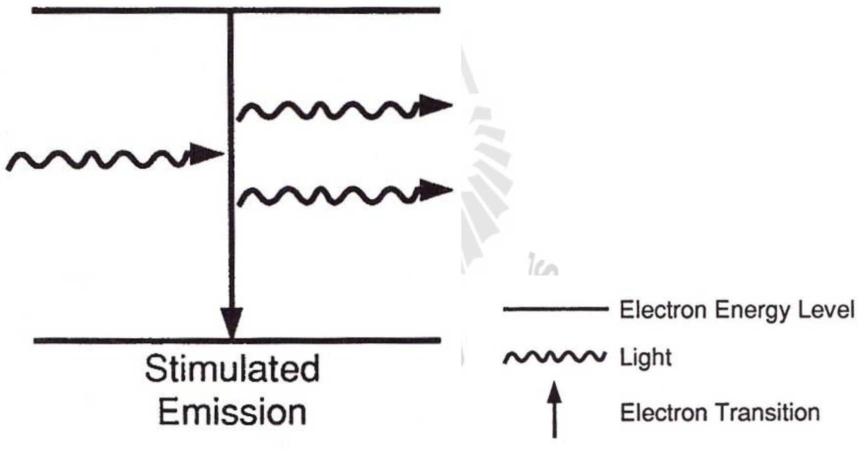


Figure 2.1 Stimulated emission schematics (Ready, 1997).

To amplify the stimulated emission, the two mirrors are placed at the ends of the material which having a high stimulated emission rate. The one mirror is a fully reflecting and other is partially reflecting mirror. The photon travel back and forth interval the mirror and was amplified by the laser material. Therefore; powerful light is accomplished. The composition of the laser is shown in Figure 2.2.

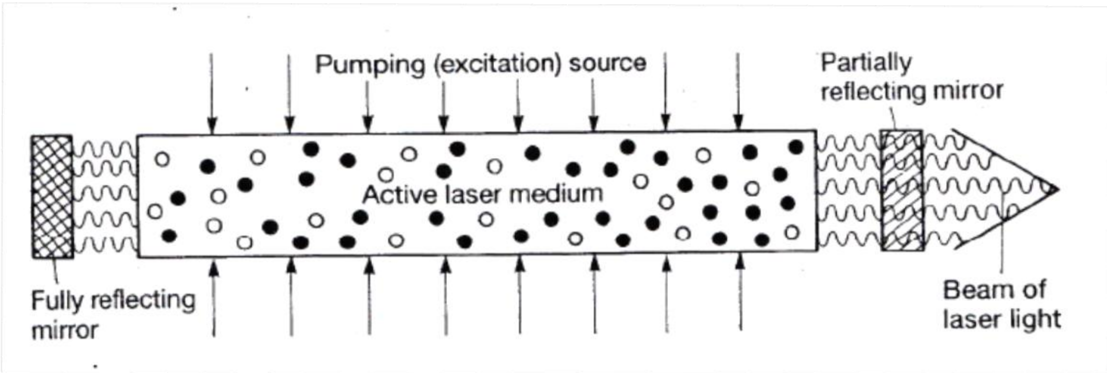


Figure 2.2 The basic elements of a laser (Dawes, 1992).

2.1 Laser beam properties

Laser provides a parallel beam which has different properties from the other light source. The properties of laser can be utilized in many of applications (Ion, 2005). The important laser properties which are significant in material processing are high power, monochromatic light, coherence, and pulsed operation which are described in following.

2.1.1 High power

The main attractive point of laser beam in material processing is a high power. The laser focusing can dramatically increase the power density. For example, the unfocused CO_2 laser beam with 10, 25, 40 and 70 mm diameter has average power density across these diameters in order, 6 to 13 W/mm^2. By focusing laser, the power density is raised to 10^3 up to 10^5 W/mm^2 (Dawes, 1992). This power density can vaporize all materials; therefore, laser is applied as the energy source of the welding. The intensity of the energy source of laser welding and other welding process is compared in Table 2.1.

Table 2.1 The comparison of the intensity of the laser beam relative to other welding process (Mazumder, 1997).

Welding process	Intensity of energy source W/cm^2	Fusion zone profile
Oxyacetylene	10^2-10^3	-Shallow for single pass
Arc welding	$5x10^2$-10^4	-Shallow for single pass
Plasma arc (PAW)	10^3-10^6	-Shallow at low energy end -Deep penetration at high energy end
Laser beam	10^5-10^7	-Shallow at low energy density range -Deep penetration at high energy density range
Electron beam	10^5-10^8	-Deep penetration

As seen in Table 2.1, the power density of laser is only rivaled by an electron beam. As using electron beam for welding, the vacuum chamber must be applied. This vacuum prevents an attenuating of electron beam due to scattering with air surrounding. The vacuum making is expensive and complicated, so the laser is more conveniently use and lower cost operation.

The power density of the beam depends on the laser power and focusing spot. At given laser power, the focusing spot is the main point for given high power density. The focusing spot is depends on the wavelength as (Kannatey-Asibu, 2009)

$$w_f = \frac{\lambda}{\pi\theta} \approx \frac{1}{\pi}\frac{f_l}{w_0}, \quad (2.1)$$

where f_l is the lens focal length, w_0 is the beam radius at the lens and θ is the angular aperture of the lens, or the angle subtended by lens at the focus as shown in Figure 2.3. The minimum focusing spot is depends on the laser wavelength and the focal length. Due to the diffraction limited, the minimal spot diameter is given by

$$d_{min} = 2w_{min} = \frac{1.22\lambda}{NA} \approx \lambda, \quad (2.2)$$

where NA = $n\sin(\theta/2)$ is the numerical aperture and n is the refractive index of the medium in which the lens is working (Kannatey-Asibu, 2009). The minimum spot diameter is about the beam's wavelength. In typical laser application such as cutting the beam diameter is about 250 µm. From the beam focusing limitation, the Nd:YAG laser, 1.06 µm wavelength, can be focused into a smaller spot than CO_2 laser, 10.6 µm.

2.1.2 Monochromatic

The monochromatic means the wave with single wavelength. The laser is a monochromatic by the stimulated emission and the cavity design. The cavity separation provides the resonant mode of the wave. In laser, the frequency width of the resonant mode is very narrow. The combination of the resonant modes and the gain of material are illustrated in Figure 2.4. In Figure 2.4(a), the distance of the cavity provides cavity mode. The inherent gain curve of the laser medium is shown in Figure 2.4(b), The output of the combination of the cavity and the gain is illsutrated in Figure 2.4(c). The purity wavelengthof laser is accomplished. The monochromatic light is important factor for the focusing into a small spot, especially in laser cutting, which needed a maximum power density.

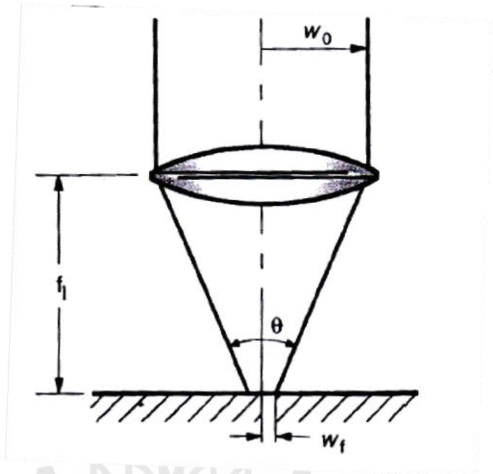


Figure 2.3 Beam focusing (Kannatey-Asibu, 2009).

2.1.3 Coherence

Coherence is used to define the fixed-phase relationship between the two waves. Laser is a high coherent light by the stimulated emission. This is obviously difference from the other light source. The coherence of laser is defined as the coherence length. The coherence length, l_{coh}, is the distance of the light which travels before the coherence changes. The wavelength and the bandwidth of the light influence the coherence length as (Ion, 2005)

$$l_{coh} = \frac{\lambda^2}{\Delta\lambda} \, , \tag{2.3}$$

where λ is the wavelength and $\Delta\lambda$ is the bandwidth. The bandwidth of the laser is illustrated in the Figure 2.4(c). The coherence length of laser can be up to 100,000 cm. in He-Ne laser with single frequency (Ready, 1997). This is very useful in holography and measurement applications.

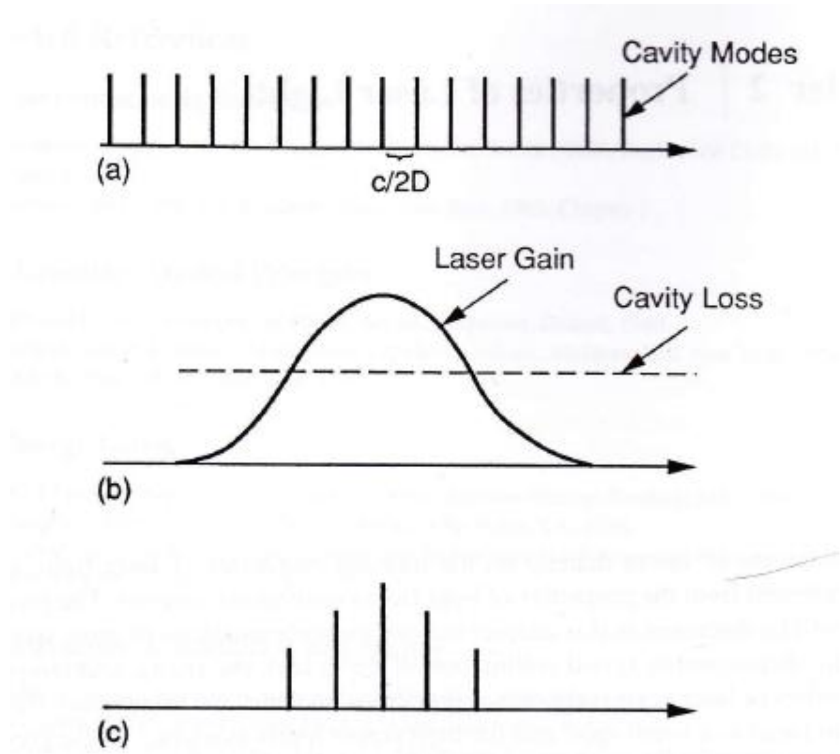


Figure 2.4 Frequency spectrum of laser output: (a) the resonant cavity of gas laser where C is light velocity and D is the mirror separation (b) the gain curve for the fluorescent emission, with the cavity loss and (c) the result of frequency spectrum (Ready, 1997).

2.1.4 Pulsed operation

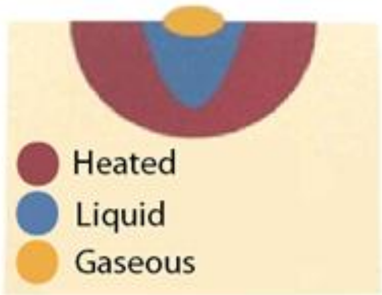
Laser can be operated in pulse mode and continuous wave mode (CW). The pulse laser is created by the pulse pumping of the flash lamp. The pulse durations range is 100 µsec to several milliseconds (Ready, 1997). With short pulse operation (Q-switch mode), the laser peak power of 20 W Nd:YAG can be up to 100 kW (Steen, 2003). This property of laser increases the more usage in the material processing. The high power of laser can be created by a low energy short pulsed laser. Moreover the pulse laser can be installed in robot which an automatic welding can be achieved. It improves the production time which established laser welding in the industry.

2.2 Laser welding

The laser beam can be focused into a small spot, leading to high energy densities. Lasers have been promoted as potentially useful welding tools for a variety of applications (Ion, 2005). Since 1965, a variety of laser systems had been applied used for making micro weld in electronic circuit boards, inside vacuum tubes, and in other specialized application where conventional technology was unable to provide reliable joining (Duley, 1999).

