ABSTRACT

PALEOCRASSAS, ALEXANDER GRANT. Feasibility Investigation of Laser Welding Aluminum Alloy 7075-T6 through the use of a 300 W, Single-Mode, Ytterbium Fiber Optic Laser. (Under the direction of Dr. Juei Feng Tu)

Aluminum alloys are important structural materials because of their high strength to weight ratio. Unfortunately, due to their high reflectivity and complexity in heat treatment, aluminum alloys are some of the hardest metals to be laser welded successfully and very high laser power is usually required. In this study, the feasibility of using a 300 W, Single-Mode, Ytterbium Fiber Optic Laser for aluminum welding is investigated. The objective is to explore an application area with low power and low welding speed. As the fiber laser offers much better beam quality (M^2 less than 1.05), the results show that, with proper control of welding parameters, the success of aluminum welding can be achieved at considerably low laser power with minimal formation of typical welding defects (porosity, cracking etc.). However, the focusing becomes highly critical as exceeding a certain power density can lead to defects such as blowholes and porosity. The deepest penetration achieved was just over 1 mm at 300W and 2 mm/sec. Other welding processes achieve about three to four times as much penetration at the expense of seven times more power. Further development of this process can lead to a more efficient use of power.

FEASIBILITY INVESTIGATION OF LASER WELDING ALUMINUM ALLOY 7075-T6
THROUGH THE USE OF A 300 W, SINGLE-MODE, YTTERBIUM FIBER OPTIC LASER

By

ALEXANDER GRANT PALEOCRASSAS

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

MECHANICAL AND AEROSPACE ENGINEERING

Raleigh, NC
2005

APPROVED BY:

Dr. Jeffrey W. Eischen
Advisory Committee Member

Dr. Fen Wu
Advisory Committee Member

Dr. Juei F. Tu
Advisory Committee Chairman

*To my parents, for all the support and guidance they have given me and the values they
have taught me.*

BIOGRAPHY

Alexander Paleocrassas was born on August 31st, 1980. He grew up in Athens, Greece and attended Greek public school until freshman year in high school. He then transferred to an American/International high school, ACS, (American Community School of Athens), where he spent his sophomore, junior and senior years.

The fact that his brother and sister were both alumni and the reputation of the engineering school made him decide to attend NC State University. In May 2003, he received his Bachelor of Science in Aerospace Engineering and then enrolled in the Mechatronics Master of Science program. He is going to receive his Master of Science in Mechanical Engineering in August of 2005.

ACKNOWLEDGEMENTS

I would first like to thank Dr. Tu for guiding me through this process and for being a great mentor. I would also like to thank my committee members Dr. Eischen and Dr. Wu for passing on their knowledge to me, even when their time was short. I would like to thank Dr. Rabiei for providing access to her lab and also for explaining the aluminum polishing process to me. I would like to thank Dr. Sun for providing specimens for me to experiment with, and also giving me a tour of his laboratory. Also, I would like to thank Dr. Park for providing me with data for the verification of the penetration model and the additional insight he gave me in laser welding.

I would like to thank Jason Dilwith, Ryan Dennis, and Ray Harp for contributing to the lab setup. I want to thank Travis Blalock for showing and helping me with the aluminum polishing process and Nick Bruno for machining all those specimens for me. I also want to thank Kara Folkert for taking the time to obtain a surface profile of my welds.

TABLE OF CONTENTS

LIST OF TABLES	vii
LIST OF FIGURES	viii
1 INTRODUCTION	1
2 PROBLEM STATEMENT	1
3 HYPOTHESIS	2
4 LITERATURE REVIEW	2
4.1 Aluminum Alloys	2
4.2 Conventional Welding of Aluminum Alloys	4
4.3 Laser Welding	5
4.3.1 Laser Welding of Aluminum Alloys	7
4.4 Weld Quality and Defects	8
4.4.1 Fusion Zone (FZ)	8
4.4.2 Partially Melted Zone (PMZ)	9
4.4.3 Heat Affected Zone (HAZ)	10
4.4.4 Porosity	11
4.4.5 Hot Cracking	13
4.4.6 Oxide Inclusions	15
4.4.7 Loss of alloying elements	15
4.4.8 Hardness	18
4.4.9 Tensile strength	18
4.4.10 Fatiguestrength	19
4.5 Fiber Laser Characteristics	20
5 SPECIFIC RESEARCH PROBLEMS	20
6 APPROACHES	21
6.1 Theoretical Modeling	21
6.2 Process Design	21
6.3 Experimental Investigation	22
6.4 Data Analysis	22
7 IDEALIZED WELDING MODEL	22

8	EXPERIMENTAL APPARATUS	28
9	EXPERIMENTAL PROCEDURE	34
	9.1 Beam profile	34
	9.2 Bead-on Welding.....	37
	9.2.1 Location of Smallest Focusing Spot.....	37
	9.2.2 Determination of Experimental Welding Parameters	38
	9.2.3 Final Experimentation with Selected Welding Parameters.....	39
	9.2.4 Sample Preparation and Examination	41
	9.2.5 Aluminum Polishing	42
10	RESULTS AND DISCUSSION.....	42
	10.1 Beam Profile	42
	10.2 Bead-on Welding	44
	10.2.1 Penetration and weld quality.....	45
	10.2.2 Welding efficiency.....	57
	10.2.3 A Look at the Microstructure.....	60
11	CONCLUSIONS	62
12	FUTURE WORK.....	63
13	REFERENCES	66
14	APPENDICES	70
	14.1 MATLAB Modeling Code.....	70
	14.1.1 Aluminum Alloy 7075-T6 Penetration Model.....	70
	14.1.2 Temperature Distribution Model	71
	14.1.3 SUS 304 Penetration Model.....	72
	14.1.4 Beam Profile	73
	14.2 Cross-Sections Welded at 80% and 90% Power.....	75
	14.2.1 90% Power	75
	14.2.2 80% Power	77

LIST OF TABLES

Table 9.1: Half weld lengths for each power setting	36
Table 10.1: Maximum Penetration for Every Welding Speed at 100% Power	46
Table 10.2: Maximum Penetration for Every Welding Speed at 90% Power	55
Table 10.3: Maximum Penetration for Every Welding Speed at 80% Power	56

LIST OF FIGURES

Figure 4.1: Schematic of Keyhole Welding (Lankalapalli, Tu, <i>et al.</i> , 1996).....	7
Figure 7.1: Keyhole Profile (Lankalapalli, Tu, <i>et al.</i> , 1996)	23
Figure 7.2: Variation of Penetration with Change in Péclet Number	25
Figure 7.3: Melting Point Isotherms of SUS 304 Steel @ Péclet = 1	27
Figure 7.4: Theoretical vs. Experimental Penetration in SUS 304.	27
Figure 8.1: 300 W Ytterbium, Single-Mode Fiber Laser Power Unit	28
Figure 8.2: XY Linear Motors	29
Figure 8.3: Galil Motion Control	29
Figure 8.4: dSPACE 4.0 Data Acquisition System.....	30
Figure 8.5: Beam Expander and Gradium Lens Setup	31
Figure 8.6: Collimator with Optical Fiber Coming from Laser Power Unit	32
Figure 8.7: Zeiss Inverted Microscope	33
Figure 8.8: XYZ Micrometer Linear Stages.....	34
Figure 9.1: Beam Profile Experimental Setup	36
Figure 9.2: Experimental Setup	38
Figure 9.3: Welding Perpendicular to the Incline.....	39
Figure 9.4: Inclined Fixtures.....	40
Figure 9.5: Bead-on Welding at 80% Power and 4 mm/s Welding Speed	41
Figure 10.1: Variation of Spot radius Within the Depth of Focus.....	43
Figure 10.2: Maximum Output Power Density Within the Depth of Focus.....	44
Figure 10.3: Penetration Values at Different Speeds at 100% Power	46
Figure 10.4: Weld cross-sections for 6 mm/s, at 100% Power.....	47
Figure 10.5: Weld cross-sections for 5 mm/s, at 100% Power.....	49
Figure 10.6: Weld cross-sections for 4 mm/s, at 100% Power.....	50
Figure 10.7: Weld cross-sections for 3 mm/s, at 100% Power.....	51
Figure 10.8: Weld cross-sections for 2 mm/s, at 100% Power.....	52
Figure 10.9: 100% Power Compared with Higher Flow Rate.....	53
Figure 10.10: Resulting Welds when using Higher Shielding Gas Flow Rate.....	54

Figure 10.11: Penetration Values at Different Speeds at 90% Power	55
Figure 10.12: Penetration Values at Different Speeds at 80% Power	56
Figure 10.13: Weld Energy per Length as Fluence per Length Increases	58
Figure 10.14: Comparison Between 2 mm/s Welds with Different Flow Rates ...	59
Figure 10.15: Base Material Microstructure at 1600x Magnification	60
Figure 10.16: Microstructure of Deepest Weld at 1600x Magnification.....	61
Figure 10.17: Microstructure of Weld with Defects at 400x Magnification	62
Figure 14.1: Weld cross-sections for 2 mm/s, at 90% Power	75
Figure 14.2: Weld cross-sections for 3 mm/s, at 90% Power	75
Figure 14.3: Weld cross-sections for 4 mm/s, at 90% Power	76
Figure 14.4: Weld cross-sections for 5 mm/s, at 90% Power	76
Figure 14.5: Weld cross-sections for 6 mm/s, at 90% Power	77
Figure 14.6: Weld cross-sections for 2 mm/s, at 80% Power	77
Figure 14.7: Weld cross-sections for 3 mm/s, at 80% Power	78
Figure 14.8: Weld cross-sections for 4 mm/s, at 80% Power	78
Figure 14.9: Weld cross-sections for 5 mm/s, at 80% Power	79
Figure 14.10: Weld cross-sections for 6 mm/s, at 80% Power	79

1 INTRODUCTION

Aluminum alloys are very popular in the industrial world as structural materials, mainly due to their high strength to weight ratio. The automobile and aircraft industries are two examples where aluminum alloys are definitely the materials of choice. Especially in the aircraft industry, it is very important to reduce the weight of airplanes as much as possible. However, despite the good strength and elastic characteristics aluminum alloys have, they are subject to fatigue failure, as are most materials. After several thousand flights, fatigue-induced cracks start to appear on aircraft components and propagate to critical lengths which may result in catastrophic failure unless they are repaired. Hence, when aircraft parts have cracks that surpass a certain critical length, they are replaced or at best repaired by lightweight composite patches, which can extend the part's fatigue life. Replacing parts every so often can be very costly and the composite patches have had limited success in increasing the fatigue life. Another method that is being considered for crack repair is fusion (welding). The challenge is that aluminum has been known to be one of the hardest metals to weld successfully. Some of the factors affecting the welding quality of aluminum alloys include different kinds of porosity formation, hot tearing, solidification cracking, oxide inclusions and loss of alloying elements.

2 PROBLEM STATEMENT

Laser welding offers several advantages over conventional welding; however, overcoming some of the problems associated with laser welding is not trivial. Therefore, it is of interest to develop an economical and efficient aluminum laser welding process that will not only create welds with adequate penetration, but will also ensure minimal to no defects.

3 HYPOTHESIS

A fiber optic laser can be used to create high quality welds in heat-treatable aluminum (7075-T6). In addition, with its excellent beam quality and relatively short wavelength (compared to CO₂ lasers), the fiber optic laser can achieve similar weld depths at considerably lower power.

4 LITERATURE REVIEW

In this section, the related aspects of laser welding aluminum are discussed. Initially, aluminum alloys and their material properties are discussed, in order to develop a good understanding of their behavior under certain conditions (i.e. rapid heating by a laser). The next section describes what different aluminum welding techniques exist today, listing advantages and disadvantages between conventional (MIG, TIG, etc.) and laser (CO₂ and Nd:YAG) welding. Laser welding of aluminum is then discussed in more detail, to identify current processes, results and obstacles (defects in welds, etc.). Finally, the characteristics of fiber lasers are discussed and their advantages over traditional lasers.

