

To the Graduate Council:

I am submitting herewith a thesis written by Jacquelyne C. West entitled "CO₂ Laser Welding of Al 6061 Using Al 4043 Filler and Spectral Monitoring of the Weld Plasma Plume to Predict Cracking." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science with a major in Engineering Science.

Mary Helen McCay
Mary Helen McCay, Major Professor

We have read this thesis
and recommend its acceptance:

C. Lopez n.b.

L. Montgomery Orrell

Accepted for the Council:

C. W. Mink
Associate Vice Chancellor and
Dean of The Graduate School

CO₂ Laser Welding of Al 6061 Using Al 4043 Filler
and Spectral Monitoring of the Weld Plasma Plume
to Predict Cracking

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Jacquelyne C. West
August 1996

ACKNOWLEDGMENTS

This research would not have been possible without the support of the faculty and staff of both the University of Tennessee and Argonne National Laboratory.

Many thanks to Drs. McCay, Dahotre, Smith, and Leong. Also, many thanks to Vlad Semak, Mike Sharp, Newt Wright, Jim Hornkohl, Bob Roach, John Hopkins, Chenghe Xiao, and Jon Winkler.

My family and friends deserve equal credit in helping to produce this work. They have counseled me. They have backed me. They have even been my most demanding critics. I would have been lost without them. Thank you for being there, Mom, Dad, Ken, Vlad, Lauri, Steve, and all the dearest people in my life.

ABSTRACT

Spectral sampling of emissions from the weld plasma plume is investigated as a technique for monitoring conditions which affect cracking in laser welded Al 6061. The approach is to study the effect of Al 4043 wire filler additions on the degree of weld cracking and to correlate the degree of cracking with the ratio of intensities from the 383.8 nm magnesium line and the 396.2 nm aluminum line emitted from the weld plasma.

A 3 kW CO₂ laser and a wire feeder were used to produce bead on plate welds for the experiment while a 0.25 m spectrometer with an optical multi-channel analyzer (OMA) was used for the spectral sampling. The feed rate of 0.76 mm diameter filler wire was varied over a range of 0 - 11500 mm/min while other welding parameters were held constant. Welds were characterized by examining overviews for surface cracks and inconsistencies in the weld bead, and by determining an average ratio of the total crack length (l) to the length of the fusion zone perimeter (p) for five transverse cross sections. Also, from seven spectral samples taken during each weld, the average ratio of intensities for the 383.8 nm magnesium line to the 396.2 nm aluminum line was found. The line intensity ratio was correlated with l/p .

For wire feed rates in the range of 6000 - 11500 mm/min, the line intensity ratio was found to vary linearly with the degree of cracking (l/p) when curve fits were applied to the data. Outside of this range, cracking was too inconsistent to be used for correlation.

TABLE OF CONTENTS

CHAPTER	PAGE
I. INTRODUCTION.....	1
II. BACKGROUND.....	5
A. Conventional Welding of Aluminum Alloys.....	5
B. Laser Beam Welding of Aluminum Alloys.....	10
1. Physics of Laser Beam Welding.....	12
2. Experimental Research in Laser Beam Welding Using Wire Fillers.....	15
3. Experimental Research in Spectral Monitoring of Laser Weld Plasma.....	17
C. Qualitative Correlation Between Cracking and Spectral Output.....	19
D. Rationale for the Experiment.....	20
III. EXPERIMENTAL PROCEDURE.....	23
A. Overview of Work.....	23
B. Equipment.....	23
C. Procedures.....	25
1. Preparing Aluminum Alloys Prior to Welding.....	25
2. Calibrating of the Spectrometer and Setting OMA Sampling.....	25
3. Calibrating the Wire Feeder.....	28
4. Welding the Coupons.....	28
5. Characterizing the Welds.....	29
6. Reducing Spectral Sample Data.....	30
IV. RESULTS.....	34
A. Weld Characterization.....	34
B. Spectral Monitoring.....	39
V. DISCUSSION.....	41
A. Qualitative Correlation of Results.....	41
B. Quantitative Correlation of Results.....	45
VI. CONCLUSIONS.....	47
LIST OF REFERENCES.....	50
APPENDICES.....	53
Appendix A: Tables.....	54
Appendix B: Figures.....	63
VITA.....	92

LIST OF TABLES

TABLE	PAGE
1. Nominal composition of alloying elements in Al 6061 and Al 4043 based on weight %.....	55
2. Significant spectral lines identified between 268 nm and 468 nm using a 300 groove/mm diffraction grating.....	55
3. Laser processing parameters.....	56
4. Results of microhardness testing.....	56
5. Crack length and fusion zone perimeter measurements from weld cross-sections.....	57
6. Spectral data for intensity ratios of the 309.3 nm and 396.2 nm aluminum lines.....	60
7. Atomic transition probability data used to calculate plasma temperature	61
8. Spectral data for intensity ratios of the 383.8 nm magnesium line and the 396.2 nm aluminum line.....	62