2.2.1 Laser beam welding process

Laser beam welding is used to create the liquid melt pool by absorption of a laser beam radiation. Laser beam welding creates three main continuous processes; absorption, melting and cooling process. Initially, the laser beam impinges on the surface of material. The large percentage of the laser energy is reflected from the surface of material. For example, absorptivity of titanium in Nd:YAG laser is 28% and CO_2 is 8% (Duley, 1999). The small amounts of energy are absorbed and heat the material surface. When the temperature of the surface is increase, the laser absorption is increased (Steen, 2003). After that heat is created at the focusing spot, it continue dissipates to surrounding area. This result causes a melting pool. The melt pool transfers into the solid state caused by the cooling process. The laser beam welding process is shown in Figure 2.5. The laser radiation toward the metal is often interrupted due to the evolution of hot gas from the laser focused beam. Under certain conditions, this hot gas may turn into plasma that can severely attenuate the laser beam due to absorption, defocusing and scattering; therefore, the weld depth is shallow. The hot gas became plasma via metal vaporization. To eliminate the plasma, the shielding gas is applied. The shielding gas pays the important role of welding process. The first role of the gas is to prevent oxidation of the weld zone. The second role which is critically is to suppress plasma formation in the vapor over the weld zone and to blow away any plasma formation that may be created during the welding process. The latter role ensures that the laser beam can reach the weld zone with minimal interruption, thus improving weld quality and enhancing penetration.



Bombardment zone shows the zone affected by heat after laser bombardment

Figure 2.5 The bombardment zone (laserstartechnology, 2012).

2.2.2 Laser welding mode

The laser welding appearance is classified in two modes: the conduction and deep penetration (keyhole) mode as shown in Figure 2.6. The difference of two modes is the penetration of the weld. The details of the welding mode are described as following.

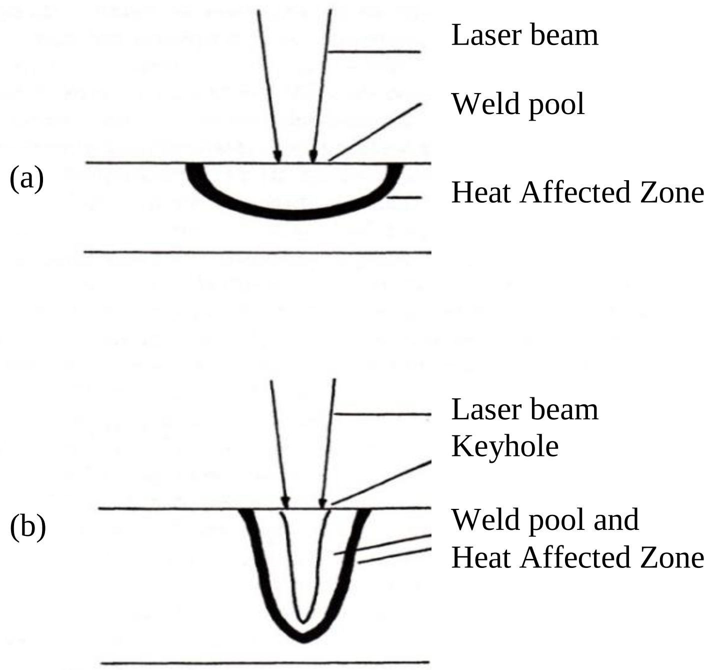


Figure 2.6 Laser welding mode (a) conduction mode (b) keyhole mode (Duley, 1992).

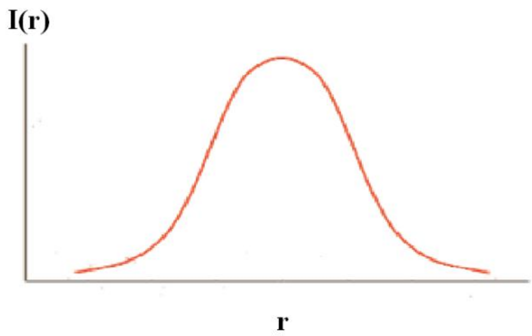


Figure 2.7 Laser beam profile.

(a) Conduction mode welding

This is the conventional welding mode. For laser welding, the conduction mode can be described by the laser beam profile. The laser has a Gaussian beam profile as a Figure 2.7. From the beam profile, the central part has high energy and skirts have low energy. When laser beam hits on a target, its energy is transferred into the workpiece and then melts the metal. With energy distribution, the central of the weld is melted and some part of energy becomes a heat which expanding to adjacent area. The edges of spot, containing energy of skirts of the beam, have not enough energy to melt. After the beam is hit, this heat could melt at area which has not been melted before. A typical conduction mode looks like a bowl shape as in Figure 2.6(a). The size and shape depends on the material properties and power density. The conduction mode offers less penetration.

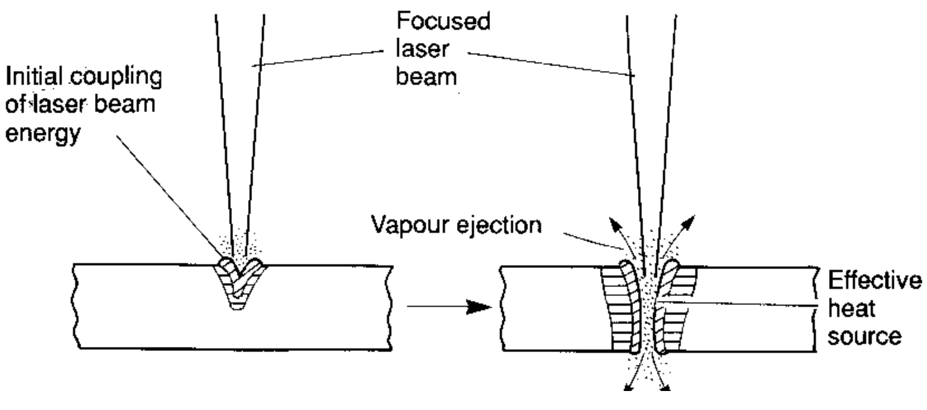


Figure 2.8 Keyhole welding process (Dawes, 1992).

(b) Keyhole mode

The keyhole welding process is shown in Figure 2.8. When laser beam hits on the target, the energy was transferred into the target. By the Gaussian beam profile distribution, the central of spot has a high energy. At high power density, the metal can vaporize and create a hole on the melt pool. The laser beam could penetrate into the melt pool leading to a coupling of laser on a keyhole wall. The coupling of laser vaporizes the metal in a keyhole wall. Vapor pressure from the melt metal continuing opens a hole during the weld. The keyhole allows the laser energy to reach deeper into the fusion zone and produce a deeper weld.

2.3 Laser welding parameters

Laser welding has many parameters which can optimize the welding. Critical parameters are shown in Table 2.2

Table 2.2 Critical parameters in laser welding (Duley, 1999).

▪ Amplitude
▪ CW or pulse wave
▪ Depth of focus
▪ Flow rate
▪ Focus above or below surface
▪ Focusing location of focal spot on surface
▪ Intensity distribution within spot on surface
▪ Laser power
▪ Nozzle flow pattern
▪ Orientation relative on focus
▪ Pulse shape and repetition rate
▪ reverse side
▪ Shielding gas type
▪ Trailing, coaxial, leading

From the scope of the thesis, the parameters information is only discussed in laser power, shielding gas and joint configuration.

2.3.1 Laser power

The laser power is a basic parameter of the laser welding. The power density of the laser is identified by the laser power and the spot diameter of laser beam. The depth of penetration of laser welding directly related to the power density of the laser beam. The depth of the weld typically increases as the beam power is increased.

2.3.2 Shielding gas

In laser welding process, undesirable effects are oxidation effect and plasma effect. Shielding gas helps improving the quality, appearance, cosmetics and metal properties of the weld. First, shielding gas protects the molten pool from the atmospheric oxygen which is created a brittle weld. Second, shielding gas suppresses the plasma which is seeded by vaporized metal and is ejected from a workpiece. The Plasma can attenuate the laser beam energy. The role shielding gas can be described in detail in the following:

In a welding process, melting pool is created by an impinged laser beam. The atmospheric gases, especially oxygen, can diffuse into the melting pool and causes a brittle metal. At pre welding, the shielding gas is initially applied to expel the oxygen on the surface. Then laser beam is applied while shielding gas is still using. After that the shielding gas continued use for a while for maintaining the non oxygen status and cool down the welded area. The oxygen could be eliminated all over the welding process with a shielding gas.

As the power density exceed 10^6 W/cm^2, metal is vaporized, ejected and then formed a cloud cover the workpiece. This hot cloud is called plasma. Plasma could absorb the laser beam energy resulting in reducing the laser intensity on the workpiece (Hansen and Duley, 1994). Moreover the plasma could scatter the laser beam. For several experiments (Ducharme et al., 1992, Heidecker et al., 1988, Matsunawa, 1990), the plasma scatters the laser beam. The relation of the scattering is inverse proportional to λ^4 (Hansen and Duley, 1994). Therefore, Nd:YAG laser (wavelength 1.06 µm) has a much scattering effect than CO_2 laser (wavelength 10.6 µm). The effect of the plasma can be shown as the results of transmitted laser intensity. At the Fe aerosol with the volume is 10^{-4} m^3, the transmitted intensity of the Nd:YAG laser (1.06 µm) is 0.01% of incident beam intensity while CO_2 laser is 0.97% (Hansen and Duley, 1994).

Over the workpiece, there are two gases (plasma and air) having a difference reflective index. At the boundary of two gases media, there is a discontinuity of reflective index formed lens like. This lens distorts the laser beam; therefore, laser density is reduced at the target area. Furthermore, the plasma continued move up and expand away (Miyamoto and Maruo, 1992). The determination of the gradient and density of the plasma is complicated at certain time and location. In order to suppress the plasma effect, the shielding gas is applied. Plasma is created during the beam hit on the target. The shielding gas expels and blows away the plasma from the target area.

The parameters of the shielding gas are the gas type and the flow rate. The gas type is described for selecting the appropriate gas for shielding.

2.3.2.1 Shielding gas type

The selection of gas type is importance of shielding process. As the gas is used to manage the plasma so the ionization potential must take into account. The ionization potential is the energy, expressed in electron volts, necessary to remove the electron form the gas atom. The value of the ionization potential decreases as the molecular weight decreases. The low ionization potential can easily turn into the ions so is not effective for shielding. Therefore; the high ionization potential gas such as helium and argon is chosen. The properties of the inert shielding gas are presented in Table 2.3. Even helium has a higher ionization potential than argon but the advantage of the use of argon is a higher density than air. When the gas is ejected, argon falls down to the weld area comparing to helium. The other advantage of argon is the cost. Helium is expensive than argon so in long term using, in the welding industry, the argon is saver.

Table 2.3 Properties of shielding gases used for welding (Larson and Meredish, 1990).

Gas	Chemical symbol	Molecular weight	Ionization potential (eV)
Argon	Ar	39.95	15.7
Helium	He	4.00	24.5

2.3.2.2 Gas flow rate

Gas flow rate is other parameter for efficiency shielding. With appropriate gas flow rate, oxygen was completely expelled and the plasma is suppressed as fast as it is created. The excessive flow rate could blanket and attenuate the incident laser beam. In high speed welding, gas flow rate is more important. For increasing speed, the shielding areas need to be covered as fast as the speed of the laser beam. For this reason, the gas flow rate has to be adjust for matching the welding speed. For the high speed welding (>10 m/min), the gas flow rate are typically 10-40 l/min base on industrial using. The gas flow geometry is another important factor. The dynamic of the shielding gas depends on the nozzle geometry. The varieties of nozzle designs have been studied (Dawes, 1992, Fieret et al., 1986 and Steen, 2003).