4.1 Aluminum Alloys

Aluminum alloys are light-weight, have relatively high strength, retain good ductility at subzero temperatures, have high resistance to corrosion, and are non-toxic. They have a melting range between 482 and 660 °C, depending upon the alloy. There is discoloration in the alloys when heated to the welding temperature range, they have high electrical and thermal conductivity (compared to steel) and they rapidly develop oxide films when exposed to air. Some other important properties of aluminum alloys include high reflectivity, hydrogen solubility, high thermal expansion and solidification shrinkage (Mandal, 2002).

There are international standards based on which aluminum alloys are designated. These alloys are distinguished by a four-digit number, which is followed by a temper designation code. The first digit corresponds to the principal alloying constituent(s). The second digit corresponds to variations of the initial alloy. The third and fourth digits correspond to individual alloy variations. Finally the temper designation code corresponds to different strengthening techniques (ibid).

1xxx—Pure Al (99.00 % or greater)
2xxx—Al-Cu Alloys
3xxx—Al-Mn Alloys
4xxx—Al-Si Alloys
5xxx—Al-Mg Alloys
6xxx—Al-Mg-Si Alloys
7xxx—Al-Zn Alloys
8xxx—Al + Other Elements
9xxx—Unused Series

Temper Designation System:

F → As fabricated
O → Annealed
H → Strain-Hardened
W → Solution heat-treated
T → Thermally treated to produce stable tempers other than F, O, or H

Subdivisions of T Temper, thermally treated:

T1 → Naturally aged after cooling from an elevated temperature shaping process, such as extruding.
T2 → Cold worked after cooling from an elevated temperature shaping process and then naturally aged.
T3 → Solution heat-treated and naturally aged.
T5 → Artificially aged after cooling from an elevated temperature shaping process.
T6 → Solution heat-treated and artificially aged.
T7 → Solution heat-treated and stabilized (over aged).
T8 → Solution heat-treated, cold worked and artificially aged.
T9 → Solution heat-treated, artificially aged and cold worked.
T10 → Cold worked after cooling from an elevated temperature shaping process and then artificially aged.

Aluminum alloys can be separated into two major categories: Non heat-treatable and heat-treatable. The initial strength of non heat-treatable alloys depends primarily upon the hardening effect of alloying elements such as silicon, iron, manganese and magnesium. The non heat-treatable alloys are mainly found in 1xxx, 3xxx, 4xxx and 5xxx series. Additional strength is usually achieved by solid-solution strengthening or strain hardening (ibid).

The initial strength of heat-treatable alloys depends upon the alloy composition, just as the non heat-treatable alloys. In order to improve their mechanical properties they need to undergo solution heat treating and quenching followed by either natural or artificial aging (precipitation hardening). This treatment involves holding the work piece at an elevated temperature and followed by controlled cooling in order to achieve maximum hardening. The heat-treatable alloys are found primarily in the 2xxx, 6xxx and 7xxx alloy series (ibid).

The 7xxx series alloys contain zinc in amounts between 4 and 8 % and magnesium in amounts between 1 and 3 %. Both have high solid solubility in aluminum. The addition of magnesium produces a marked increase in precipitation hardening characteristics. Copper additions between 1 and 2 % increase the strength by solid solution hardening, and form the basis of high strength aircraft alloys. The addition of chromium, typically up to 0.3 %, improves stress corrosion cracking resistance. The 7xxx series alloys are used predominantly in aerospace applications, 7075-T6 being the principal high strength aircraft alloy (Ion, 2000). Research will be focused more on this alloy's characteristics after laser welding has been performed, mainly because of its applicability in aircraft components.

4.2 Conventional Welding of Aluminum Alloys

There are many different types of conventional welding. These include oxyacetylene welding, shielded metal arc welding, gas-tungsten arc welding, plasma arc welding, gas-

metal arc welding, flux-core arc welding, submerged arc welding, electroslag welding, electron beam welding, resistance spot welding (Kou, 2003). Of these techniques the most popular are oxyacetylene welding (OAW), gas-tungsten arc welding (GTAW), gas-metal arc welding (GMAW) and electron beam welding (EBW). GTAW is a process that melts and joins metals by heating them with an arc established between a non-consumable tungsten electrode and the metals. OAW is the most commonly used gas welding process due to its high flame temperature. The main difference between GTAW and GMAW is that GMAW uses a continuously fed filler wire as an electrode instead of tungsten. These welding processes use inert gases such as argon and helium to provide shielding of the arc and the molten weld pool. This is why GTAW and GMAW are also called tungsten-inert gas (TIG) and metal-inert gas (MIG) welding processes, respectively. EBW is a process that melts and joins metals by heating them with an electron beam. These electrons are accelerated by an electric field between a negatively charged bias electrode and the anode. They pass through a hole in the anode and are focused by an electromagnetic coil to a point at the workpiece surface (ibid). EBW is characterized by high power densities (as high as 10^{10} W/m²), which enables it to use a deep penetration welding method called keyholing. EBW should probably be categorized with laser beam welding, since the power densities are much higher than conventional welding.

The conventional welding techniques are usually desirable due to their simplicity, low cost, portability (in most types) and are generally used in maintenance, repair and field construction sites (ibid). On the other hand, some of the disadvantages associated with conventional welding, are the low aspect ratios compared to electron and laser beam welding, the large heat affected zone, high distortion and slower welding speeds.

4.3 Laser Welding

Laser welding is a process that melts and joins metals by heating them with a laser beam. The laser beam can be produced either by a solid-state laser or a gas laser. In either case,

the laser beam can be focused and directed by optical means to achieve high power densities. In a solid-state laser, a single crystal is doped with small concentrations of transition elements or rare earth elements. For instance, in a Nd:YAG laser the crystal of yttrium-aluminum-garnet (YAG) is doped with neodymium. The electrons of the dopant element can be selectively excited to higher energy levels upon exposure to high-intensity flash lamps. Lasing occurs when these excited electrons return to their normal energy state by emitting energy in the form of light (ibid).

Out of all the welding techniques that exist today, laser welding is one of the most promising metal joining methods because it provides high productivity, high weld quality, high welding speed, high weld aspect ratio, low heat input, low distortion, manufacturing flexibility and ease of automation (Cao, *et al.*, 2003b). According to a study on phase transformations in weldments (Cieslak, 1992), solidification rates of 10^2 to 10^3 °C/sec encountered in conventional arc welding processes, are much lower compared to high-energy density laser processes which reach 10^5 to 10^6 °C/sec as a result of low heat input experienced at high travel speeds. Under these processing conditions the weld metal microstructure may bear no resemblance to that expected as the result of arc welding. Consequently, the weldment (specifically the fusion zone) is mostly comprised by fine-grained microstructures.

The two fundamental modes of laser welding are: a) conduction welding and b) keyhole or penetration welding. The basic difference between these two modes is that the surface of the weld pool remains unbroken during conduction welding and opens up to allow the laser beam to enter the melt pool during keyhole welding. Figure 4.1 shows a visualization of what keyhole welding is. Conduction welding offers less perturbation to the system because laser radiation does not penetrate into the material being welded. As a result, conduction welds are less susceptible to gas entrapment (porosity) during welding. With keyhole welding, intermittent closure of the keyhole can result in porosity (Duley, 1999).

Figure 4.1: Schematic of Keyhole Welding (Lankalapalli, Tu, *et al.*, 1996)

Since maximum penetration depth is desired, keyhole welding is the method used for this study. Usually, since aluminum alloys have high reflectivity and thermal diffusivity, it is difficult to generate a keyhole in laser penetration welding. This must be overcome by sufficient laser power and proper focusing, in order to achieve the required power density.

4.3.1 Laser Welding of Aluminum Alloys

Weld depth (penetration) is probably one of the most important welding metrics due to the fact that it dictates how thick the pieces to be welded can be. It is of interest to determine what kind of penetration results have been obtained through CO₂ and Nd:YAG lasers, in order to be able to compare with later on. Dausinger, *et al.*, (1996) report that with a 2.2 kW Nd:YAG laser, weld depths of up to 3.7 mm in AA 6082 have been obtained at approximately 16.7 mm/s, at a power density of 3 MW/cm². Also, Yoshikawa, *et al.* (1995), report that successful butt welds of 3 mm thick 5 and 6 series

aluminum alloys can be obtained. They also used power modulation (pulsing) to prevent cracks and blowholes with a high duty cycle. A 3 kW CO₂ laser has been able to achieve approximately 2.5mm weld depth in aluminum alloy 7075-T6 at about 25 mm/s (Katayama and Mizutani, 2002). Also, a 4.5 kW CO₂ produced penetrations of 3.5 mm in aluminum alloy series 5000 (non heat-treatable) and 6000 (heat-treatable), at a speed of approximately 33 mm/s; in comparison, a 4 kW Nd:YAG Produced Weld Depths of 4 mm at same speed (Cao, *et al.*, 2003a). Even though the speeds at which these welds were pretty high (approximately 16 mm/s), the laser output power is still significantly high compared to the 300 W Fiber Laser. Ramasamy and Albright (2000), however, showed that when welding with a pulsed 2 kW Nd:YAG, or a 3 kW continuous wave Nd:YAG, or a 3-5 kW CO₂ laser, vaporization of magnesium and/or silicon can occur from aluminum alloy 6111-T4 and also the metal hardness was reduced. This means that when operating at very high power densities, loss of alloying elements is going to be a significant problem that needs to be overcome.

4.4 Weld Quality and Defects

During laser welding there are three different regions that are produced, the fusion zone (FZ), the partially melted zone (PMZ), and the heat affected zone (HAZ). These regions have been categorized based on the temperatures that occur during welding. The thickness of these three zones put together is usually much narrower than conventional welding techniques (Cao, *et al.*, 2003b).

4.4.1 Fusion Zone (FZ)

The material in the fusion zone is completely melted during welding with temperatures surpassing the liquidus temperature of the alloy. According to a study performed on laser welding alloy A6061-T6 (Hirose, *et al.*, 1999) with a CO₂ laser, the FZ was found to be approximately half the width of what it was in TIG welded joints. The defects found in this region are usually porosity, solidification cracking and sometimes loss of alloying

elements (Cao, *et al.*, 2003b). Contrary to casting processes in which a large fraction of equiaxed grains is encountered, the grain structure in laser-welded (5xxx and 6xxx) alloys primarily consists of fine columnar dendrites, originating from the fusion line and some equiaxed grains in the weld center. Higher travel speeds lead to a more elongated weld pool which leads to finer dendrite structures and grain sizes, resulting from low heat input. Also, columnar grains grow approximately normal to the welding direction at higher speeds. In contrast, lower welding speeds cause columnar grains to curve away from the normal and they align themselves with the welding direction eventually. Therefore, as has been observed, there is a decrease in ductility with increase in welding speed. Also, columnar grain structures are very susceptible to hot tearing. Equiaxed grains are more desirable because they are isotropic. They increase weld strength, reduce susceptibility to solidification cracking because of better resistance to crack formation and propagation (Gaumann and Kurz, 1998). As a result, research and development efforts are directed toward obtaining fine-grained equiaxed growth during laser welding. There are several ways to promote this transition from columnar to equiaxed growth: a) decreasing the solidification rate or welding speed, b) decreasing temperature gradient in the weld pool (by preheating or increasing size of melt pool), c) adjusting chemical composition (higher initial solute concentration), d) decreasing nucleation under cooling and e) increasing number of nucleation sites (*ibid*). During solidification, rejection of solute atoms ahead of the solid or liquid solidification front requires adequate time for diffusion. The faster the solidification rate, the greater the probability that solute atoms will be trapped within the growing solid. Thus it is expected that the segregation in laser welds is not serious. However, laser-welded joints are characterized by high degrees of anisotropy. Inhomogeneity will have important effects on mechanical properties and service (Cao, *et al.*, 2003b).