LIST OF FIGURES

FIGURE	PAGE
1. An Al 6061-T6 aircraft-engine oil-line failure caused by welding flaws.....	64
2. Schematic of a fusion weld transverse cross-section.....	65
3. Hydrogen solubility in pure aluminum.....	66
4. An example of solidification cracking in arc welded aluminum...	67
5. An example of liquation cracking in a badly overheated oxyacetylene weld in Al 6061-T6.....	68
6. Relative crack sensitivity versus weld composition for various binary aluminum systems.....	69
7. Relative crack sensitivity ratings of selected aluminum (base alloy / filler alloy) combinations.....	70
8. Common TEM shapes and corresponding plots of relative intensity versus radial position in the beam.....	71
9. Schematic of a transverse cross-section of keyhole mode welding showing the melted metal pool with a coincident laser beam and resulting keyhole.....	72
10. Mercury calibration lamp emission sample taken with the 300 grooves/mm diffraction grating	73
11. Copper vapor calibration lamp emission sample taken with the 1200 grooves/mm diffraction grating.....	73
12. Weld plasma plume emission sample taken with the 300 grooves/mm diffraction grating.....	74
13. Weld plasma plume emission sample taken with the 1200 grooves/mm diffraction grating.....	74
14. Deuterium calibration lamp emission sample taken with the 300 grooves/mm diffraction grating.....	75

15.	Relative intensity of the 383.8 nm magnesium line versus the elapsed time (ms) from the moment of triggering the OMA for 5500 mm/min wire feed rate.....	76
16.	Schematic of experimental set-up.....	77
17.	Photograph of fixturing with weld coupon, fiber optic cable, wire feeder, and laser head in position for welding.....	78
18.	Weld cross-section with the crack length (l) and fusion zone perimeter (p) labeled.....	79
19.	Overviews showing the top surface (a) and the bottom surface (b) of a weld made with the wire feed rate at 5000 mm/min.....	80
20.	Overviews showing the top surface (a) and the bottom surface (b) of a weld made with the wire feed rate at 11500 mm/min.....	81
21.	Cross-section views of welds made with wire feed rates of (a) 3000 mm/min, (b) 4500 mm/min, (c) 6500 mm/min, (d) 11500 mm/min	82
22.	Schematic of a weld coupon showing the orientation of transverse cross-section slices.....	86
23.	Total Crack length (l) divided the length of the fusion zone perimeter (p) versus wire feed rate (mm/min).....	87
24.	SEM/EDS results from quantitative analysis of the element content in the base alloy, the wire filler, and the fusion zones of welds with wire feed rates 5000 - 11500 mm/min.....	88
25.	Ratio of 309.3 nm line intensity to 396.2 nm line intensity versus wire feed rate (mm/min).....	89
26.	Intensity ratio of the 383.8 nm magnesium line and the 396.2 nm aluminum line versus wire feed rate (mm/min).....	90
27.	Intensity ratio of the 383.8 nm magnesium line and the 396.2 nm aluminum line versus total crack length (l) divided by the length of the fusion zone perimeter (p).....	91

NOMENCLATURE

a	Designation for the element undergoing the <i>nm</i> transition
A	Einstein transition probability coefficient
AA	Aluminum Association
Al	Aluminum
ASM	American Society for Metals
b	Designation for the element undergoing the <i>ji</i> transition
c	Speed of light
C _{1,2,3}	Constants
cm	Centimeter (10 ⁻² meters)
CNC	Computer numeric control
Cr	Chromium
CW	Continuous wave
E	Electron transition energy
EDS	Energy Dispersive Spectroscopy
g	Statistical weight
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
h	Planck constant
HAZ	Heat Affected Zone
i	Designation for the lower electron energy transition level of a second emission line
I	Relative intensity
ipm	Inches per minute
J	Joule
j	Designation for the upper electron energy transition level of a second emission line
k	Boltzmann constant
K	Kelvin
kJ	Kilojoules
kW	Kilowatt
l	Total crack length (mm)
LBW	Laser Beam Welding
m	Meter; designation for the lower electron energy transition level
Mg	Magnesium
mm	Millimeter (10 ⁻³ meters)

n	Designation for the upper electron energy transition level
N	Population density (of plasma specie)
OMA	Optical Multi-channel Analyzer
p	Length of fusion zone perimeter (mm)
nm	Nanometer (10^{-9} meters)
PC	Personal computer
RF	Radio Frequency
s	Second
SEM	Scanning electron microscope
T	Plasma temperature
TEM	Transverse electromagnetic mode
ϵ	Volume emission coefficient
λ	Emission wavelength
θ	Designation for the total of all possible transitions for an element
μm	Micrometer (10^{-6} meters)

CHAPTER I

INTRODUCTION

Wrought aluminum alloys containing magnesium and silicon make up the Aluminum Association (AA) 6xxx series. Aluminum-magnesium-silicon systems are medium strength in wrought form and may be heat treated to attain higher strengths. In addition, they have good formability, machinability, and corrosion resistance. A particularly popular alloy in the 6xxx series is Al 6061.