2.3.3 Joint configuration

The typical joint geometry of conventional welding can be applied for laser welding. The joints which widely used for laser welding are butt joint, lap joint, spot weld, flank weld etc. is shown in Figure 2.9. The butt joint is a simple geometry which is basically used in laser welding. The filler metal is not necessary to supplied in this joint configuration. For butt joint, edges of materials were put closer with each other. The gap width between the sheets is critically for laser welding because of the small beam diameter. The referenced butt joint fit up is shown in Figure 2.10 (Schwartz, 1979). The face gap tolerance should within 15% of the thickness of the material. The side view misalignment should be less than 25%. In application, a butt joint welding is used in welding the tailor blank of the car's door.

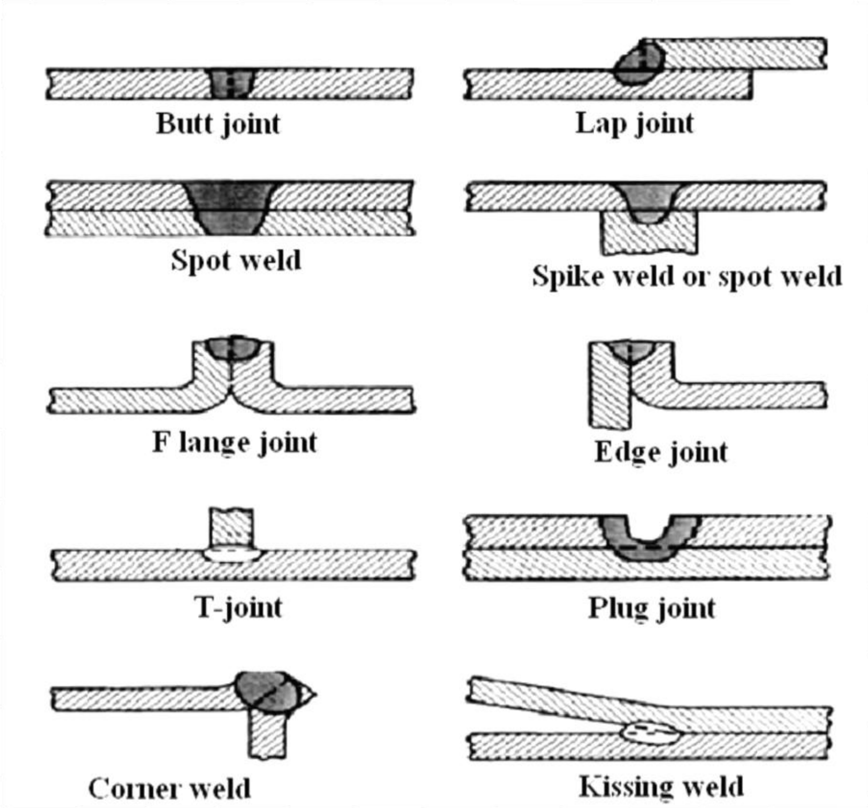


Figure 2.9 The joint design of laser welds on sheet materials (Shewell, 1977).

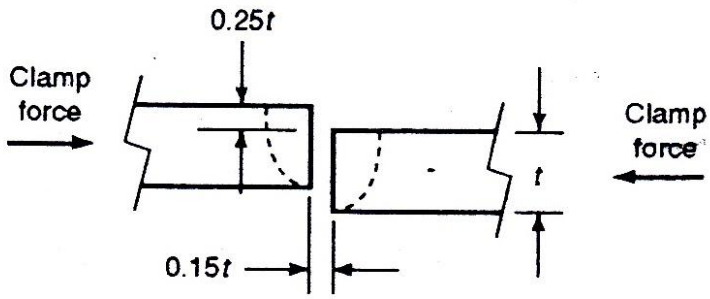


Figure 2.10 Tolerance of the butt welding of material of thickness t. (Schwartz, 1979).

2.4 Titanium

Titanium and titanium alloys have properties which are applied to various applications. The low density, excellent high temperature mechanical properties and good corrosion resistance are the attractive properties of titanium. Titanium and titanium alloy are used in many applications including medical, aerospeace, automotive, petrochemical, nuclear and power generation industries (Wang et al., 2003 and Casalino et al., 2005). When the temperature exceeds 130 ºC, titanium alloys can be used as replacements for aluminium-based materials in applications such as the external shells of turbines, the power units for avionics and the landing gear structural components in Boeing 747 and 757 (Lima, 2005). Moreover, titanium express very low corrosion rates in human body fluids as demonstrated (Choubey et al., 2005), other applications that are relevant to medical industry include prosthetic devices such as artificial heart pumps, pacemaker case, heart valve parts as well as load bearing bone such as for hip bone replacement. The example of the titanium application, the pacemaker, is shown in Figure 2.11.

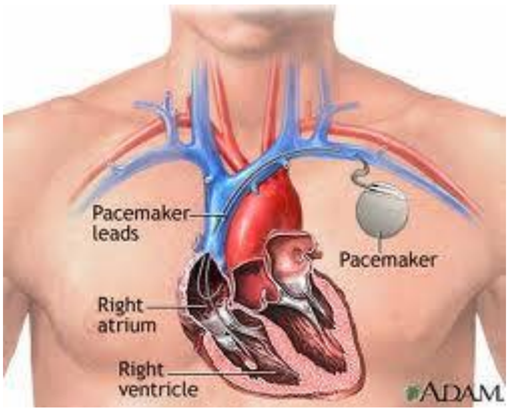


Figure 2.11 Pacemaker (Berger and Zive, www, 2008).

2.4.1 Problem of welding titanium

Titanium and titanium alloys have a drawback for welding. Whereas at temperature above 550 ºC, titanium has a high reactivity with oxygen causing a crack weld. The conventional welding method for titanium is a Gas-Tungsten Arc Welding (GTAW). This welding method, using a high different voltage creates an arc, is applied for welding titanium. The limitations of GTAW are a large weld area which damage nearby and distortion of the weld. The comparison of GTAW and laser welding is shown in Figure 2.12.

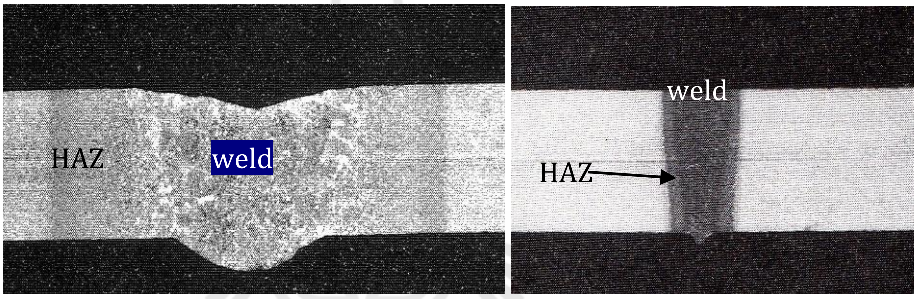


Figure 2.12 The comparison of welding method (left) GTAW and (right) laser welding (Dawes, 1992).

Titanium has a high absorption in laser as shown in a Table 2.4. Therefore; laser welding can efficient apply to titanium. The advantage of the high absorptivity of laser is the lower power density input resulting in low heat damage area. The laser wavelength which has a high absorptivity, Nd:YAG, is able to weld titanium with low incident power density. This is profitable of less damage the nearby area by the unabsorbed energy. Meanwhile, the low absorptivity wavelength, CO_2 laser, must be applied the higher power density and could damage the workpiece because of unabsorbed energy.

2.4.2 Commercial pure titanium

Unalloyed Commercially Pure (CP) titanium is classified into four grades, including 1, 2, 3 and 4. CP titanium is ordered in relation to the corrosion resistance, formability (ductility) and strength requirements of a specific application. CP titanium ranges from grade 1, which has the highest corrosion resistance, formability and lowest strength, to grade 4, which offers the highest strength and moderate formability. CP titanium end users utilize excellent corrosion resistance, formability and weld ability characteristics for many critical applications. The Composition and mechanical properties of CP titanium are shown in Table 2.5.

The mechanical of CP titanium grade is proportional to the oxygen composition. With high oxygen composition, the strength is increased and the ductility (% of elongation) is decreased. According to the thesis, CP titanium grade 2 is used and the information is described as following. CP titanium grade 2 is widely used in the industrial application. The acceptable yield strength is 275 MPa with good ductility and formability. This amount of yield strength is comparable to stainless steels. The applications of the CP titanium grade 2 are chemical, marine, and similar applications, airframe skin and nonstructural components, heat exchangers, cryogenic vessels, components for chemical processing and desalination equipment, condenser tubing, pickling baskets, anodes, shafting, pumps, vessels, and piping systems (Welsh et al., 1994).

Table 2.4 The absorptivity of Nd:YAG laser and CO_2 laser in metal (Duley, 1999).

Laser Type	Wavelength µm	Absorptivity in metal at room temperature
Nd:YAG laser	1.06	Al 0.06 Cu 0.05 Fe 0.1 Ni 0.15 Ti 0.26 Stainless steel 0.31
CO_2 laser	10.6	Al 0.02 Cu 0.015 Fe 0.03 Ni 0.05 Ti 0.08 Stainless steel 0.09

Table 2.5 Properties and composition of four grades of CP titanium (Williams, 1998).

CP Ti type	O (max.)	Fe (max.)	E (GPa)	UTS (MPa)	Elong. (%)	0.2 yield strength (MPa)
Grade 1	0.18	0.20	105	240	24	170
Grade 2	0.25	0.30	105	345	20	275
Grade 3	0.35	0.30	105	445	18	380
Grade 4	0.40	0.50	105	550	15	480

2.5 Specimen investigation

The proper specimen investigation is important for the accurate and easy for analyze result. The method of investigated the welding specimen in this thesis are metallography and tensile test. Metallography is the method for observation the structure of the metal. This method used for analyze the laser interaction with titanium by the laser weld profile. Other method, tensile test, is a method for observation the strength of laser weld titanium.

2.5.1 Metallography

Metallography is the method the observation the physical structure and components of metals by applying the optical microscopy. Other type of material can be used this method for observe the structure of the material. The preparation of the metallographic specimen is described as following.

The surface of a metallographic specimen is prepared by grinding, polishing, and etching. After preparation, optical or electron microscope is used to analyze the structure of the specimens. Mechanical preparation is the most common preparation method. The finer abrasive particles are used to remove material from the specimen surface until reach the desired surface quality for many times. Many different types of equipment are used for grinding and polishing to meet the quality, capacity, and reproducibility. A successful preparation method achieves by revealing the true structure of material. Sample preparation must follow the rules which are suitable for most materials. The metallography method can be applied into the material which has similar properties. The specimens are typically mounted with the resins. The type of the resin is classified into 2 regimes: a hot mounting and the cold mounting. The hot mounting is using a compression thermosetting resin applied to the specimen. This hot mounting can be applied to the specimen which is not sensitive by temperature. The cold mounting is applied into a very sensitive to temperature specimen. The hot mounting can be automatic mounted by the machine but the specimen size must be a standard. Specimen which beyond the standard size can be used a cold mounting method. Safety, standardization, and failure protection of holding a specimen during the grinding and polishing methods is the main reason of mounting the specimen.

After mounting, the specimen is wet ground to reveal the surface of the specimen. Silicon carbide abrasive paper (SiC paper) was used for grinding. It starts with a coarse SiC paper and follows with the finer and finer paper until finishing. After grinding the specimen, polishing is continuing. A typically specimen is polished with fine alumina particle, silica, or diamond on a napless cloth to remove a scratch due to the SiC paper. The mirror grade of specimen is achieved for finishing the polishing process. After polishing, true microstructures can be seen with the microscope. The microstructure of the specimen is obviously revealed by using an appropriate chemical or electrolytic etchant. A great many etchants was developed to reveal the structure of material. The etchant is specific used for the selected metal and alloys. The varieties of etchant can used to reveal the structure of the material. A one type metal can be etched by many etchant for reveal selected phases and structure. The etching time is important parameter for optimization the etching process.