4.4.2 Partially Melted Zone (PMZ)

The PMZ experiences temperatures between eutectic and liquidus temperatures of the alloy (Zhao, *et al.*, 1999). Therefore, the low melting point eutectic phases which

commonly exist at the grain boundaries of recrystallized grains remelt during laser welding. Liquation cracking may occur along the weakened grain boundaries in the PMZ. The PMZ in laser welded aluminum alloys is generally narrow approximately one or two grains wide (ibid).

4.4.3 Heat Affected Zone (HAZ)

The HAZ is the outermost area of the three and is characterized by its softness. This softened region is defined as the area where hardness values fall below 90% those of the base metal. It experiences temperatures below the eutectic temperatures of the alloy. No bulk metal melting occurs. It has been shown that the widths of softened regions in the HAZs of the laser welds are of the order of one seventh to one quarter those for TIG welds (Hirose, *et al.*, 1999). Although the HAZs of laser-welded joints are very narrow, many solid-state reactions such as grain growth and precipitate coarsening may occur in the zone. In non heat-treatable aluminum alloys, softening occurs because of localized annealing in HAZ by grain growth or loss of strain hardened structure. However, in heat-treatable alloys, welding heat will destroy the temper in the HAZ. Softening in precipitate-hardenable alloys involves the dissolution of strengthening phases and formation and growth of non-strengthening phases (Guitterez, *et al.*, 1996).

One of the most important parameters affecting laser weldability of aluminum is penetration. In order to have any penetration at all, the laser beam must surpass the power density threshold. Due to its high reflectivity, aluminum requires a relatively high power density in order to be able to create a keyhole, which is approximately of the order of 10^6 - 10^7 W/cm². Power densities of this magnitude are easily achieved with commercially available CO₂ lasers; however, considerations must include spot size at focus, as well as maximum power output (Martukanitz and Smith, 1995). The absorptivity of a material is a function of the laser beam's wavelength. Typically, lower wavelength lasers have demonstrated higher absorptivity with metallic surfaces. This is an advantage the fiber laser has over CO₂, along with a better beam profile (nearly perfect

Gaussian distribution) and better focusability (down to 9 microns). There are other factors, however, that affect penetration such as welding speed. According to a mathematical model for estimating penetration (Lankalapalli, Tu, *et al.*, 1996)—which used two dimensional heat conduction and conical keyhole geometry as assumptions—the depth of the weld is related to incident power, thermal conductivity of the material, the difference between the vaporization temperature of the material and room temperature and a quantity called the Péclet number. The Péclet number is equal to the product of the welding speed and keyhole radius divided by two times the thermal diffusivity of the material.

In laser welded joints there is a variety of defects that can occur. A deep hole made in liquid is principally unstable, which is likely to lead to characteristic defects or unstable phenomena in laser welding. Also, the thermal cycle of laser welding is extremely high and hence the solidification rate of the weld pool becomes very rapid, which enhances the formation of cracking (Matsunawa, 1994). The understanding of these defects—how they occur and how they affect the mechanical properties of the joint—is imperative in order to improve the quality of the welds. There are four major categories in which defects can be divided: a) porosity, b) cracking, c) inclusions and d) loss of alloying elements. These categories can be broken down further into subcategories, like for example hydrogen porosity, oxide inclusions, and so on (Cao, *et al.*, 2003b).

4.4.4 Porosity

Hydrogen porosity: Hydrogen is very soluble in aluminum and its alloys. Most gas porosities precipitated in aluminum alloys are attributed to hydrogen. The solubility of hydrogen in liquid aluminum is an exponential function of temperature, which is why its porosity is a much bigger problem in laser welding (than in conventional welding) due to increased temperatures. Also, the high cooling rate is very unfavorable because it does not allow for diffusion or floatation of the trapped hydrogen. Normal hydrogen levels in molten Al vary from approximately 0.10 to 0.40 mL/100g. It is worth noting here that in

order for a part to pass aerospace quality inspections, the gas contents have to be less than 0.06 mL/100g. There possibly exists a critical welding speed at which formation and growth of hydrogen porosity can be prevented. Also, another way to reduce hydrogen porosity is to increase power density, because it keeps the keyhole stable, increases solidification time, allowing the hydrogen to escape (Cao, *et al.*, 2003b). Another thing to keep in mind is that hydrogen porosity can depend on the alloys composition. According to a study conducted on porosity formation (Kutsuna and Yan, 1998), the rate of hydrogen porosity shows a tendency to rise considerably as the magnesium content increases. This happens because magnesium in aluminum alloys raises the hydrogen solubility in the molten pool and hence the segregation of magnesium enhances the segregation of hydrogen during solidification. In other words, aluminum alloys containing a large amount of magnesium will have higher hydrogen solubility in the liquid phase than pure aluminum, since magnesium itself has a higher solubility than aluminum. During solidification a large quantity of hydrogen generates gas bubbles at the solid-liquid interface, interacting with the segregated magnesium.

Porosity caused by collapse of unstable keyholes: Even with the proper control of the material surface preparation, laser parameters, shielding gas and material compositions, aluminum alloys are susceptible to random blowholes while laser welding (Weeter, 1998). Keyhole instability and the coupling of the laser beam into the metal are suspected to cause these random events. These blowholes have irregular or turbular form and are large enough to be visible with x-ray analysis (Dausinger, *et al.*, 1997). They are usually located in the keyhole path, whereas hydrogen pores are more or less equally distributed with slight enrichment at the melting line. The number of cavities is strongly influenced by processing parameters such as the power per unit welding depth, focusability and wavelength. Most likely, stability is increased with the shorter wavelength lasers (Nd:YAG) because the beams are not as drastically affected by the weld plume as the beams with larger wavelengths (CO₂). In the latter case, the weld plume periodically blocks the beam from impinging on the metal and thus causes an instability in the keyhole. The shorter wavelength laser beams can pass through the plume and can provide a more consistent heat input into the metal (Weeter, 1998). It has

also been observed that the highest level of porosity is concentrated in the regions where an unstable keyhole is formed. They are mainly composed of metal vapor but will condense at room temperature. The way to reduce this type of porosity is to keep the keyhole stable, but this can be achieved by welding at high speeds and the addition of filler wire. Also, the use of high-power continuous wave (CW) can improve the stability of keyholes (Cao, *et al.*, 2003b).

Porosity resulting from entrapment of gases by surface turbulence: The turbulent motion in a weld pool is supposed to be extensively met in laser welding; however, no investigation has been conducted on this mechanism in laser welding. The entrapped gas by surface turbulence may be metal vapor, shielding gas, air or any combination of the aforementioned (ibid).

Porosity due to shrinkage: Another type of porosity occurs during solidification (due to shrinkage) resulting from the lack of liquid metal feeding (ibid).

4.4.5 Hot Cracking

Aluminum alloys exhibit a strong propensity for welding crack formation because of their large solidification temperature range, high coefficient of thermal expansion, and large solidification shrinkage. The restrained contraction of a weld during cooling sets up tensile stresses in the joint which may cause cracking. There are two types of hot cracking: cracking that occurs in the weld FZ during solidification of the weld metal is known as solidification cracking, whereas cracking that takes place in the PMZ due to tearing of the liquate is called liquation cracking (Zhao, *et al.*, 1999).

Solidification cracking: Solidification cracking occurs at high temperatures above the solidus under circumstances where the material has low ductility and is under high contraction stresses. Solidification of the liquid weld metal begins at one temperature (the liquidus) and completes at a somewhat lower temperature (the solidus). Between the

two levels the alloy forms an incompletely solidified mass which is brittle and has little or no ductility until cooled to lower temperatures. The brittleness is present in liquid films which surround the solidifying grains or dendrites and when subjected to the high transverse contraction stresses, during weld cooling, solidification cracking may result in the film boundaries; usually those near the centerline of the weld which are the last to cool. If the materials are prone to cracking and the addition of suitable elements (filler wire, powder metal, etc.) to modify the weld is not possible, partial penetration welds should be avoided and, where possible, modifications to the joint design should be made to reduce the weld contraction stresses on cooling. Also, to combat contraction stresses if possible, the weld faces should be held together under pressure during the weld cycle (Dawes, 1992). Certain special features are commonly observed when solidification cracking occurs: a) the fractured surface is always dendritic in nature, b) fracture usually occurs at the grain boundaries, c) the crack tip is dull, and d) the fractured surface is usually covered with oxides if the crack reaches the specimen surface where it can be exposed to oxygen, otherwise it has a silvery color characteristic of unoxidized metal (Zhao, *et al.*, 1999).

HAZ liquation cracking: The low melting point grain boundary films may also be present in the HAZ and may melt and form fine cracks under the influence of thermal stresses induced during welding (Dawes, 1992). Liquation cracking usually takes place in heat-treatable alloys as a result of the large quantities of alloying additions that are available to form eutectic phases with low melting points. The liquate (melt) will tear if sufficient stress is present, especially in high heat input conditions. Liquation cracking can be reduced by minimizing heat input and small HAZ and PMZ. However, liquation cracking still needs to be further investigated in laser welding of aluminum alloys in which alloy composition, cooling rate, material thickness, and weld geometry may all influence cracking susceptibility (Cao, *et al.*, 2003b).

4.4.6 Oxide Inclusions

Oxides are one of the main types of inclusions in aluminum alloys. During keyhole laser welding, because the vaporization of alloying elements in keyholes is not uniform and keyhole positions vary with time, the inherently unstable keyhole flow may entrap shielding gas or even air because of imperfect gas shielding (Matsunawa, *et al.*, 1998). The shielding gas cannot be truly pure. Therefore, some oxide particles may occur in the keyhole vapor. The surface of liquid metal in weld pools (strictly speaking, the surface here should be referred to as the interface between the liquid metal in the weld pool and metal vapor or shielding gas) may also be partly oxidized to form oxide films because of the entrapment of air or shielding gas into the pools. Depending on the Mg contents in Al alloys, oxides such as Al_2O_3 , Al_2MgO_4 , MgO , or their combination may occur. When aluminum alloys contain magnesium, because it is surface active in liquid aluminum, the oxidizing tendency of the molten aluminum increases rapidly with magnesium contents. When the aluminum alloys contain a trace of magnesium, a mixed oxide (MgAl_2O_3), spinel, is formed. When the magnesium content of the alloy exceeds approximately 2%, the liquid oxidizes rapidly to form MgO . The oxides entrained into welded metal because of surface turbulent flow in welding are referred to as young oxide. Oxides in base metal originally from primary processing of aluminum alloys are termed old oxides.

4.4.7 Loss of alloying elements

The high power density used for laser welding may cause selective vaporization of some alloying elements with low fusion point such as lithium, magnesium, and zinc because of their higher equilibrium vapor pressure than aluminum. Selective vaporization of alloying elements can take place in both keyhole and conduction mode laser welding. The vaporization mechanism is divided into three stages. The first involves transport of vaporization elements from the bulk to the surface of the molten weld pool. Then the vaporization of elements occurs at the liquid/vapor interface, and finally the vaporized species are transported into the surrounding gas phases (Cao, *et al.*, 2003b). This will

also cause a void on the top of the weld called underfill. It was found that the intrinsic vaporization of alloying elements at the weld pool surface controls the overall vaporization (Zhao, *et al.*, 1999).

Some techniques have been developed that minimize the defect formations in the weld seams. Some of these include variable welding speeds, variation of power, use of shielding gases, filler metals etc. However, it is also true that using one technique might minimize one type of defect, but can be the cause of several others. For example, porosity can be minimized by keeping the keyhole stable (only achievable during high speed welding) and high power density input. However, high power density can lead to liquation cracking, while high speed welding decreases penetration and keeps the grain growth columnar, which is more susceptible to hot tearing. Also, these effects vary with different alloys and different types of heat sources (lasers). Therefore, it is imperative to find a balance of these techniques that would produce the highest strength welds.