2.5.2 Mechanical Testing

Tensile testing or tension testing is a fundamental materials test which a sample is pulled by uniaxial tension until failure. The results from the test are commonly used to select a material for an application, for quality control, and to predict how a material will react under other types of forces. Properties which obtained from tensile test are ultimate tensile strength, maximum elongation, yield strength maximum force and area reduction.

A tensile specimen is a standardized sample in cross-section. The geometry of the tensile specimen is illustrated in Figure 2.13. It has two shoulders between gauges.

The shoulders are large for tightly gripped. The gauge section which the deformation and failure is performed, has a smaller area.

The shoulders of the test specimen can be manufactured in various ways to match the grips in the testing machine. Each system has advantages and disadvantages on itself. The more information of tension test is described in the American Standard of Testing Material (ASTM) book in ASTM E-8 series. According to the thesis, the flat type is applied because of the standardized and convenient supply. A Table 2.6 gives examples of test specimen dimensions and tolerances per standard ASTM E-8.

Table 2.6 Flat test specimen dimensions (ASTM E-8).

Dimensions in mm	Standard size (ASTM E-8)	Subsize 1	Subsize 2	Subsize 3
G-Gage length	50.0±0.1	25±0.1	25±0.1	12.5±0.1
W-Width	12.5±0.2	6.0±0.1	4.8±0.1	3.2±0.05
R-Radius of fillet (minimum)	12.5	6.0	6.0	4.0
L-Overall length	200	100	100	84
A-Length of reduced section (minimum)	57	32	32	16
B- Length of grip section (minimum)	50	30	30	30
C- Width of grip section (approximate)	20	10	10	10

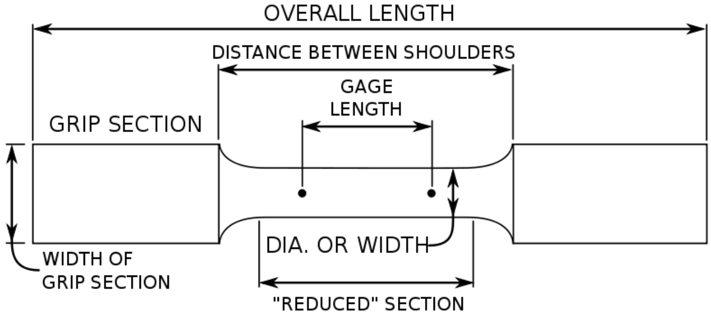


Figure 2.13 Test specimen geometry (ASTM E-8).

The most common machine for tensile testing is the universal testing machine as shown in Figure 2.14. This machine has two crossheads; one is used to fix the specimen and the other is driven by applying a force to subject the test specimen. There are two types: hydraulic powered and electromagnetic powered machines. There are three main parameters for tensile testing: force, speed, and accuracy. Force refers that the machine must have enough force to fracture the specimen. Moreover the machine must be able to apply the force quickly or slowly enough to properly application. Finally, the machine must be able to accurately and precisely measure the gage length and forces applied. The example of the importance of precise measurement: a large machine that is designed to measure a large elongation material is not suitable with a brittle material that having a short elongation to fracturing. Alignment of the test specimen in the testing machine is critical. Without precise alignment, the machine will bend the specimen. This is especially error for brittle materials. This situation can be minimized by using spherical seats or U-joints between the grips and the test machine. A misalignment is indicated when running the test if the initial portion of the stress-strain curve is curved and not linear.

The test process involves placing the test specimen in the testing machine and applying tension to it until it fractures. During the application of tension, the elongation of the gauge section is recorded during the applied force. The data is manipulated so that it is not specific to the geometry of the test sample. The elongation measurement is used to calculate the engineering strain, ε, using the following equation:

$$\varepsilon = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0}\ , \tag{2.4}$$

where ΔL is the change in gage length, L_0 is the initial gage length, and L is the final length. The percentage of elongation is the index of ductility which define as

$$\% \text{ of Elongation } = \frac{L - L_0}{L_0} x100 \,, \tag{2.5}$$

The force measurement is used to calculate the stress, σ, using the following equation:

$$\sigma = \frac{F_n}{A} \,, \tag{2.6}$$

where F_n is the normal direction force perpendicular to the area A. The tensile stress is the maximum of stress of material. Tensile stress is the important data which used for engineering design.

Figure 2.14 A universal testing machine.

CHAPTER III

RESEARCH METHODOLOGY

The research objective is to investigate the argon shielding gas on the Nd:YAG laser welding in titanium. The power density and gas flow rate are the main parameters of this thesis. The power density was varied by a laser power. The CP titanium grade 2 is cut into two type specimens: weld profile and tensile test specimen. After that, the specimens are cleaned by the solution to remove the contamination. Each specimen is mounted on the slide and then placed on the jig. The welding operation was starting later. After welding, all specimens were observed by the optical microscope. Then the weld profile specimen must be investigated by metallography and the tensile specimen is tested by a tensile testing. The experiment set up is presented in details as following

3.1 Specimen preparation

The two type specimens are used in research: first, the weld profile and second, the tensile test. The preparation process is presented as following.

3.1.1 Cutting

For unique standard, the specimens were cut by wire-cut machine as shown in Figure 3.1 which using high speed electric wire for cutting material. The cutting size for laser welding profile is 6 mm x 20 mm x 1 mm. The size of a tensile specimen is shown in Figure 2.13 and Table 2.6. The tensile test specimen size follows ASTM E-8 sub-size1 specimen. ASTM E-8 is the tensile testing standard. The experimental specimen size is the subsize 1 because of price of titanium plate is high and the other sized specimen is too small for alignment and mounting on the slide.

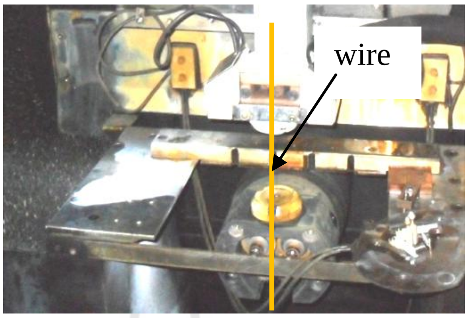


Figure 3.1 The CNC wire-cut machine.

3.1.2 Cleaning and Mounting

After cutting, the specimens were cleaned by Kroll's reagent, a conventional etching solution for titanium (Boyer, 1995). The Kroll's reagent consisted of 2 ml of HF 40% wt, 6 ml of HNO_3 60% wt and 100 ml of water. The Kroll's reagent has removed the wire-cut contamination as shown in Figure 3.2. The time duration of cleaning used at 75 s for completely removes the contamination. Since the burn surface is appeared when the time is longer. The specimen is repeat cleaned by acetone in order to remove grease on the specimen. After all of the cleaning process, each specimen is mounted in the microscope slide with glue. The tolerance of a side view and the face gap width critically take into account. The tolerance geometry is measured by the Dino-lite microscope as shown in Figure 3.3. The example of the mounted specimen is shown in Figure 3.4. The specimen tolerance in this experiment is less than 60 µm. The example of the measurement method is shown in Figure 3.5.

The tolerance of all specimens is identified in Appendix A. The ratio of tolerance should be less than 0.15% and the misalignment should be less than 0.25% of the thickness referred to the Material information society (ASM) standard. The geometry of the tolerance and misalignment is shown in Figure 2.10. Such as in this thesis, CP titanium thickness is 1 mm (1000 µm) so that the gap should be less than 150 µm and the misalignment should be less than 250 µm. so the specimen in this experiment is acceptable referring to the standard.

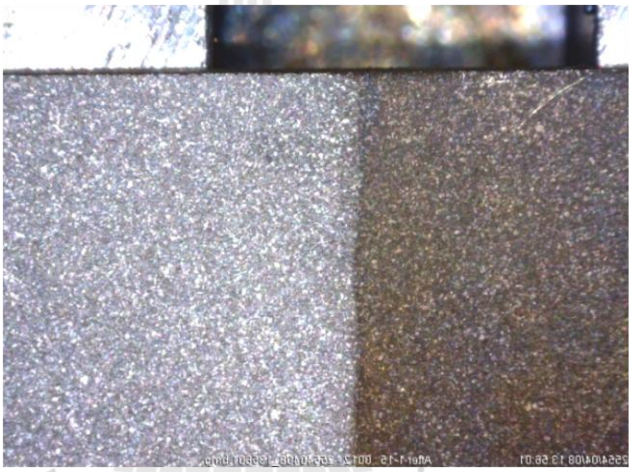


Figure 3.2 The titanium with Kroll's reagent (left) and without Kroll's reagent (right).

Figure 3.3 Dino-lite microscope for gap measurement.

(a) (b)

Figure 3.4 Mount specimen (a) weld profile specimen (b) tensile specimen.

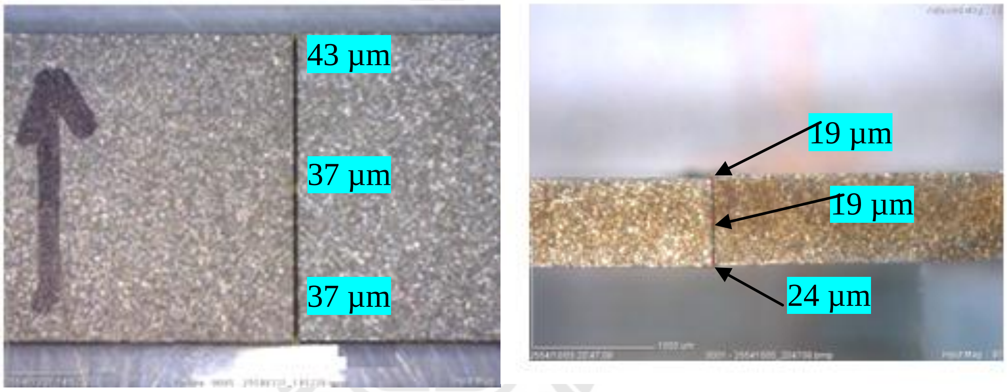


Figure 3.5 Measurement of specimen gap at topview (left) and sideview (right) the top view gap is 43, 37 and 37 µm, the side view gap is 19, 19 and 24 µm.

3.2 Welding equipment

3.2.1 Laser Equipment

Nd:YAG laser is used for welding CP titanium. The laser is manufactured by Z-tech advance technology from United State of America. The laser is a pulsed laser which maximum energy 150 J, power 75 W, pulse duration 0.5-25 ms and wavelength 1.06 µm. The laser workstation is expressed in Figure 3.6. The laser consisted of the microscope and the welding chamber. The microscope is used for observation the welding operation inside the chamber. Moreover, the alignment of the laser beam is accomplished by the microscope.

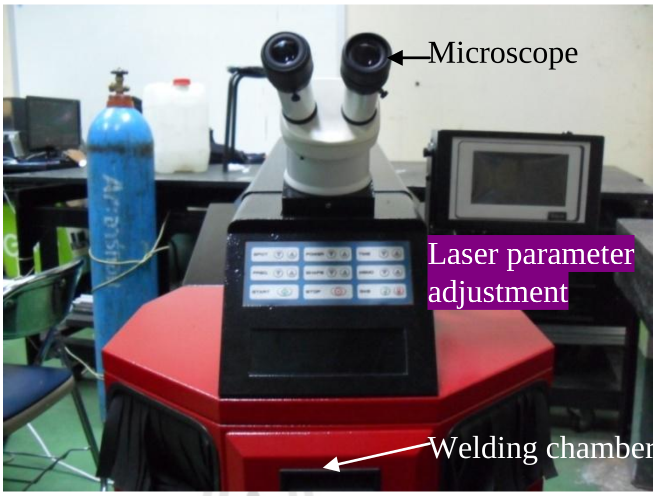


Figure 3.6 Nd:YAG laser welding work station.