Based on a study that was conducted to develop porosity prevention procedures it was concluded that with high welding speed, the amount of porosity was reduced and sometimes produced no pores. Also, full penetration welding, pulse-modulated welding, welding in vacuum or under low pressure welding with tornado nozzle were reported to be able to reduce or suppress porosity. Finally, it was also reported that the forward welding with about 15 to 20 deg. of beam inclination was able to reduce porosity (Katayama, *et al.*, 2003). However, these approaches are not completely effective.

The loss of alloying elements can be minimized by controlling the beam power density distribution during continuous wave (CW) laser welding, which can influence the temperature of the molten metal in the welding pool (Cao, *et al.*, 2003b). Another way of reducing this loss is through the use of filler metal, which is used as an auxiliary source of material to fill the gap. It also provides a means of controlling the metallurgy of the weld bead and ensures weld quality (Ion, *et al.*, 2001), by helping replenish the loss of alloying elements and also prevent solidification cracking. However, there are some drawbacks involved with this method. Firstly, welding with a filler wire requires an

increase in heat input, which is a function of air gap width, due to the larger melt volume produced. The use of filler metal in laser welding is justified only if the joint gap and sheet metal thickness is larger than the beam and loss of alloying elements is significant (Molian, 2004). The melting efficiency is reduced if the wire is fed to at a higher or lower position compared with the optimum, which is the focal point. An offset from the focal point of 2 mm reduces the efficiency by 35 % and an offset of 4 mm produces a reduction of 50 % in efficiency. In the case that the filler wire is too thick, powder metal can also be used (Salminen, *et al.*, 1994). Some skepticism remains about the process, mainly because it is considered to be complex and requires high precision. The interactions between the large number of process variables involved are also not well understood (Ion, *et al.*, 2001).

A shielding gas flow coaxial with the laser beam or impinging on the laser from the sides serves several purposes and is a common feature in laser welding systems. The first role of this gas often is to prevent oxidation of the weldment and creation of slag in the vicinity of the fusion zone. A second, and critical function is to suppress plasma formation in the vapor over the weld zone and to blow away any plasma that may be created in 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 the uniformity of such factors as penetration depth and weld bead profile. It is not unusual to have both coaxial and side flow gas nozzles directing gas at the weld region (Duley, 1999).

Helium and Argon are commonly used as shielding gases, with He the gas of choice because of its high ionization potential and resistance to breakdown. Nitrogen also is commonly used as a replacement for He and has many of the same properties but is much cheaper. Gas flow rates are typically 10-40 l/min, with the higher rates necessary for high-speed welding (>10 m/min) (*ibid*).

The most important goal of laser welding fatigue cracks in aluminum alloys is to ensure that the mechanical properties of the weld are not deteriorated significantly compared to

the rest of the part. This is especially important when dealing with aerospace components, because they have been designed with very low safety factors in order to minimize weight. If the mechanical properties of the welds are significantly less than what the part has been designed for, there is a serious concern for catastrophic failure originating from the weld seams. Therefore, it is imperative to examine the effect that laser welding has in the FZ, the PMZ and the HAZ. The properties which need to be examined are hardness, tensile strength and fatigue strength.

4.4.8 Hardness

In contrast to steel generally showing an increased hardness in the weld zone due to martensitic hardening, in the case of aluminum alloys the effect of precipitation or work hardening is destroyed partially or totally by the heat load of the laser welding process (Dausinger, *et al.*, 1997). The amount of thermal damage is considerably lower than with arc welding, however, and decreases with increasing beam quality, allowing higher welding speed. In the case of heat-treatable alloys, the loss of precipitates in the welds and over aging in the HAZ has been identified as the main cause of hardness reduction. Solution and aging heat treatments after welding can be used to recover the hardness to the level of the base metal. However, it is undesirable to perform solution treatment at high temperatures after welding. Natural aging usually cannot achieve recovery of a hardness level within the FZ and the HAZ comparable to that of the base metal (Cao, *et al.*, 2003b).

4.4.9 Tensile strength

Aluminum alloys usually do not display significant difference in tensile and yield strengths before and after welding, if welded in fully annealed conditions. However, they still display some decrease in strength after laser welding. Higher power and shorter wavelengths are beneficial in the production of higher strength joints of aluminum alloys. Welding speed was reported to have an important influence on the tensile properties of

laser-welded joints. The tensile strength usually decreases with increasing welding speed because of less penetration depth. Results have shown that the total elongation in the longitudinal and transverse directions decreased with increasing travel speed. It was thought that the orientation of the grains has the predominant effect on the decreased ductility with increasing travel speed. For heat-treatable alloys, Nd:YAG and CO₂ laser welds have approximately 60% to 80% of the original metal tensile strengths and reduced elongation to failure of 1% to 3%. Depending on what alloys are welded and what type of heat treatment they have undergone before welding these percentages can vary (ibid).

The mechanical properties of weld joints are mainly controlled by welding defects, composition, microstructure and metallurgical states of weld metal and neighboring base metal. The presence of defects will reduce the mechanical properties of the joints. Alloy composition dominates solid solution and precipitation strengthening. Selective vaporization of volatile constituents from the laser-welded FZ degrades the mechanical properties of the weld metal. The loss of tensile strength for the precipitation-hardened alloys is caused by dissolution of the precipitate phases and the presence of weld defects such as porosity and hot cracking (ibid).

4.4.10 Fatigue strength

Fatigue properties of laser butt-welded aluminum alloys have shown to decrease to approximately 60% of the base material properties. Also, it has been observed that failure during fatigue testing occurred at the FZ interfaces. Geometrical defects usually have a strong influence on fatigue properties. The joints welded with filler material have shown a smoother transition between the workpieces, thus the sensitivity to fatigue failure was reduced. However, one cannot draw substantial conclusions about the fatigue properties of welded joints since very little data has been published on fatigue properties of laser welded aluminum alloys (ibid).

4.5 Fiber Laser Characteristics

The power source used in this study is a 300 W, Single-Mode, Ytterbium Fiber Optic Laser. The characteristic that sets it apart from Nd:YAG lasers is the excellent beam quality, with an M^2 value of approximately 1.04 which is very close to a Gaussian (normal) power distribution (Steen, 2003). This allows the beam to be focused to much smaller spots and therefore achieving higher power densities. In addition to the excellent beam quality, this laser has a wavelength of approximately 1075 nm (near infrared spectrum), which is relatively short compared to CO₂ lasers. This allows for good penetration which is needed when welding highly reflective materials, like aluminum. The beam diameter exiting the collimator is approximately 5 mm, and can be focused down to about 10.8 μm , through the use of a 5x beam expander and a 150 mm focal length lens. At 300 Watts, a max power density of about 340 GW/cm² can be achieved.

Dr. Miyamoto was the first to recognize the advantages of the fiber laser and propose that it be used in laser welding (Miyamoto, *et al.*, 2003).

5 SPECIFIC RESEARCH PROBLEMS

There are several known challenges that need to be overcome when laser welding aluminum. In order to recover the mechanical properties of the original alloy, one has to minimize defects, such as, hydrogen porosity, porosity caused by unstable keyholes, entrapment of other gases (shielding), or solidification shrinkage. Also there are a couple different types of cracks that can occur such as solidification or liquation cracks (hot tears). Other problems that can arise are oxide inclusions and loss of alloying elements. In addition to minimizing defects, it is imperative that the penetration depth is maximized.

6 APPROACHES

The goal of this study is to investigate the feasibility of laser welding heat-treatable aluminum (7075-T6) with an ytterbium fiber laser. The weld characteristics of interest are penetration depth and high quality, which can be ensured by zero or minimal defects.

6.1 Theoretical Modeling

The first step of this investigation is to use a theoretical model in order to predict the upper bound of welding performance (penetration), and also to predict the variation with respect to controlled parameters, such as welding speed and keyhole radius (which can be adjusted by changing the focus spot).

6.2 Process Design

This laser welding model is then used to determine the best combination of welding speed, power, and focusing in order to obtain experimental results as close to the aforementioned upper bound (ideal weld). However, it is also important to take into consideration the quality of the weld when determining the best welding conditions.

Fiber lasers have a relatively small wavelength (as opposed to CO₂ lasers), which means that they can potentially achieve high penetration for the same power, and extremely good beam quality (as opposed to Nd:YAG lasers), which means that the beam can be focused to a smaller spot and it is possible to achieve much higher power densities with less power because the beam quality can be maintained, as it is focused all the way down to 10 μm or less. However, unlike with other lasers, since much larger power densities can be achieved, it is possible that there exists a threshold which, if exceeded, can destroy the weld quality.

6.3 *Experimental Investigation*

In order to determine the best welding conditions that will achieve the highest penetration and best quality welds, the upper and lower bounds of welding speed need to be determined (based on penetration). Once this has been done, the speeds in between need to be examined at different focusing (how deep into the plate the beam is focused). Since there is a relationship between welding speed and power density, different focusing will be required for different speeds. Finally, it would be beneficial to examine the variation of these welds as the power is changed.

6.4 *Data Analysis*

Finally, the weld's cross section, depth and the presence of defects need to be examined and used as metrics for the weld quality. Also, it is of interest to compare these results to ones obtained from the established laser welding techniques.

7 IDEALIZED WELDING MODEL

Before proceeding with experimentation, it is of interest to be able to predict the behavior of the welding process theoretically; penetration is arguably the most important issue concerning this type of research. Since, full penetration is not feasible with the available power range, it is imperative to predict the maximum penetration possible. This can be done through the use of the theoretical two dimensional heat conduction model (Lankalapalli, Tu, *et al.*, 1996) discussed previously. This model makes several assumptions which significantly reduce its complexity. The general idea of the model is to calculate the heat conduction over an infinitesimally thin layer of thickness (depth) dz at a specific distance from the top of the surface (Figure 7.1).

Figure 7.1: Keyhole Profile (Lankalapalli, Tu, *et al.*, 1996)

One of the assumptions made, is that the walls of the keyhole within this layer are straight and that heat conducted in the z direction is much less than the heat conducted in the radial direction. Therefore, a conical keyhole can be divided into an infinite number of such infinitesimally thin layers and the depth can be approximated by cylindrical heat sources of varying radius, moving together at a constant speed in each of these thin layers. Another assumption made is that there is a quasi-steady state environment in which a cylindrical surface of radius a , at uniform temperature T_v , moving with a constant speed, v , along the x direction, in an infinite medium initially at constant temperature, T_0 . Finally, assuming that the thermal properties of the medium are constant and that the axis of the cylindrical surface passes through the origin of the coordinate system, the governing differential equations and boundary conditions for the temperature distribution can be written as:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{v}{\alpha} \frac{\partial T}{\partial x} = 0 \quad (7.1)$$

$$T = T_v \text{ at } x^2 + y^2 = a^2 \quad (7.2)$$

$$T(x, y) \rightarrow T_0 \text{ as } x \rightarrow \pm \infty \text{ and } y \rightarrow \pm \infty \quad (7.3)$$

where x and y are the surface coordinates, z is the depth coordinate, a is the keyhole radius, v is the welding speed, α is the thermal diffusivity, T_0 is the initial temperature and T_V is the vaporization temperature of the material (Carslaw and Jaeger, 1962).

After several derivations, the following equation which estimates penetration was found as (Lankalapalli, Tu, *et al.*, 1996)

$$d = \frac{P_i}{k(T_V - T_0)} \frac{1}{\sum_{i=1}^6 \frac{c_i}{i} (Pe_0)^{i-1}} \quad (7.4)$$

where k is the thermal conductivity of the material and c_i are coefficients to a polynomial fit to the equation that was evaluated numerically for 100 different values of Pe in the operating range of 0 - 0.025:

$$g(Pe) = \int_0^{2\pi} G(\theta, Pe) d\theta = C_1 + C_2 Pe + C_3 Pe^2 + C_4 Pe^3 + C_5 Pe^4 + C_6 Pe^5 \quad (7.5)$$

where

$$G(\theta, Pe) = -Pe * e^{(-Pe \cos \theta)} * \left[\sum_{n=0}^{\infty} \varepsilon_n I_n(Pe) \cos(n\theta) \left(\frac{n}{Pe} - \frac{K_{n+1}(Pe)}{K_n(Pe)} - \cos \theta \right) \right] = \frac{\partial}{\partial r^*} \left(\frac{T_V - T}{T_V - T_0} \right) \Big|_{r^*=1} \quad (7.6)$$

where

$$\frac{T_V - T}{T_V - T_0} = 1 - e^{(-Pe * r^* \cos \theta)} * \sum_{n=0}^{\infty} \varepsilon_n \frac{I_n(Pe)}{K_n(Pe)} K_n(Pe * r^*) \cos(n\theta) \quad (7.7)$$

is the closed-form solution in polar coordinates (r, θ) of the aforementioned governing differential equation with the specified boundary conditions for the temperature distribution, where $Pe = v * a / (2\alpha)$ is the Péclet number, $r^* = r/a$ is the normalized radial

coordinate, $\varepsilon_n = 1$ for $n = 0$ and 2 for $n \geq 1$, I_n is a modified Bessel function of the first kind, of order n and K_n is a modified Bessel function of the second kind of order n .

Figure 7.2 shows the variation of penetration in 7075-T6 aluminum with respect to changes in Péclet number, at different incident powers ($P_i = 240 - 270$ W). Penetration values were calculated using equation 7.4 (see Appendix 14.1 for MATLAB model).

Figure 7.2: Variation of Penetration with Change in Péclet Number

In order to verify the validity of the results of this model, it is essential to be able to compare the prediction of the model with some actual experimental results. Since this model is not material specific, it was possible to use some readily available experimental results of SUS 304 (stainless steel) and show that this model is an accurate approximation. Several SUS 304 specimens, 300 microns thick, were welded at relatively high speeds (200—1000 mm/s), and the penetration was determined from the microscope-magnified pictures that were taken (Miyamoto, *et al.*, 2003). In order to determine the operating Péclet number, apart from the welding speed and the thermal diffusivity, the keyhole radius is also required. Determining the keyhole radius is not

trivial. There exists a method (Lankalapalli, Tu, *et al.*, 1996), however, to estimate the Péclet number from the weld width. The idea is that a contour plot (Figure 7.3) can be generated for specific Péclet numbers using equation 7.7 (see Appendix 14.1 for MATLAB model), and by measuring the width of the curve corresponding to the melting temperature range, the normalized weld width (w/a) and Péclet number can be correlated. The normalized weld width is obtained by taking twice the maximum y value (due to symmetry) of the melting temperature isotherm curve. Therefore, an equation can be calculated numerically which can be used to determine the Péclet number at the surface of the specimen, for a corresponding weld width. This technique was used to approximate the Péclet number for each of the SUS 304 experimental results (see Appendix 14.1 for MATLAB model). Figure 7.4 shows the model prediction compared to the actual results. From the chart it is apparent that the model is relatively accurate. It seems that the theoretical curves are “shifted” upwards slightly. One possible explanation for this could be that the model does not account for any power losses (it assumes 100% absorption). Also, it seems that the experimental values with lower Péclet values are more “off” than at higher values. This is, most likely, because the plasma forms easier at lower Péclet values.

Figure 7.3: Melting Point Isotherms of SUS 304 Steel @ Péclet = 1

Figure 7.4: Theoretical vs. Experimental Penetration in SUS 304.

8 EXPERIMENTAL APPARATUS

In this section the experimental apparatus is going to be listed and briefly described.

The 300 W Ytterbium, Single-Mode, Fiber Laser (Figure 8.1) is the type of laser used for this investigation. It plugs in to a NEMA two-phase 220V outlet. The beam is fiber deliverable and comes out of the collimator as a cylindrical 5 mm beam.

Figure 8.1: 300 W Ytterbium, Single-Mode Fiber Laser Power Unit

The Parker Automation X-Y linear motors (Figure 8.2) are used to move the workpieces. These work based on electromagnetic principles. They have a resolution of $.5 \mu\text{m}$ and a range of 1 m. The maximum acceleration/deceleration is $\pm 2 \text{ g's}$ and maximum speed is 1.5 m/s.

Figure 8.2: XY Linear Motors

Galil Motion Control (Figure 8.3) is used to control the linear motors (see Appendix 14 for Configuration and Setup).

Figure 8.3: Galil Motion Control

The data acquisition system used is dSPACE 4.0. It is mainly used as an external control for the laser. This helps automate the operation of the laser. Simulink is used to create different operation schemes and can be synchronized with the movement of the linear motors.

Figure 8.4: dSPACE 4.0 Data Acquisition System

A 5x beam expander is needed, in combination with the 150 mm Gradium lens, in order to obtain a minimum focus spot size of 10.8 μm . Equation 8.1 shows how to calculate the minimum spot size.

$$\begin{aligned} \text{Spot size} &= \frac{\text{Lens Focal Length}}{\text{Collimator Optics Focal Length} * \text{Beam Expantion Factor}} * \text{Fiber Diameter} \\ &= \frac{150}{25 * 5} * 9 \text{ microns} = 10.8 \mu\text{m} \end{aligned} \quad (8.1)$$

Figure 8.5: Beam Expander and Grating Lens Setup

The collimator (Figure 8.6) is where the beam exits from. It contains a combination of lenses that enlarge the beam from the fiber diameter's size to 5 mm. Also, the beam exits the beam with almost no divergence (parallel beam).

Figure 8.6: Collimator with Optical Fiber Coming from Laser Power Unit

The Zeiss inverted microscope was used to examine all the weld cross-section and obtain pictures of them. There are a number of different magnifications that can be obtained. The current objectives are 2.5x, 8x, 16x, 40x and 80x. There is also a 2x magnification factor that can be multiplied to these aforementioned objective magnification. Also, the eyepieces provide the user with a 10x magnification. Therefore, the maximum magnification that can be obtained is 1600x (80x times 2x times 10x).

Figure 8.7: Zeiss Inverted Microscope

XYZ Linear Micrometer Stages (Figure 8.8) are used to align the optics with the beam. Also, the Z stage is used to change the focusing of the beam. Their resolution is $10\ \mu\text{m}$ and their range is approximately 26 mm.

Figure 8.8: XYZ Micrometer Linear Stages

Most of the apparatus is set up on a 4' by 8' vibration isolated optical table.

9 EXPERIMENTAL PROCEDURE

9.1 *Beam profile*

There is a common technique that is used to measure the beam profile which uses a scanning beam sensor. This sensor is used to determine beam modes at a cross-section. This test can be repeated at several positions to find out the beam profile. However, it is very difficult to determine the beam profile near the focusing point because of very high power densities that would destroy the sensor (Tu, 2005). This new and relatively simple method was developed to approximate the beam profile in the area where the beam is focused. By inclining the workpiece at a certain angle, the spot radius will vary as it moves along the incline. As the height at which the beam hits the workpiece changes, the radius will become smaller and smaller until it reaches its smallest focus, and then start to enlarge again (since the smallest focused spot will be somewhere above the workpiece).

There exists a critical power density (at a specific speed) where melting occurs and a weld starts forming. It is possible to reach this critical power density with a combination of different powers and spot radii. Equation 9.1 shows this more explicitly.

$$\frac{P_1}{\frac{\pi}{4} * d_1^2} = \frac{P_2}{\frac{\pi}{4} * d_2^2} = \dots = \frac{P_n}{\frac{\pi}{4} * d_n^2} = \text{constant} \quad (9.1)$$

Rearranging equation 9.1, we can solve for $\frac{d_n}{d_m}$, yielding equation 9.2.

$$\frac{d_n}{d_m} = \sqrt{\left(\frac{P_n}{P_m}\right)} \quad (9.2)$$

where P is output power, d is spot diameter and $m \neq n$.

If d_m is arbitrarily set to 1 (normalized), then d_n can be determined based on the ratio of the power settings. The normalized spot radii can then be determined and can be plotted with respect to distance away from focus spot. The way to determine this distance is by multiplying half of the weld length by the sine of the inclination angle (equation 9.3).

$$D = \frac{l_w}{2} * \sin(\alpha) \quad (9.3)$$

where D is the depth (distance away from most focused spot), l_w is the length of the weld, and α is the inclination angle. These dimensions are shown in Figure 9.1. It should be noted that the figure is not drawn to scale in order to show the features more clearly.

Figure 9.1: Beam Profile Experimental Setup

Once the plot is generated, showing the normalized radius with change in focusing depth, a parabolic curve fit is applied. The last step is to “denormalize” the radii values by multiplying them by the ratio of the minimum theoretical spot radius and the parabola’s value at $D = 0$ (vertex).

The actual procedure involved moving the beam along the incline long enough to let the weld start and end, for four different power settings at .25 mm/s. The lengths of the welds were recorded and converted into depth values based on an angle of approximately 12° . Table 9.1 shows the half weld lengths obtained for each power setting.

Table 9.1: Half weld lengths for each power setting

Power (W)	<i>Half of Weld Length (mm)</i>
39	1.849
53.5	3.585
72	5.673
97	6.831

It is important to note that this technique is an approximation and is based on certain assumptions: a) the beam profile is symmetric about the horizontal axis (it focuses and

defocuses symmetrically), b) the power is constant throughout each weld and c) the smallest possible spot radius with the current lens is 5.4 μm .

This technique was developed out of necessity. Due to the high reflectivity of aluminum, it was determined that the workpieces could not be laid flat, because the beam reflected back up through the optics and damaged the collimator. The remaining experiments were also conducted using fixtures that would tilt the workpiece at an angle of approximately 12°.

9.2 Bead-on Welding

9.2.1 Location of Smallest Focusing Spot.

The aforementioned procedure was also used in order to find the exact location of the most focused spot. The smallest possible power setting was used in order to create a very small weld, which indicated where the beam was focused. Again, the linear stage speed was very small (.25 mm/s) and moved the workpiece in such a way that the beam would travel down the incline. After this process was complete the beam was positioned at the center of the small weld and focused at the desired depth using the linear stage micrometer (in the Z-direction).

The laser and specimen were setup in a way shown in Figure 9.2.

Figure 9.2: Experimental Setup

The beam exits the collimator at a diameter of approximately 5 mm in diameter and is expanded 5 times using the beam expander. After it exits the beam expander it is focused down to the desired spot size (approximately 10.8 microns in diameter). Shielding gas (helium) is used to prevent any oxidation from occurring and also to blow away most of the generated plasma. As mentioned before, one of the problems encountered, was that the beam was reflected back into the collimator due to aluminum's high reflectivity. By tilting the plate more than 10° this problem was avoided successfully. This introduced some complexities in the process, like the fact that the focusing can change very easily with a slight movement in the direction of the incline.

9.2.2 Determination of Experimental Welding Parameters

Initially, several welding tests were performed in order to determine the desired welding speed and to get some experience with laser welding of aluminum. These welds were

performed at a constant height, as shown in Figure 9.3 (perpendicular to the incline), at speeds ranging from 0.25 mm/s to 10 mm/s. After visually inspecting the welds produced at these different speeds, it was determined that the desired welding speed range was between 2 mm/s and 6 mm/s. Also, the effect of focusing was examined, and the range that seemed to produce decent welds was between 0 (on the surface) and 1.75 mm depth (focused into the surface). This method was used to determine the desired welding parameters to be investigated. It was implemented due to the process' high time consumption.