3.2.2 Shielding gas

The argon gas is a commercial grade (99.9% purity). The commercial grade of argon is used in the experiment because of the versatile use in industry, convenient supply gas and low cost. The argon gas needs a regulator installation for controlling the gas flow rate. The argon regulator is shown in Figure 3.7. This regulator is a conventional argon regulator which can maximize the argon flow rate about 20 liters/min. At this flow rate, the argon flow rate is not stable. The maximum gas flow rate which is stable is 15 liters/min so this flow rate is applied in the thesis. The amount of gas flow rate is identified by the center of the metal ball.

Figure 3.7 Argon gas flow rate regulator.

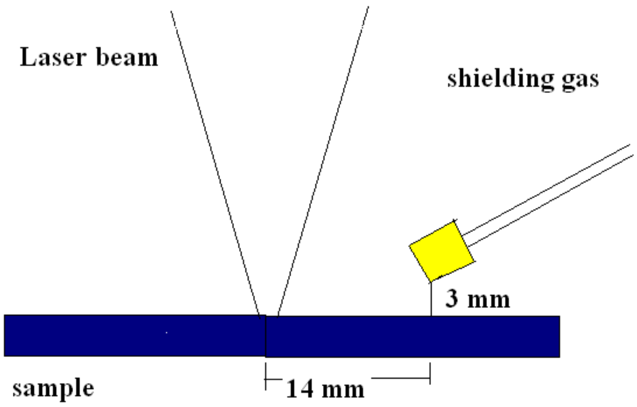
3.2.3 Parameters

The main character of laser welding in this research is the laser power and gas flow rate. The control factors are 1.5 ms pulse duration, 10 Hz repetition rate, nozzle shielding gas geometry and position, gap configuration of the specimens and square pulse shape. The power variations used in this thesis are 2.0, 2.8 and 3.5 kW. The gas flow rates are 0, 5, 10 and 15 liter(s)/min.

3.3 Welding method

3.3.1 Set up

The laser alignment is achieved by using a microscope of the laser workstation. The test laser beam impinges on the test metal for setting. The laser beam can be aligned by the manipulating the focusing lens which located inside the chamber. The L-type crew tool and the mirror are used for alignment. The alignment is time consuming, it achieved when the central of the beam is located in the central of marked sign which is on a microscope eye lens. After alignment, a gas nozzle is set up as shown in Figure 3.8. The shielding gas nozzle is applied in dimension as shown.



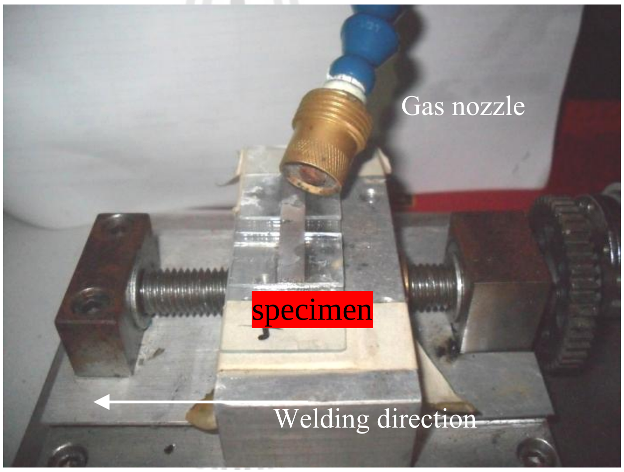


Figure 3.8 Set up of the laser welding.

The jig is the fixture and the basement of placing the specimen above. The figures of the jig are shown in Figure 3.9 and 3.10. The jig was design for compact size in order to possible placing inside the chamber. Moreover set up the depth of the focused laser beam depend on the height of the jig. All specimens are welded on the jig which moving in x-axis direction.

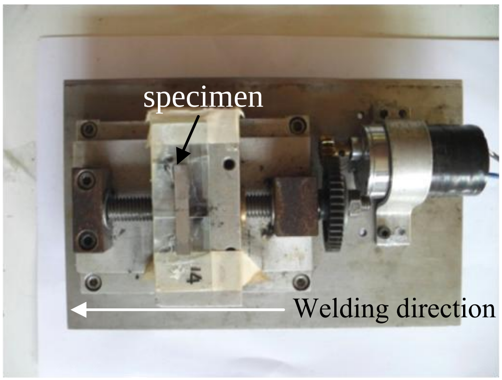


Figure 3.9 A weld profile specimen set up on the jig.

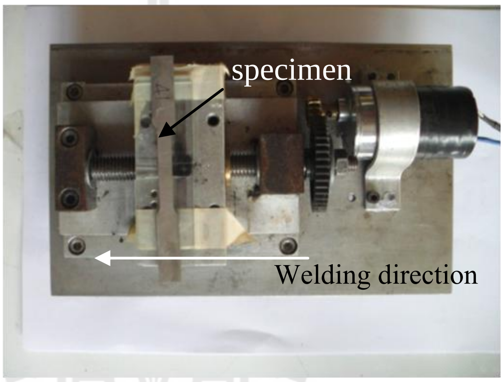


Figure 3.10 A tensile test specimen set up on the jig.

3.3.2 Welding specimen

The welding of specimen is a continuous shot. The welding speed is 0.43 mm/s. The welding speed is low because of the welding repetition rate of laser is 10 Hz. The energy more transfers into titanium because of high interaction time. The beginning starts at the outside of the specimen. The period of applying shielding gas is five second after the applying shot so the starting point is outside the specimen for assuring that a gas shielding cover entirely the welding area. The appearance is observed and stored as a data before the investigation process.

After welding process, the two type specimens are removed from the microscope slides and observed by an optical microscope. The weld profile specimens follow the metallography method and the tensile test specimens follow the tensile test method. The detail of the process is expressed as following.

3.4 Specimen investigation

After the specimen was welded by the given parameters, the investigation is start with the information as following.

3.4.1 Weld profile specimen

Avoiding cracking during the polishing process, the clip is used for clamping the specimen. The clip is set the side view of the specimen perpendicular to the surface. After clamping the specimen, the transparent resin is used for mounting, fixing specimen and protecting the specimen from crack and failure. Another advantage of this resin is an easy observation the side view of the weld. The mounting method of resin is described as First; the mould of the resin which is typically the plastic bottle or PVC pipe is cut by the convenient handle size. Second, the mould is placed on the mirror in order to given the smooth surface after finishing. The mould must be prevented from resin leaking after mounting. Finally, the specimen is aligned in the central of the mould. After that resin which mixes with the hardener mixer smoothly poor to the mould. The solidification time of the resin is about 12 hours. After that period, resin is removed from the mirror and ready achieved for grinding and polishing. The resin mounted weld profile specimen is shown in Figure 3.11.

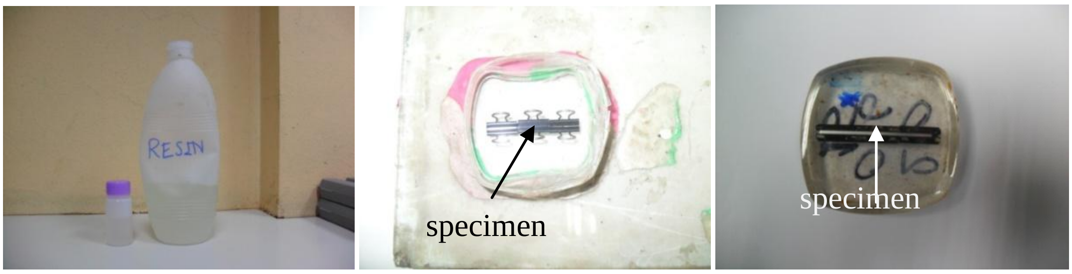
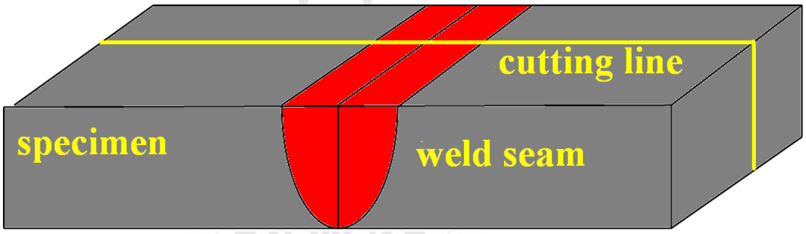
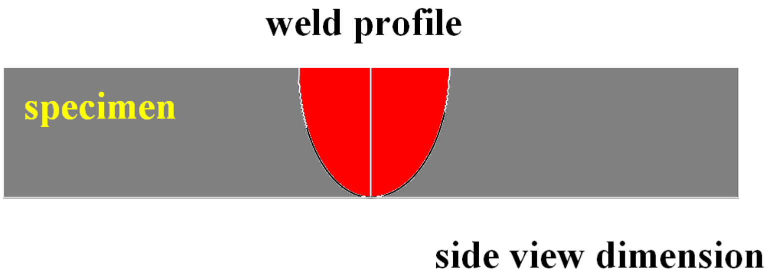


Figure 3.11 The resin mounted specimen for investigation of the weld profile.

After mounting, the specimen was cut in the center as shown in Figure 3.12(a). The weld profile of the specimen can be observed in side view geometry which illustrated in the Figure 3.12(b).



(a)



(b)

Figure 3.12 The weld profile geometry: (a) an isometric dimension (b) a side view dimension.

The mounted specimen is grinded and polished by a SiC paper on the polishing machine as shown in Figure 3.13. The SiC papers have several grits. The number identifies the finest of the paper. The low number is the coarser and high number is finer. The purpose of grinding and polishing is to reveal the weld profile of the laser weld specimen. The grinding and polishing process of the specimen is presented as following.

No. 80 grits: remove the resin on the surface and rapidly remove titanium metal in order to reaching a center of weld spot.

No. 180 grits: remove the scratch of the N0.80 and smoothen the surface of specimen.

No. 400, 600 and 800 grits: smoothen the surface and polish the side view of specimen.

No. 1000 and 1200 grits: polish the surface.

After using SiC paper, the alumina with 0.05 μm bead size is used to polish the surface specimen as mirror grade finishing. The requirement of mirror grade is because of the investigation by optical microscope.

After grinding and polishing, the specimen is etched by Kroll' etchant (2 ml of HF 40% wt, 6 ml 60% wt HNO_3 and 100 ml of water) to reveal the exact weld area and observed by a high magnification microscope.

Figure 3.13 The grinding and polishing machine.

3.4.2 Tensile test

The tensile test specimen is unnecessary mounted with resin. After welding with given parameters, the specimen is removed from the slide and then test with tensile test with universal testing machine. The process of the tensile testing is described as First, the specimen is first gripped on the bottom and then the upper is following by the gripper. The gripping method and applying force direction are expressed in Figure 3.14. This method is applied to avoid the crack during gripping. Perpendicular specimen is set up to assure that uniaxial force is directly applied on the specimen as shown in Figure 3.15. Second, Calibration is very importance for tensile test because the error of the extension length could affect the tensile value. After calibration of the initial length and the force, the specimen is pulled with the constant increment force and detected the force data and the extension length.

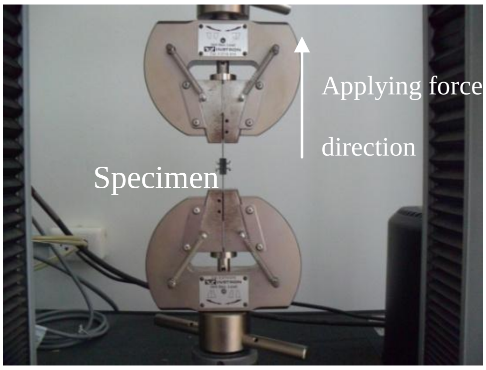


Figure 3.14 Gripping method and force applying direction.

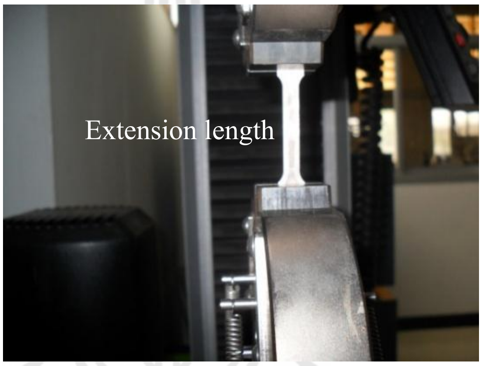


Figure 3.15 The perpendicular setting of specimen for tensile testing.

CHAPTER IV

RESULTS AND DISCUSSIONS

The results of the laser welding in titanium are presented in this chapter. The parameters of the experiment were laser powers and gas flow rates. The laser powers were 2.0, 2.8 and 3.5 kW and the argon flow rates were 0, 5, 10 and 1.5 liter(s)/min. In order to thoroughly investigate; the weld profile and the mechanical test are discussed.

The specimens with a gap within 60 µm were placed on the jig which moving at speed 0.43 mm/s. The laser operated in pulsed mode with 10 Hz repetition rate. The general view of the weld quality is presented in Table 4.1.

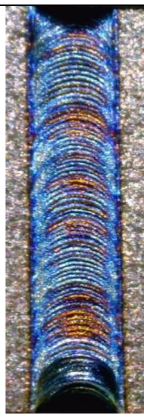
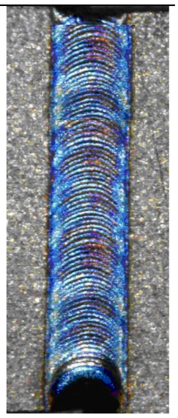
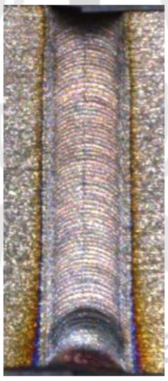
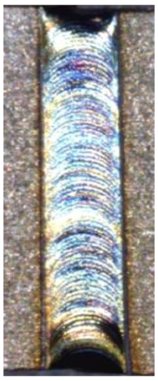
Table 4.1 is the top view of the laser welding in titanium. The columns and the rows of the table express the laser power and the gas flow rate. The results of the welding are described. At power 2.0 kW, the four gas flow rates provide a different weld quality. The color of the weld is blue in zero gas flow rate and brighten as increase the gas flow rate. The same color of the weld is observed at using gas 10 and 15 liters/min. The crack is observed at no gas condition, while the other flow rates are not. This behavior is found at the different laser power. The crack is caused by the oxygen diffusion into the melt pool. From the result, the gas shielding can protect the melt pool from the oxygen diffusion and improve the weld quality. Moreover the power of laser was related to the weld quality. Cracking was lower as increased the power of laser as shown in no gas conditions: 2.0(a), 2.8(a) and 3.5(a). The higher laser power can penetrate into the metal and increased the joint strength.

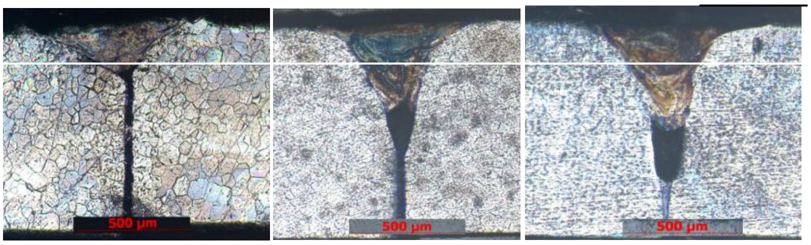
The side view metallography of the laser welding is presented in Figure 4.1. The laser power was fixed at 2.0 kW and the gas flow rates were 0, 10 and 15 liters/min. The comparison of the depth was expressed by the white cross line. In Figure 4.1(a), the zero gas flow rate, the depth was shallow. As the presence of the argon gas, the weld depth was obviously improved. The laser welding mode transition was occurred. The conduction mode transfers to the keyhole mode. The laser power density was reduced by the presence of the plasma (Hansen and Duley, 1994) so the weld penetration is shallow. As the shielding gas was applied to the specimen, the plasma was suppressed and move away from the welding area. Therefore; the incident laser power density was increased resulting in the weld depth was improved as shown in Figure 4.1(b) and (c).

When the laser power was increased, 3.5 kW, and the argon gas flow rated was 5 liters/min. The porosity was observed in the weld as shown in Figure 4.2. The porosity was caused by the air trapping during the transition of metal state from liquid to solid. The presence of the gas suppressed the plasma and increased the laser absorption and the excessive power density is applied on the specimen.

As increased the argon flow rate to 15 liters/min, the splatter is observed as shown in Figure 4.3. The splatter weld was caused by the excessive gas flow rate. The argon expelled the hot liquid metal and immediately solidified. The metal loss was also observed.

Table 4.1 The results of welding tensile specimen in top view directions.

Gas flow rate liters/min / Laser power (kW)	0	5	10	15
2.0	 (a)	 (b)	 (c)	 (d)
2.8	 (a)	 (b)	 (c)	 (d)
3.5	 (a)	 (b)	 (c)	 (d)



(a) (b) (c)

Figure 4.1 The weld profile specimen of 2.0 kW by gas flow rate variation (a) no gas condition (b) 10 liters/min and (c) 15 liters/min.

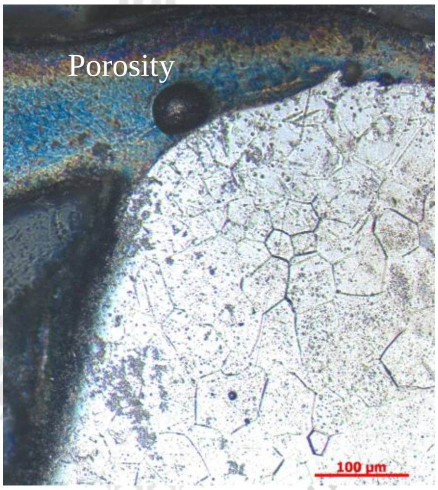


Figure 4.2 Porosity in weld profile specimen with 3.5 kW and 5 liters/min gas flow rate.

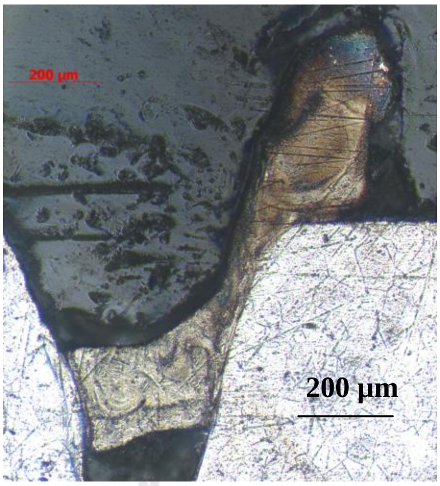


Figure 4.3 The splatter welded titanium with 3.5 kW power at 15 liters/min gas flow rate.

The mechanical test in this thesis is tensile strength. The tensile strength is the maximum value of the stress applied on the specimen in transverse direction. The speed of the test was 0.5 mm/min. The tensile strength is represented the strength of the welding joint. The result of the tensile test is represented in the Figure 4.4 and the raw data are shown in Appendix B.

Figure 4.4 presents the relationship between the tensile strength and the variation of the gas flow rate at given laser power. The unit of the tensile strength is mega pascal (MPa). The laser powers of the experiment are 2.0, 2.8 and 3.5 kW. Each laser power parameters contain the variation of the gas flow rate; 0, 5, 10 and 15 liter(s)/min. The result of the tensile strength is presented as following

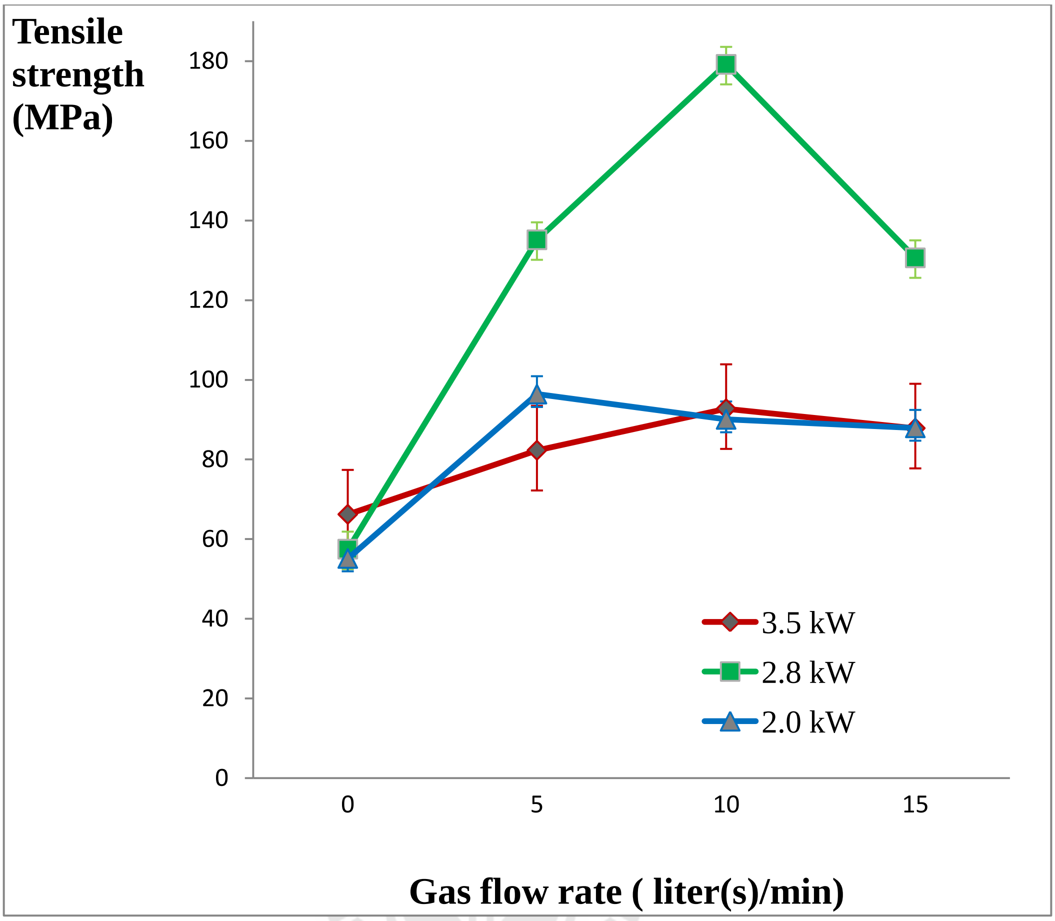


Figure 4.4 Tensile strength of laser welding in titanium with power and shielding gas variation.

The triangle spot represent the tensile strength of 2.0 kW laser power. The tensile strength was increased and then saturated as the gas flow rate increased. This behavior was also observed in the other laser powers, 2.8 and 3.5 kW. The increase of tensile strength was caused by the presence of the shielding gas. The shielding gas expelled the oxygen from the melt pool resulting in no crack and suppressed the plasma which created during the welding. This plasma could absorb and attenuate the incident laser beam resulting in a low tensile strength. The shielding gas applying improved the tensile strength of the laser welding. Moreover the plasma which was attached near the surface of the workpiece increased the coupling of the laser beam (Duley, 1999). With appropriate adjustment of shielding gas, the plasma was covered at the surface of the workpiece, increased the coupling of laser beam and the incident power density was increased. The result of the appropriated shielding gas was the maximum tensile strength at the power 2.8 kW at flow rate 10 liters/min. When increasing the gas flow rate, the incomplete weld was observed on the weld as shown in Figure 4.5. The incomplete weld was created by the excessive shielding gas. The argon expelled the coupling plasma which on the surface resulting in decreasing of incident laser power density. The excessive shielding gas decreased the tensile strength in 2.8 kW at 15 liters/min. The excessive power density, 3.5 kW, could explode the titanium surface. Even though applying the gas flow rate, the result of the weld is not acceptable. The porosity is occurred at lower flow rate, 5 liters/min (the porosity weld is shown in Figure 4.2) and the weld splatter is observed at 15 liters/min (the splatter weld is shown in Figure 4.3). The result of the poor quality weld was also observed in the tensile strength. The tensile strength of the 3.5 kW was approximately equal to the 2.0 kW even though applying a high power laser. The laser power and the shielding gas flow rate must be proper adjusted to optimize laser welding in titanium.