Figure 9.3: Welding Perpendicular to the Incline

9.2.3 Final Experimentation with Selected Welding Parameters

In order to examine six different focusing positions per welding speed for five different welding speeds, and at three different power settings, ninety welds needed to be performed. Since performing the spot location process is rather time consuming, a

welding procedure needed to be determined that would reduce the experimentation time significantly. Six 3 in. by 9 in. by .125 in. plates were used. Each plate was set up using the inclined fixtures as shown in Figure 9.4.

Figure 9.4: Inclined Fixtures

Since the same focus had to be tested for each speed at each power setting, a series of welds at different speeds was performed at a specific focusing. This effectively reduces the number of times the spot location process needs to be performed. All the welds were set to be the same length, which was 1.5 in. The weld length was chosen large enough, in order for the weld to get a chance to reach steady-state absorption. The speeds were chosen to go from 6 mm/s down to 2 mm/s, in order to reduce the amount of preheating of the aluminum plate. Rotating through six plates allows them to cool off, while the others are being welded and therefore keeps the distortion to a minimum. Each plate signified a different focusing (i.e. plate 1 corresponded to 0 mm focusing depth, for speeds 2—6 mm/s at 80%, 90% and 100% power, etc.). Due to the fact that the lower powers could not achieve as high power densities, the focusing range was reduced accordingly (80% power was tested at 0—1.25 mm focusing depth, 90% power was

tested at 0—1.50 mm focusing depth and 100% power was tested at 0—1.75 mm focusing depth). Figure 9.5 shows one of the plates being welded at 80% power, at a speed of 4 mm/s.

Figure 9.5: Bead-on Welding at 80% Power and 4 mm/s Welding Speed

9.2.4 Sample Preparation and Examination

After all the experiments were complete, the cross sections needed to be examined. The plates were cut near the end of each weld, and gone through 4 stages of sanding to get a smooth surface. The first two stages involved using a belt sander and the other two were with the use of 500 grit and 1500 grit sand paper. After the sanding was satisfactory, the samples were etched in order to bring out the distinction between base material, HAZ and weld. The samples were then examined with the microscope at a magnification of 12.8x. Pictures were taken and processed with a program called Motic Images Plus. With this program the weld lengths and areas could be measured, but only after the program was calibrated. The way this was done, was by locating the tracks of a burnt cd under the

microscope, taking a picture, and inputting the known distance between each track (1.6 μm).

9.2.5 Aluminum Polishing

The aforementioned sample preparation is good enough to be able to determine weld lengths, areas and major defects. In order to look at microstructure, the sample needs to be polished in a certain way. Using a specialized grinding wheel and sand paper, the samples were ground through a series of different grit papers (240, 400 and 600 grit). Special care needed to be taken in order to keep the surface as flat as possible. After the grinding was done, the samples were taken through two steps of polishing. A different type of material was used that was composed of micro fibers. A liquid was sprayed onto the material, which did all the polishing. This liquid contained “diamond dust” of a certain size which with the help of friction would polish the samples. The two steps involved two different sizes of diamond dust, 9 microns and 3 microns. After, the samples were polished very carefully, they were etched, again, in order to distinguish the base material from the HAZ and the weld.

10 RESULTS AND DISCUSSION

10.1 Beam Profile

In this section experimental results will be presented and analyzed. The beam profile experiment is the first to be examined since the ensuing findings rely on its results. The depth of focus has been approximated in the range of ± 2 mm. Figure 10.1 shows the variation of the spot’s radius within that range.

Figure 10.1: Variation of Spot radius Within the Depth of Focus.

Most beam profile estimation methods examine the beam at farther distances from the most focused spot, due to the fact that most sensors cannot withstand such high power densities. Knowing the beam profile within this region is an advantage, given the fact that output power density (Figure 10.2) and energy per unit area can be calculated.

Figure 10.2: Maximum Output Power Density Within the Depth of Focus

This plot is a great tool that can be used to determine what power density thresholds correspond to what focusing depths. For example, if an optimum power density range for welding is determined to be between 2×10^8 and 3×10^8 W/cm², then it is apparent that the beam needs to be focused between 0.5 and 1 mm away from the most focused spot.

10.2 Bead-on Welding

The weld conditions that were examined in this study were speed, power and focusing depth. The welding speeds were in the range of 2 to 6 mm/s, the power settings were 80 percent, 90 percent and 100 percent, and the beam was focused between 0 and 1.75 mm into the workpiece.

The cross-sections of these welds were examined under a microscope and pictures were taken and processed to determine the approximate penetrations, weld widths, and cross-sectional areas. From this information, several conclusions can be made about the overall

feasibility of welding aluminum with the Ytterbium Single-Mode Fiber Laser, relating to the penetration, quality and welding efficiency.

10.2.1 Penetration and weld quality

Penetration is a very important weld characteristic because it dictates the maximum thickness of the part that can be welded. If both sides of the part can be accessed, this maximum thickness is doubled. Also, from examining figure 7.2, it can be concluded that higher powers will shift the penetration curve higher. What this means is that using a 1 kW Ytterbium Single-Mode Fiber Laser, even deeper penetration can be achieved at similar Péclet values.

Since weld characteristics are influenced by several different LASER welding parameters (power, beam focusing, velocity, etc.), it is important to see their variation with respect to a metric that takes all these parameters into account. One such metric is fluence (total irradiated energy per unity area) which can be defined as follows:

$$Fluence = \frac{P}{\pi * r^2} * \frac{l_{weld}}{v} \quad (10.1)$$

where P is total power output, r is the spot radius (as calculated from the beam profile approximation) and $\frac{l_{weld}}{v}$ is the total welding time (weld length divided by welding speed).

Figure 10.3 shows the penetrations achieved at 100% power at different speeds and focusing.

Figure 10.3: Penetration Values at Different Speeds at 100% Power

The maximum penetration achieved for these settings was just above 0.9 mm. Table 10.1 shows the maximum penetration values for each welding speed and the corresponding focusing depth.

Table 10.1: Maximum Penetration for Every Welding Speed at 100% Power

Speed (mm/s)	Max Penetration (mm)	Focusing Depth (mm)
2	0.5708	0.00
3	0.9107	0.00
4	0.9022	0.00
5	0.8502	0.00
6	0.8537	1.00

Compared to the theoretical values of penetration (Figure 7.1), the aforementioned maximum penetration values come very close. Again, it should be pointed out that the theoretical model does not account for any losses due to the reflectivity of aluminum or the energy absorption from the plasma.

When examining Figure 10.3 it is observed that as a general trend the penetration increases up to a certain point and then starts leveling off. This probably happens because the further the keyhole penetrates the material, the harder it is for the plasma to escape out of it. The plasma then acts as a lens (Park, 2005) and defocuses the beam and instead of creating further penetration, the weld just gets wider. Plasma will also absorb some of the energy of the beam and eventually, the penetration will stop increasing (and possibly decrease a little bit).

In order to gain a better understanding of what is going on it can be useful to examine the cross-sections of the welds and correlate them to Figure 10.3. Figure 10.4 shows the cross-sections for the welding speed of 6 mm/s at 100 % Power.

Figure 10.4: Weld cross-sections for 6 mm/s, at 100% Power

From left to right, the top row shows the welds resulting from focusing depth of 0 mm, 0.75 mm and 1 mm. The bottom row (again from left to right) shows the resulting cross-sections from focusing depth of 1.25 mm, 1.5 mm and 1.75 mm. It is relatively obvious that the deepest penetration occurs at focusing depths of 0.75 mm and 1 mm. Also, it is pretty apparent that when the beam is focused too deep, the weld hardly has any

penetration and resembles the conduction welding mode rather than the keyhole mode. At 1.25 mm focusing depth a nice weld starts to form and increases in penetration at 1 mm focusing depth. Instead of increasing in penetration the weld just becomes wider as was proposed. At the surface welding condition the weld seems to be wider and shallower, probably due to more plasma generation. Since the focusing is so critical with the incline, it is also possible that the beam was focused slightly above the surface, which would mean that the beam would start diverging into the workpiece.

Another factor that needs to be considered is the weld quality. From a quick glance it seems that the deeper welds (focusing depth between 0 and 1.25 mm) are free from major defects. One of the defects that is a concern, is the underfill that occurs at the surface. This is probably due to the vaporization of alloying elements and probably of some aluminum, especially at higher power densities. The other two weld cross-sections seem to have either some type of porosity or inclusion in the weld. This can occur in a number of different ways; from shielding gas, or hydrogen (from moisture) getting entrapped, and not having enough time to escape before the molten pool solidifies, to aluminum oxides getting mixed in the molten pool.

Figure 10.5 shows the cross-sections for 5 mm/s at 100 % power, for the same focusing depths (in the same order).

Figure 10.5: Weld cross-sections for 5 mm/s, at 100% Power

In this case, the trend is pretty similar with the exception that the deepest penetration is achieved at the surface weld. Again, as the focusing moves closer and closer to the surface, the rate at which penetration increases drops dramatically. Instead the weld increases in width and only slightly in penetration.

For the higher power density welds, again, underfill can be observed. However, no major porosities or inclusions seem to be present.

In Figure 10.6 the same trend seems to be going on. For the focusing depths of 1.25 through 1.75, there is little to no penetration and at 1 mm a weld starts to form at 0.75 mm the penetration increases significantly. Finally, for the surface weld, the penetration increases slightly, but the weld width increases noticeably.

Figure 10.6: Weld cross-sections for 4 mm/s, at 100% Power

Again, the deeper welds seem to be free of major porosities and inclusions but have an underfill “dimple.” In the rest of the welds some porosities can be detected.

Figure 10.7 shows the cross-sections resulting from a welding speed of 3 mm/s at 100% power.

Figure 10.7: Weld cross-sections for 3 mm/s, at 100% Power

This welding condition yields the highest penetration so far, but the rest of the welds are horrible. They have little to no penetration and they are full of cavities. Again the deep penetration weld is practically defect-free, if the small underfill is excluded.

Finally, in Figure 10.8 the cross-sections are shown of welding at a speed of 2 mm/s at 100% power.

Figure 10.8: Weld cross-sections for 2 mm/s, at 100% Power

These were by far the most unsuccessful welds that were run at 100% power. They achieved barely any penetration and the ones that did had significant amount of defects in them.

These results were a little troublesome at first because intuitively, slower speeds should yield better penetration. For this reason, another experiment was conducted at the same welding speed with a slightly higher shielding gas flow rate (from approximately 28 l/min, it was increased to approximately 32 l/min).

Figure 10.9 shows the comparison between the results with different shielding gases.

Figure 10.9: 100% Power Compared with Higher Flow Rate

The results of the latest experiment shows that increasing the shielding gas slightly, makes a significant difference. In fact the highest penetration of all the experiments was achieved at a focusing depth of 0.75 mm. Focusing on the plate, however, did not produce as high of a weld. This could be due to two reasons. Either, the plasma generated at such a high fluence absorbs too much energy or the beam was focused slightly above the workpiece.

Figure 10.10: Resulting Welds when using Higher Shielding Gas Flow Rate

Figure 10.10 shows the resulting cross-sections with higher shielding gas flow rate (at 2 mm/s, 100% power). With the exception of the weld that had the beam focusing on the surface, the rest of the welds are without any underfill. They do have some inclusions and porosities, however. The deepest weld was achieved at a focusing depth of 0.75. The penetration depth was 1.02 mm.

The trends that occurred during welding at 100% power, also appeared at lower powers (80% and 90%). Figures 10.11 and 10.12 show the resulting equivalent plots.

Figure 10.11: Penetration Values at Different Speeds at 90% Power

The maximum penetration achieved at 90% power was just under 0.9 mm. Table 10.2 shows the maximum penetration values for each welding speed and the corresponding focusing depth.

Table 10.2: Maximum Penetration for Every Welding Speed at 90% Power

Speed (mm/s)	Max Penetration (mm)	Focusing Depth (mm)
2	0.4098	0.00
3	0.7991	0.00
4	0.7497	0.00
5	0.8954	0.50
6	0.8758	0.50

These penetration values, again, are reasonably close to the theoretical predictions. In fact, the overall maximum penetration is pretty close to the value of the maximum penetration at 100% power. Essentially, what this means is that penetration is more dependant on how much energy can be irradiated per area per length (fluence) and especially how much of that energy can be absorbed by the weld.

Figure 10.12: Penetration Values at Different Speeds at 80% Power

At 80 % power, the maximum penetration achieved was just over 0.75 mm. Table 10.3 shows the maximum penetration values for each welding speed and the corresponding focusing depth.

Table 10.3: Maximum Penetration for Every Welding Speed at 80% Power

Speed (mm/s)	Max Penetration (mm)	Focusing Depth (mm)
2	0.2820	0.00
3	0.5274	0.00
4	0.7531	0.00
5	0.7480	0.75
6	0.7156	0.25

Since the weld cross-sections of the 80% and 90% power have similar characteristics and trends, they have been added in Appendix 14.3 in order to avoid repetitiveness.

10.2.2 Welding efficiency

Due to high reflectivity of aluminum alloys and the plasma plume formation during welding, the total irradiated energy (a.k.a. fluence) from the fiber laser is not going to be completely absorbed by the material. Therefore it is of interest to determine the weld efficiency by examining the total energy absorbed and compare it to total fluence. The total energy absorbed is shown in equation 10.1.

$$\text{Weld Energy} = m_{\text{weld}} * \zeta = \rho * V_{\text{weld}} * \zeta = \rho * A_{\text{weld}} * l_{\text{weld}} * \zeta \quad (10.2)$$

where m_{weld} , V_{weld} , A_{weld} , and l_{weld} are the mass, volume and length of the weld, respectively, ρ is the density and ζ is the specific energy of the material and is approximated by equation 10.2.

$$\zeta = C_p * \Delta T + \text{Latent Heat of Fusion} \quad (10.3)$$

Figure 10.3 shows the relationship between energy absorbed per unit length and fluence per unit length.

Figure 10.13: Weld Energy per Length as Fluence per Length Increases

There is a trend that can be observed from these experimental results. With the exception of the weld at 2 mm/s, the welding efficiency (slope of weld energy and fluence) is the same for each welding condition. Also, as fluence increases, the efficiency drops, but again is approximately the same with speeds of 4, 5 and 6 mm/s. Another observation that has been made is that with slower speeds, higher fluence per length is possible, but the absorbed energy increases only slightly and then reduces again, and the efficiency drops dramatically at a welding speed of 2 mm/s. Also, for speeds of 2, 3 and 4 mm/s, initially, the efficiency is very low and after a certain point has a sudden “jump.” This is probably the transition point from conduction to keyhole welding.

One would expect that with slower speeds, the energy absorbed would be higher due to the higher fluence. However, the increase in absorbed energy is not as expected. In fact, it only increases slightly and then drops back down. One reasonable explanation is that with increase in irradiated energy, there is an increase in plasma plume formation. Essentially, the plasma plume consists of ionized particles from the vaporization of the material. These ionized particles practically act as a cloud which absorbs some of the

beam's energy, and hence, reduces the absorptivity of the material. A common practice that is a partial solution to this problem is to use shielding gas, to blow away the plasma. However, the shielding gas also has the tendency to ionize and form a plasma “cloud” of its own.

In order to verify the assumption that the plasma plume is a contributing factor to the lower welding efficiency at a welding speed of 2 mm/s, the experiment was repeated for those conditions, with a slightly higher shielding gas flow rate. The results are compared to the original results at the same welding speed in Figure 10.4.

Figure 10.14: Comparison Between 2 mm/s Welds with Different Flow Rates

By observing the different slopes of the two lines it is apparent that increasing the shielding gas flow rate slightly, improves the welding efficiency. This means that with slower speeds more plasma is produced and therefore absorptivity is reduced. Increasing the shielding gas flow rate even further might seem like the solution to get even further penetration at slower speeds, but as mentioned before, the shielding gas can also ionize and decrease the absorptivity. Another interesting observation is that even though the efficiency improves with increase in shielding gas flow rate, eventually the weld energy drops again. This is, most likely, the result of increase in plasma formation. Finally, one

might notice that the weld energy that was absorbed has much lower values than the irradiated energy. This is not too concerning because the calculation of the absorbed weld energy was just an approximation of the energy that was used to create the weld and did not take into account any energy that was dissipated throughout the HAZ, or that was used to vaporize some of the material. Also, a great amount of energy is reflected away from the workpiece.

10.2.3 A Look at the Microstructure

Three different sections were selected in order to make a microstructural comparison. The base material is shown in Figure 10.15. There are two types of materials that can be distinguished here. The light colored material is probably the aluminum and the dark circular specs are most likely the alloying elements. By looking at the base material the dark specs look like they are more or less distributed evenly.

Figure 10.15: Base Material Microstructure at 1600x Magnification

Figure 10.16 shows the microstructure of the largest achieved weld. It is quite obvious that the two pictures are pretty similar, with the exception that the specs are more “clustered” together in the weld. However, defects do not seem to be present.

Figure 10.16: Microstructure of Deepest Weld at 1600x Magnification

In order to make sure that there is a distinction between the microstructure of a weld with defects and a weld without defects, Figure 10.17 was examined. Even though it is focused at a lower magnification, it is pretty obvious that the defects are significantly larger than the circular specs.

Based on this comparison it can be said with a reasonable amount of confidence that the 1 mm weld does not have any significant defects in it, however, its microstructural composition has changed somewhat.

Figure 10.17: Microstructure of Weld with Defects at 400x Magnification

11 CONCLUSIONS

The 300 W Ytterbium, Single-Mode Fiber Optic Laser has been used to create bead-on welds with depth of just over 1 mm. In addition, these welds are created with minimal defects. Underfill and loss of alloying elements are the biggest defect concerns. The optimum welding speed is between 2 and 3 mm/s, focused slightly into the workpiece (no deeper than 0.75 mm). It has been determined that a flow rate in between 28 and 32 l/min (depending on welding speed) should be used in order to blow away most of the plasma.

By achieving 1 mm deep welds with a 300 W Fiber Laser, it has been shown that aluminum can be welded more efficiently than with Nd:YAG or CO₂ lasers. Even though these lasers have achieved deeper welds at higher speeds, they have done so with much higher wattage. Although the relationship between penetration and power is not linear, based on these results, it is likely that with a 1 kW Fiber Laser, the penetrations that are realized with 2 kW Nd:YAG and 5 kW CO₂ lasers will be matched or even exceeded.

However, penetration depth is irrelevant if the quality of the weld is bad. Current results show that the deep welds that were produced suffered only from underfill and loss of alloying elements. This is usually solved by adding some kind of filler metal to fill the gap and replenish the alloying elements. Microstructure was briefly examined, again, yielding no significant defects.

Finally, a simple and effective method was developed to approximate the beam profile at and around the focused spot. This can prove to be a useful tool to approximate the power density distribution at different focusing depths.

12 FUTURE WORK

This investigation has shown that there is great potential for aluminum alloy welding with fiber optic lasers. However, this investigative research has only touched the surface. The biggest obstacle so far has been aluminum alloys' high reflectivity. If the workpiece is positioned perpendicular to the beam, it reflects a big portion of it back into the collimator and damages it. One of the solutions to this problem is to fit an isolator onto the collimator which will divert the reflected beam away from it. Although the beam quality may be sacrificed slightly, some of the problems that occur with the current (tilted) setup will be eliminated. Currently, any variation perpendicular to the weld direction will change the focus of the beam with respect to the workpiece.

The results reported in this study had a power density limitation. The output power available was only 300 W. It would be beneficial to examine the welding effects at higher power densities. This can also be achieved with a shorter focal length lens. However, the closer the lens moves to the workpiece, the easier it is to get damaged from spatter, so an experimental setup needs to be established that will protect the lens from being damaged.

Another area that needs to be examined, is the effect of shielding gas flow rate. In this study, flow rate was held as a constant (after some minor adjustments), in order to determine the effects of focusing and welding speed had on penetration. Shielding gas flow rate, though, can be a contributing factor to the quality of the weld. Depending on the welding conditions, higher flow rate may be required to remove the plasma plume from above the keyhole, and therefore yield penetration. Also, it would be important to investigate the characteristics of the plasma plume for different welding conditions, which would indicate a need for higher or lower shielding gas flow rate.

Microstructure is another field that needs to be addressed. This investigation focused mostly on major defects like blow holes, porosities and underfill. The orientation of grains (equiaxed or dendritic) can tell a lot about the weld's properties such as ductility and strength. Polishing aluminum alloys, however, is a challenge in itself. Special equipment is required, and it is a very delicate process.

The problems with underfill and loss of alloying elements are also defects that need to be addressed. A common solution with other laser welding processes is to add filler metal. This is usually done in the form of filler wire, although some processes use powder metal. This process introduces a few more variables such as wire feeding speed, supply angle, and positioning with respect to the beam (ahead or behind of the keyhole). For this reason it is important to have established welding parameters (speed, focus, shielding gas flow rate) and hold them constant, while the effects of different filler metal procedures are examined.

Since bead-on welds have been the main focus of this study, it is desired to lead up to butt welding and crack welding, due to their applications in industry. The added gap introduces some different effects, compared to bead-on welding, that should be examined. Also, for crack welding it is important to investigate methods for crack detecting and tracking (since they are not straight). The welded cracks need to be tested for strength and fatigue resistance and compared to base material properties. These results will be an indication of whether crack repair is feasible in aircraft grade aluminum

alloys, either stand-alone or with a combination of other repair techniques (composite patches).

13 REFERENCES

Cao, X., Wallace, W., Immariageon, J.-P., and Poon, C., 2003, "Research in Laser Welding of Wrought Aluminum Alloys. I. Laser Welding Processes," *Materials and Manufacturing Processes*, 18(1), pp. 1-22.

Cao, X., Wallace, W., Immariageon, J.-P., and Poon, C., 2003, "Research in Laser Welding of Wrought Aluminum Alloys. II. Metallurgical Microstructures, Defects, and Mechanical Properties," *Materials and Manufacturing Processes*, 18 (1), pp. 23-49.

Carslaw, H. S., Jaeger, J. C., 1962, Conduction of Heat in Solids, 2nd edition, Oxford: Clarendon, pp. 390.

Cieslak, M. J., 1992, "Phase Transformations in Weldments: New materials and New Perspectives," 3rd Int. Conf. on Trends in Welding Research, Gatlingburg, TN, pp. 229.

Dausinger, F., Rapp, J., Beck, M., Faisst, Hack, R., Hugel, H., 1996, "Welding of Aluminum: A Challenging Opportunity for Laser Technology," *Journal of Laser Applications*, Vol. 8, 285-290.

Dausinger, F., Rapp, J., Hohenberger, B., Hugel, H., 1997, "Laser Beam Welding Of Aluminum Alloys: State Of The Art And Recent Developments," *Proc. Int. Body Engineering Conf. IBEC '97: Advanced Technologies & Processes*, Vol. 33, pp. 38-46.

Dawes, C., 1992, Laser Welding, 1st edition, McGraw-Hill, Inc., pp. 74-76.

Duley, W. W., 1999, Laser Welding, 1st edition, John Wiley & Sons, Inc., pp. 4-65.

Gaumann, M., Kurz, W., 1998, "Why is it so difficult to produce an equiaxed microstructure during welding," *Math. Model. Weld. Phenom.* 4 (695), pp. 125-136.

Guitterez, L. A., Neye, G., Zschech, E., 1996, "Microstructure, Hardness Profile and Tensile Strength in Welds of AA6013 T6 Extrusions," *Welding Journal*, 75 (4), pp. 115S-121S.

Hirose, A., Kobayashi, K., Yamaoka, H., Kurosawa, N., 1999, "Evaluation of properties in laser welds of A6061-T6 aluminium alloy," *Journal of Light Metal Welding & Construction*, 37 (9), pp. 1-9.