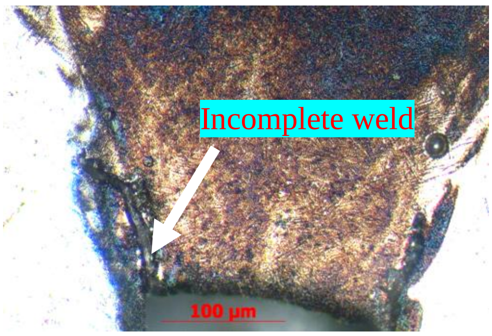


Figure 4.5 The weld profile specimen of 2.8 kW and 15 liters/min.

CHAPTER V

CONCLUSIONS

In this thesis, the argon gas was used for shielding overall the laser welding in titanium process. The parameters of the experiment were the Nd:YAG laser power and the gas flow rate. The powers of the laser were 2.0, 2.8 and 3.5 kW and the gas flow rates are 0, 5, 10 and 15 liter(s)/min. The results of the welding were investigated by optical microscope, metallography and the tensile test. The results were summarized in the following.

First, the argon shielding gas expelled oxygen and protected the melt pool from oxidation. The oxidation caused a cracking weld. Moreover the shielding gas changed the color of the weld. The zero flow rate weld had the darken color while the brighten weld obtained by presenting argon. As increasing the gas flow rate, the color of the weld was not changed.

Next, the shielding gas suppressed the plasma which attenuated the incident laser beam. Therefore the penetration was improved and a mode transition from conduction to keyhole mode was occurred. The shielding gas in an excessive power density caused a poor weld quality. The porosity and the weld splatter were observed. Furthermore, the tensile strength was increased and then saturated by presence of the argon. The proper shielding gas limited the plasma dynamic and increased the coupling of laser beam on the surface of titanium. The result was shown in the maximum tensile strength at 2.8 kW with 10 liters/min argon flow rate. The excessive gas flow rate eliminated the surface plasma. The incomplete weld was created and the tensile strength was decreased.

In addition, controlling the result of laser welding process is complicated. The laser parameters were adjusted by the weld result. The control parameters of this experiment were spot diameter at 0.6 mm, welding speed at 0.43 mm/s, the repetition rate at 10 Hz and a fixed geometry of nozzle gas. The further study should be the higher flow rate in 3.5 kW power and the varieties of the laser power between 2.8 and 3.5 kW.

REFERENCES

REFERENCES

Berger, A. and Zive, D. (2008). [On-line] Pacemaker Available: http://www.health central.com/ency/408/imagepages/19566.html.

Boyer, R. (1995). Titanium and Titanium alloys. In Kiepura, R and Sanders, B (eds.). **ASM Handbook. Volume 9 Metallography and Microstuctures.** (6th ed.). United State of America (USA): ASM International.

Casalino, G., Curcio F., Memola, F., and Minutolo, C. (2005). Investigation on Ti6Al4V laser welding using statistical and Taguchi approaches, **J. Mater. Process. Tech.** 167: 422-428.

Choubey, A., Basu, B., and Balasubramaniam, R. (2005). Electrochemical behavior of Ti-Based alloys in simulated human body fluid environment. **Trends Biomater. Artif. Organs** 18: 64-72.

Cowen, R. (27 September 1997). A gamma-ray burst's enduring fireball. **Science News.** 152: 197.

Dawes C. (1992). **Laser welding: A practical guide.** Cambridge, England: Abrington Publishing.

Ducharme, R.F., Kapadia, P. and Dowdene, J. (1992). A mathematical model of the defocusing of the laser light above a workpiece in laser material processing. **Proceeding ICALEO'** 92: 187.

Duley W. (1999). **Laser welding.** Canada: John Wiley & sons, Inc.

Fieret, J., Terry. M. J., and Ward, B. A. (1986). Aerodynamic interactions during laser cutting. In: Duley W. W., editor. **Proceedings of the SPIE conference on laser processing fundamentals, applications and systems engineering** 668: 53.

Hanson, F. and Duley, W (1994). Attenuation of laser radiation by particles during laser material processing. **J. Laser Appl.** 6: 137.

Heidecker, E., Schäfer, J. H., Uhlenbusch J. and Viöl, W. (1988). Time-resolved study of a laser-induced surface plasma by means of a beam-deflection technique. **J. Appl. Phys.** 64: 2291.

Havrilla D. (March 1990). **Laser welding of saw blades.** (n.p.): Rofin sinar Inc special Publication.

Ion, J. (2005). **Laser processing of engineering materials principles, procedure and industrial application.** Norfolk: Elsevier.

Kannatey-Asibu, E., Jr (2009). **Principle of Laser Materials Processing.** New Jersey: John Wiley & son.

Larson N. E. and Meredish W. F. (1990). **Shielding gas selection manual,** Union Carbide Industry Gases Technology Corp.: 10.

Laserstartechnology corporation, (2012). **Benefits of Laser Welding Technology** [On-line] Available: http://www.laserstar.net/welding-products/manual-weld.cfm.

Lima, M. S. F. (2005). Laser beam welding of titanium nitride coated titanium using pulse shaping. **Mater. Res.** 8: 323-328.

Liu J., Watanabe, I., Yoshida, K. and Atsuta, M. (2001). Joint strength of laser-welded titanium. **J. Dent. Mater.** 18: 143-148.

Luttke H. (Dec 1987). Use of laser and electron beam in seam welding of gear and engine parts. Seminar on **"Application of laser processing in automobile fabrication and releated industries".** Cambridge: The welding institute.

Matsunawa A. (1990). Physical Phenomena and their interpretation in laser material processing. **Proceeding ICALEO** 90, SPIE 1601: 313.

Mazumder, J. (1997). Laser-Beam Welding. In Davis. J, Ferjutz K, Wheaton, N and Woods M. (eds.). **ASM Handbook. Volume 6 Welding, Brazing, and Soldering** (4th ed.). USA: ASM International.

Ming, G. Xiaoyan, Z. and Qianwu, H. (2007). Effect of gas shielding parameters on weld penetration of CO2 laser- TIG hybrid welding. **J. Mater Process. Tech.** 184: 177-183

Miyamoto, I. and Maruo, H. (1992). Spatial and temporal characteristics of laser-induced plasma in CO_2 laser welding. **Proceeding LAMP**, OSAKA 311.

Notenboom G. (Nov 1982). Laser spot welding in electronics industry. Seminar on **Practical application of lasers in manufacturing industry.** Coventry: The welding institute.

Qi, Y., Deng, J., Hong, Q., and Zeng, L. (2000). Electron beam welding, laser beam welding and gas tungsten arc welding of titanium sheet. **J. Mater. Sci. Eng., A** 280: 177-181.

Ready J. (1997). **Industrial applications of lasers** (2nd ed.). USA: Academic Press.

Schwartz M. M. (1979). **Metallurgical Joining Manual** (n.p.): Mc Graw-Hill.

Shewell, J. R. (Jun 1977). Design for laser beam welding. **Weld Des. Fabr.** P. 106.

Steen, W. M. (2003). **Laser material processing** (3rd ed.). New York: Springer-Verlag.

Togoya, T., and Shinotaki, T. (1999). Introduction to laser welding in dentistry. **Quint. Dent. Tech**. 24: 740-749.

Ucellini, J. (October, 2003). **The right cutting and welding tips** [On-line] Available: www.thefabricator.com/article/consumables/identifying-the-right-cutting-and welding-tips.html.

Virein A., Kumar J., and Yadlapalli D. (2006). **World Laser Machine Tools Markets** [On-line] Available: www. Research Analyst-Industrial Automation and Process Control.com.

Wang R., and Welsch, G. E. (1995). Joining titanium materials with tungsten inert gas welding, laser welding, and infrared brazing. **J. Prosthet. Dent**. 74: 521-530.

Wang, S. H., Wei, M. D., and Tsay, L. W. (2003). Tensile properties of LBW welds in Ti–6Al–4V alloy at evaluated temperatures below 450 ºC, **Mater. Lett.** 57: 1815-1823.

Watanabe, I. and Topham, D. (2006). Laser welding of cast titanium and dental alloys using argon shielding. **J. Prosthodontics.** V15: 102-107.

Welsh, G., Boyer, R. and Collings E.W. (1994). **Materials Properties Handbook: Titanium alloys.** USA: ASM International.

William D. F. (1998). **Titanium and titanium alloys.** Boca Raton: CRC Press.

Yamagishi, T., Ito, M. and Oshida, Y. (1993). Tensile strength and elongation of laser-welded titanium. **J. Dent. Res.** 72: 13.

APPENDICES

APPENDIX A

GAP OF THE SPECIMENS

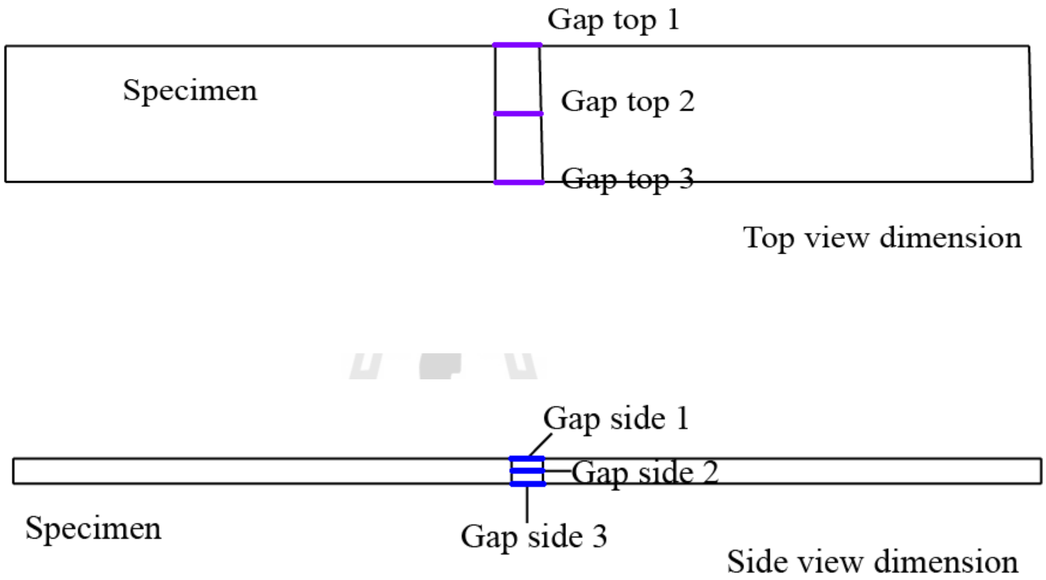


Figure A.1 The geometry of the measurement of the specimen gap.

Table A.1 The table of the weld profile specimen gap.