Ion, J. C., 2000, "Laser beam welding of wrought aluminium alloys," *Sci. Technol. Weld. Joining*, 5 (5), pp. 265-276.

Ion, J.C., Jokinen, T., Salminen, A., Kujanpaa, V., 2001, "Laser beam welding using filler wire," *Ind. Laser Solutions Manuf.*, 16 (2), pp. 16-18.

Katayama, S., Mizutani, M., 2002, "Laser Weldability of Aluminum Alloys," *Trans. JWRI*, 31 (2), pp. 147-155.

Katayama, S., Mizutani, M., and Matsunawa, A., 2003, "Development of Porosity Prevention Procedures during Laser Welding," *Proc. of SPIE*, Vol. 4831: 281-288.

Kou, S., 2003, Welding metallurgy, 2nd edition, Hoboken, N.J., Wiley-Interscience, pp.1-197.

Kutsuna, M., Yan, Q. U., 1998, "Study on porosity formation in laser welds of aluminium alloys (Report 2). Mechanism of porosity formation by hydrogen and magnesium," *J. Light Met. Weld. Constr.*, 36 (11), pp. 1-17.

Lankalapalli, K. N., Tu, J. F., Gartner, M., 1996, "A model for estimating penetration depth of laser welding processes," *J. Phys. D, Appl. Phys.*, 29, pp. 1831-1841.

Mandal, N. R., 2002, Aluminum Welding, 1st edition, Narosa Publishing House, pp. 1-19

Martukanitz, R. P., Smith, D. J., 1995, “Laser beam welding of aluminum alloys,” Proc 6th Int. Conf. on Aluminum Weldments, AWS, pp. 309-323.

Matsunawa, A., 1994, “Defects Formation Mechanisms in Laser Welding and Their Suppression Methods,” Proc. of ICALEO: 203-219.

Matsunawa, A., Katayama, S., Fujita, Y., 1998, “Laser Welding of Aluminum Alloys—Defects Formation Mechanisms and their suppression methods,” Proc. 7th Int. conf./INALCO '98: Joints in Aluminum, Cambridge, pp 65-76.

Miyamoto, I., Park, S.-J., and Ooie, T., 2003, “Ultrafine-Keyhole Welding Process Using Single-Mode Fiber Laser,” Proc. of ICALEO: 203-212.

Molian, A., 2004, Private conversation.

Park, S. J., 2005, Private conversation.

Ramasamy, S., Albright, C. E., 2000, “CO₂ and Nd:YAG laser beam welding of 6111-T4 aluminum alloy for automotive applications,” J. of Laser Appl., 12 (3), pp. 101-115.

Salminen, A. S., Kujanpaa, V. P., and Moisio, T. J. I., 1994, “Effect of Use of Filler Wire on Requirements of Laser Welded Butt Joints,” Proc. of ICALEO: 193-202.

Steen, W. M., 2003, Laser Material Processing, 3rd edition, Springer-Verlag London Limited, pp. 61-106.

Tu, J. F., 2005, Private conversation.

Yoshikawa, M., Kurosawa, T., Nakata, K., Kimura, S., Aoki, S., 1995, "YAG Laser Welding of Aluminum Alloys," *Journal of Light Metal Welding & Construction*, 32 (9), 15-23.

Weeter, L., 1998, "Technological advances in aluminum laser welding," *Pract. Weld. Today*, 2 (1), pp.56-58

Zhao, H., White, D. R., DebRoy, T., 1999 "Current issues and problems in laser welding of automotive aluminum alloys," *Int. Mater. Rev.*, 44(6): 238-266.

14 APPENDICES

14.1 MATLAB Modeling Code

14.1.1 Aluminum Alloy 7075-T6 Penetration Model

```
clear;
clc;

% Material Properties of Al 7075-T6

k = 130;           % Thermal conductivity in W/(m*K)
alpha = 48.36e-6;  % Thermal diffusivity in m^2/s
Tv = 2773.15;     % Vaporization temperature in K

% Model constants

C = [.7557 142.2 -1.727e4 1.266e6 -4.524e7 6.167e8];

% Welding conditions

Pi = [.2488 .2799 .311 3.5 4 4.5] * 1e3; % Incident power in W
T0 = 293.15; % Ambient temperature in K

Pe0 = 2.5e-4:2.5e-4:2.5e-2

for i = 1:100

    for j = 1:6

        d(i,j) = (Pi(j) / (k * (Tv - T0))) * (1 / ((C(1) / 1) * Pe0(i)^(1-1) + (C(2) / 2) * Pe0(i)^(2-1) + (C(3) / 3) *
        Pe0(i)^(3-1) + (C(4) / 4) * Pe0(i)^(4-1) + (C(5) / 5) * Pe0(i)^(5-1) + (C(6) / 6) * Pe0(i)^(6-1)))));

    end

end

hold on;
plot(Pe0, d(:,1), 'r-');
plot(Pe0, d(:,2), 'k-');
plot(Pe0, d(:,3), 'g-');
% plot(Pe0, d(:,4), 'k+');
% plot(Pe0, d(:,5), 'k. ');
% plot(Pe0, d(:,6), 'k*');
%title('Penetration in 7075-T6 at different powers (240 W, 270 W and 300 W)');
xlabel('Peclet number');
ylabel('Penetration (m)');
% gtext('300 W');
% gtext('270 W');
% gtext('240 W');

grid
hold off;
```


14.1.2 Temperature Distribution Model

```
clear;

clc;

T0 = 293.15;           % Ambient temperature (K)
Tv = 2573.15;          % Vaporization temperature (K)
Pe = 1;                % Peclet number

delta = .1;            % Plot area resolution parameter
range = 10;            % Plot axis maximum range

x = -range:delta:range; % Determination of X-axis range
y = -range:delta:range; % Determination of Y-axis range

lim = (2 * range / delta) + 1; % Number of data points

for i = 1:lim
    for j = 1:lim

        % Conversion to Polar Coordinates

        r(i,j) = sqrt(x(i)^2 + y(j)^2);

        if r(i,j) < 1

            r(i,j) = 1;

        end

        if (x(i) == 0) && (y(j) >= 0)

            theta(i,j) = pi/2;

        elseif (x(i) == 0) && (y(j) < 0)

            theta(i,j) = -pi/2;

        elseif (x(i) > 0) && (y(j) >= 0)

            theta(i,j) = atan(y(j)/x(i));

        elseif (x(i) < 0) && (y(j) >= 0)

            theta(i,j) = pi - atan(y(j)/x(i));

        elseif (x(i) < 0) && (y(j) <= 0)

            theta(i,j) = pi + atan(y(j)/x(i));

        else

            % (x(i) > 0) && (y(j) < 0)

            theta(i,j) = 2*pi - atan(y(j)/x(i));

        end

    end

end
```

```

% Calculation of Temperature Distribution

summ(i,j) = 0;

for n = 0:10

    if n == 0

        en = 1;

    else

        en = 2;

    end

    summ(i,j) = summ(i,j) + en*(Bessell(n,Pe)/BesselK(n,Pe))*BesselK(n,Pe*r(i,j))*cos(n*theta(i,j));

end

T(i,j) = Tv - (Tv-T0)*(1-exp(-Pe*r(i,j)*cos(theta(i,j))))*summ(i,j);

end
end

% Generation of Contour Curves for Material's Melting Temperature

[X,Y] = meshgrid(x,y);
v = [1675.65 1725.65]; % Tm = 750.15-908.15 (avg = 829.15) Al 7075
contour(Y,X,T,v);
grid;
set(gca, 'XTick', [-range:1:range], 'YTick', [-range:1:range]);
% xlabel('x (normalized)');
% ylabel('y (normalized)');

```

14.1.3 SUS 304 Penetration Model

```

clear;
clc;

% Material Properties of SUS 304

k = 21.5; % Thermal conductivity in W/(m*K)
% Cp = 500; % Specific heat capacity in J/(kg*K)
% ro = 8000; % Density in kg/m^3
alpha = 4.05e-6; % Thermal diffusivity in m^2/s
Tv = 3273.15; % Vaporization temperature in K

% Model constants

C = [2.1995 6.2962 -4.994 .0461];

% Welding conditions

```

```

Pi = [25 45 50 65 85 90 100 130 170 200]; % Incident power in W
T0 = 293.15; % Ambient temperature in K

lim = 5;
delta = 0.1;

Pe0 = 0:delta:lim;

for i = 1:lim/delta + 1

    for j = 1:10

        d(i,j) = (Pi(j) / (k * (Tv - T0))) * (1 / ((C(1) / 1) * Pe0(i)^(1-1) + (C(2) / 2) * Pe0(i)^(2-1) + (C(3) / 3) *
        Pe0(i)^(3-1) + (C(4) / 4) * Pe0(i)^(4-1)));

    end

end

% hold on;
% plot(Pe0, d(:,1), 'ro');
% plot(Pe0, d(:,2), 'ko');
% plot(Pe0, d(:,3), 'kx');
% plot(Pe0, d(:,4), 'k+');
% plot(Pe0, d(:,5), 'k. ');
% title('Penetration in SUS 304 at different powers (50-200 W)');
% xlabel('Peclet number');
% ylabel('Penetration (m)');
% gtext('300 W');
% gtext('270 W');
% gtext('240 W');

% grid
% hold off;

```

14.1.4 Beam Profile

```

clear;
clc;

% P = [15 20 25 30]; % Corresponding Power Percentages
P = [39 53.5 72 97 119]; % Power settings in Watts

D(1) = 1; % Normalization of Spot Diameters

for i = 1:3

    D(i+1) = sqrt(P(i+1)/P(1))*D(1); % Calculation of Normalized Spot Diameters

end

% Resulting Measurements of Half of Weld Length

```

```

x = [-6.831 -5.673 -3.585 -1.849 1.849 3.585 5.673 6.831];

% Depth Calculation
x = x.*sin(12.2*pi/180);

% Conversion to Radii (applying symmetry)
R(1) = D(4)/2;
R(2) = D(3)/2;
R(3) = D(2)/2;
R(4) = D(1)/2;
R(5) = D(1)/2;
R(6) = D(2)/2;
R(7) = D(3)/2;
R(8) = D(4)/2;

% plot(x,R,'x')          % Initial(Normalized) Plot Generation
% xlabel('x (mm)');
% ylabel('R (microns)');
% axis([-2 2 0 1]);

% Actual Radii Calculation
for i = 1:8

    realR(i) = abs(R(i)*5.4/.4872); % Min Spot Radius = 5.4 microns
                                   % Vertex of Parabola = .4872
                                   % (@ D = 0)

end

% Final ("Denormalized") Plot Generation
plot(x,realR,'x')
xlabel('Distance Away from Most Focused Spot (mm)');
ylabel('Spot Radius (microns)');
title('Spot Radius Variation as the Distance Away from the Most Focused Spot changes')
axis([-2 2 0 10]);
% grid;

```

14.2 Cross-Sections Welded at 80% and 90% Power

14.2.1 90% Power

Figure 14.1: Weld cross-sections for 2 mm/s, at 90% Power

Figure 14.2: Weld cross-sections for 3 mm/s, at 90% Power

Figure 14.3: Weld cross-sections for 4 mm/s, at 90% Power

Figure 14.4: Weld cross-sections for 5 mm/s, at 90% Power

Figure 14.5: Weld cross-sections for 6 mm/s, at 90% Power

14.2.2 80% Power

Figure 14.6: Weld cross-sections for 2 mm/s, at 80% Power

Figure 14.7: Weld cross-sections for 3 mm/s, at 80% Power

Figure 14.8: Weld cross-sections for 4 mm/s, at 80% Power

Figure 14. 9: Weld cross-sections for 5 mm/s, at 80% Power

Figure 14.10: Weld cross-sections for 6 mm/s, at 80% Power