Conditions Power(kW)/gas flow rate (liter(s)/min)	Specimen name	Gap (µm)					
		side 1	side 2	side 3	top 1	top 2	top 3
2.0/0	1	37	31	49	31	37	56
2.0/5	13	35	41	41	43	37	37
2.0/10	18	37	37	55	49	31	31
2.0/15	11	19	19	24	43	37	37
2.8/0	7	43	37	37	37	43	43
2.8/5	21	49	49	50	49	43	49
2.8/10	8	25	31	37	51	50	43
2.8/15	4	28	31	31	49	49	43
3.5/0	27	19	12	18	43	43	43
3.5/5	20	31	31	37	43	43	43
3.5/10	9	31	25	31	61	43	37
3.5/15	10	49	43	43	43	37	43
Spare specimens	16	23	24	37	61	55	49
	17	43	49	61	55	43	43
	19	6	6	18	43	43	49
	14	67	56	56	61	43	43
	22	49	49	49	55	43	43
	23	74	74	61	61	43	43
	24	43	49	49	43	49	49
	2	92	74	67	51	37	43
	3	24	24	37	50	43	43
	5	50	34	30	55	48	43
	12	43	43	49	49	43	37
	15	37	37	37	37	37	37

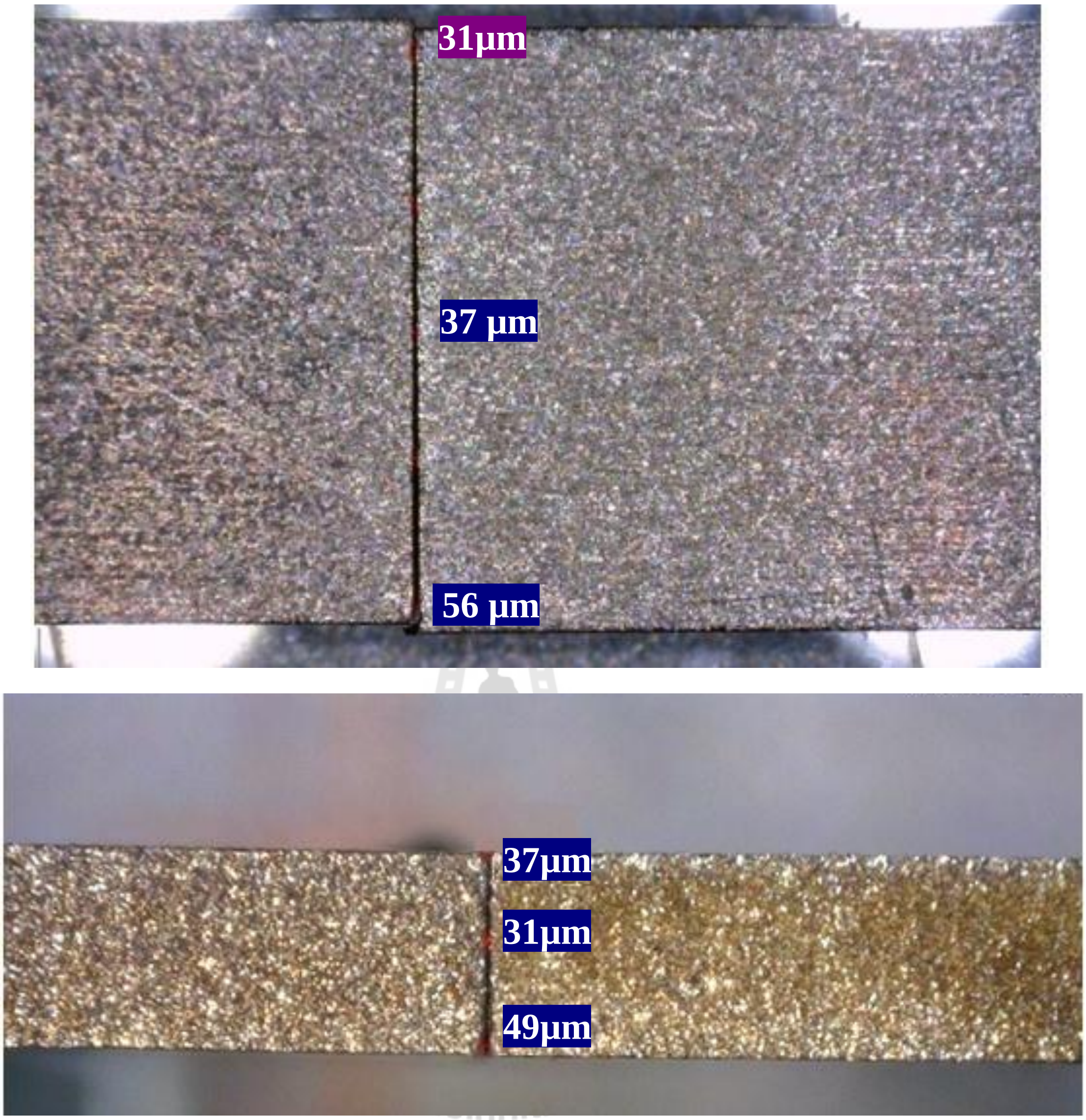


Figure A.2 The weld profile specimen gap measurement.

Table A.2 The tensile specimen gap.

Conditions) (power/gas flow rate)	Specimen no.	Sideview Recommend	Topview (µm)				
			1	2	3	4	5
2.0/ 0	1	ok	33	33	33	33	33
2.0/ 0	19	ok	44	44	44	44	44
2.0/ 0	23	ok	44	44	44	44	44
2.0/ 5	2	ok	44	44	33	44	44
2.0/ 5	18	ok	44	44	44	33	33
2.0/ 5	21	ok	44	44	44	44	44
2.0/ 10	3	ok	55	44	44	44	44
2.0/ 10	16	ok	55	55	44	44	55
2.0/ 10	21	ok	44	44	44	44	44
2.0/ 15	4	ok	44	44	44	44	44
2.0/ 15	22	ok	55	44	44	44	55
2.0/ 15	15	ok	55	44	44	44	55
2.8/ 0	5	ok	55	55	55	55	57
2.8/ 0	24	ok	33	44	44	55	57
2.8/ 0	13	ok	44	44	44	55	52
2.8/ 5	6	ok	44	44	44	55	44
2.8/ 5	14	ok	65	44	44	44	44
2.8/ 5	17	ok	55	55	49	55	55
2.8/ 10	7	ok	55	44	44	44	55
2.8/ 10	20	ok	56	55	55	77	58
2.8/ 10	24	ok	55	55	44	55	55
2.8/ 15	8	ok	55	44	44	44	44
2.8/ 15	25	ok	44	44	44	55	44
2.8/ 15	29	ok	55	55	44	44	55
3.5/ 0	9	ok	44	55	44	44	55
3.5/ 0	30	ok	44	55	44	55	55
3.5/ 0	33	ok	44	55	44	55	55
3.5/ 5	10	ok	44	44	44	33	44
3.5/ 0	31	ok	44	55	55	55	44
3.5/ 0	26	ok	33	55	44	44	44
3.5/ 10	11	ok	33	44	44	44	55
3.5/ 10	28	ok	44	44	44	44	44
3.5/ 10	27	ok	44	55	55	55	44
3.5/ 15	12	ok	55	44	44	44	33
3.5/ 15	32	ok	44	44	44	44	44
3.5/ 15	33	ok	55	44	44	44	44

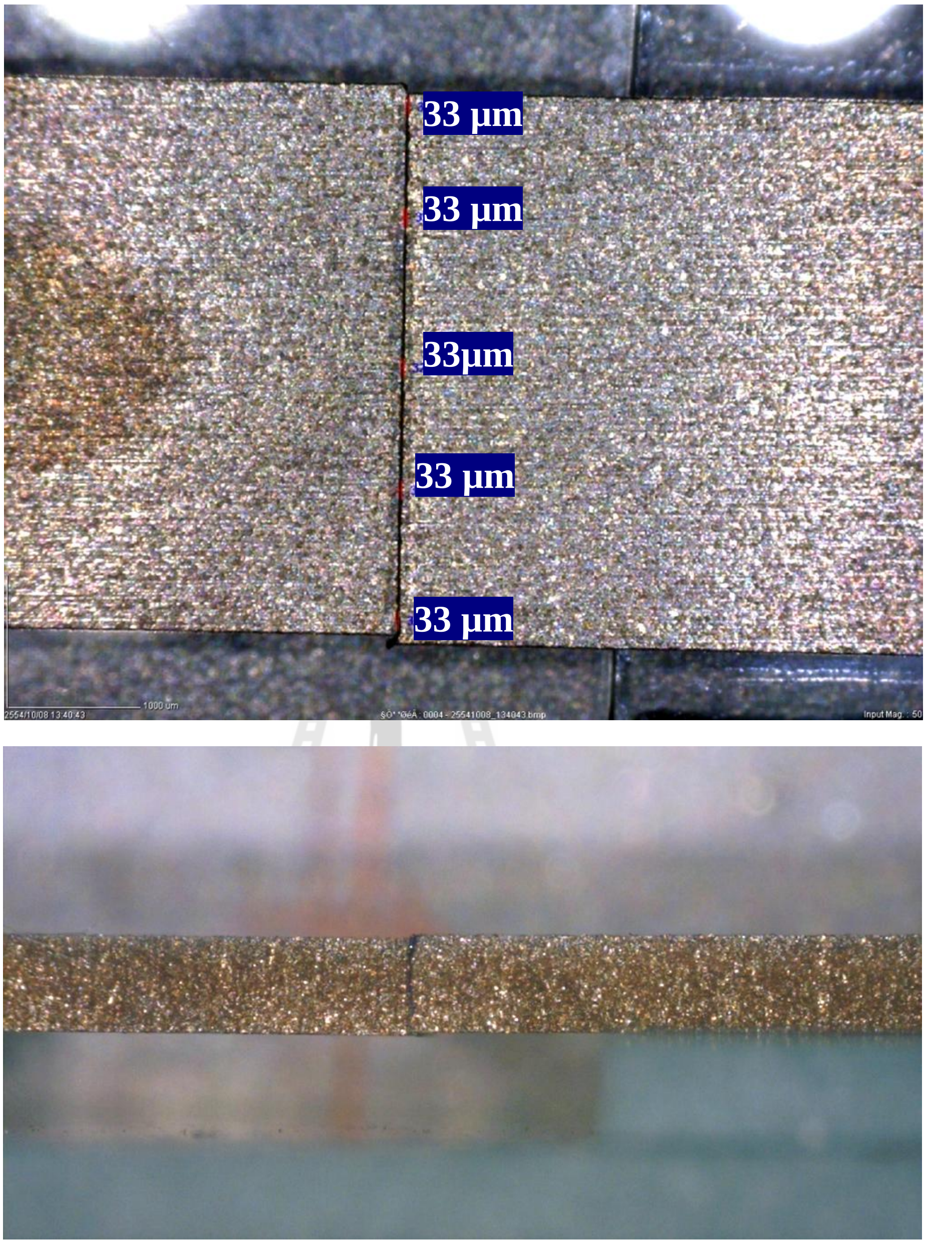


Figure A.3 The tensile test specimen gap measurement.

APPENDIX B

TENSILE STRENGTH RAW DATA

Table B.1 The raw data of tensile strength of laser welding in titanium with three times repetitions.

Conditions Power (kW) / gas (liter(s)/min)	Tensile strength (MPa) Specimens 1	2	3	Average tensile strength (MPa)	Standard Deviation (S.D.)
2.0/0	54.6024	52.7528	58.1312	55.16213	2.231109
2.0/5	93.18221	100.9115	95.14723	96.41365	3.280076
2.0/10	89.24743	88.30342	92.65324	90.06803	1.868203
2.0/15	89.69112	86.3803	87.77136	87.94759	1.357369
2.8 /0	42.16013	56.12347	61.88657	53.39006	8.281979
2.8/5	134.9846	130.1274	140.3355	135.1492	4.169043
2.8/10	182.6567	180.4518	174.4613	179.1899	3.462686
2.8/15	135.607	130.1496	126.1041	130.6202	3.893787
3.5/0	65.17835	77.38744	56.14727	66.23769	8.703558
3.5/5	88.67764	80.14724	78.12343	82.3161	4.573536
3.5/10	89.31268	92.14511	96.7759	92.74456	3.07619
3.5/15	90.65678	88.77142	84.14783	87.85868	2.734524

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