Since Al 6061 has a high strength to weight ratio, it is used frequently in structural applications where weight reduction is important. From aircraft and automobile frames to pipelines to lawn furniture, the alloy can be found in a vast array of products. It would probably be used even more extensively except for one drawback. Like most of the 6xxx series alloys, Al 6061 has a relatively low weldability, meaning the ease of making sound welds is hampered by flaws such as porosity and cracks [1].

The ability to weld reliably Al 6061 is critical to many engineering designs. Gas-tungsten arc welding (GTAW) and gas-metal arc welding (GMAW) are proven methods of producing acceptable welds, but both processes are relatively slow and result in a large heat affected zone (HAZ) where the alloy grain structure is larger and weaker than surrounding regions in the weldment. Arc welding is also labor-intensive, costly, and subject to many quality control difficulties.

Failures that result from low quality welds can be catastrophic and happen unexpectedly. An example of a failure in an aircraft oil-line subassembly where a V-joint in welded tubing separated into two pieces is shown in Figure 1* [2]. The assembly is made of Al 6061-T6 (solution heat treated and artificially aged) joined by GTAW. Despite post-weld heat treating to T6 temper, making the expected life of the part near that of the aircraft, the assembly broke less than a year after it entered service. Consequently, aircraft engine oil was lost in flight. An investigation showed the weld failed due to fatigue cracking initiated by flaws that were not detected during manufacturing. Subassemblies on other aircraft failed similarly. Attempts to reweld the tubes and return the parts to service were unsuccessful. As a corrective measure, the subassemblies were replaced using a new design to lower stresses in the weld. The manufacturer also improved the training of its welders and stepped up quality control inspections, all at considerable cost.

This case, along with many others, demonstrates why better welding processes and better techniques for monitoring weld quality are valuable to industry. Laser beam welding (LBW) is one process which offers improvements over GTAW and GMAW by increasing weld speeds and reducing the HAZ size in aluminum alloy welds [3]. In addition, spectral sampling of the radiation emissions generated during LBW has been shown to be useful as an "in-process" tool for monitoring weld

* All figures and tables may be found in the appendices.

properties [4] [5] [6], promising a means of detecting problems *before* parts leave the production floor. LBW, however, has unique processing parameters that have not been completely characterized for Al 6061, and research in spectral monitoring of weld quality is currently limited.

In this study, spectral sampling of emissions from the weld plasma was investigated as a technique for monitoring conditions that affect cracking in laser welded Al 6061. Cracks can cause devastating failures in aluminum alloy welds since they act as severe stress concentration points, therefore in a production setting it is imperative to have the ability to identify and reject cracked welds. Often, cracks are not detectable except by destructive testing. This can pose serious quality control problems in industrial applications. Investigating means of reducing the sensitivity of aluminum alloys to cracking during laser welding is essential to improving the process. In addition, a means of monitoring -- during welding -- the conditions which lead to cracking would certainly be beneficial. Therefore, the present work has made use of wire filler additions to address the difficulties of determining the degree of cracking in laser welded Al 6061.

The approach was to study the effect of Al 4043 filler additions, in the form of wire feed, on the degree of weld cracking and to monitor plasma emissions. A 3kW continuous wave (CW) CO₂ laser and a wire feeder were used to produce bead on plate welds for the experiment while a 0.25 m spectrometer with an optical multi-channel analyzer (OMA) was used for the spectral sampling. The feed rate of 0.76 mm (0.030 inch) diameter filler wire was varied over a range of 0 - 11500 mm/min

while other welding parameters were held constant. Welds were characterized by examining overviews for surface cracks and inconsistencies in the weld bead, and by determining an average ratio of the total crack length (l) to the length of the fusion zone perimeter (p) for five transverse cross sections. Also, from spectral samples taken during each weld, the average ratio of intensities for the 383.8 nm magnesium line to the 396.2 nm aluminum line was found. The line intensity ratio was correlated with l/p .

The purpose of the study was to show a qualitative correlation between crack formation, as the wire feed rate was varied, and the ratio of intensities from two atomic spectral emission lines radiated from the weld plasma.

Subsequent chapters include the background, experimental procedure, results, discussion, and conclusions. The background chapter contains a description of crack formation in conventional welding and LBW. Also included is a survey of current literature on the subject. In the experimental procedure chapter, equipment and procedures are described along with techniques for data analysis. Experimental data are presented in the results chapter and interpreted in the discussion chapter. Finally, conclusions and recommendations appear in the conclusion chapter.

Research for this work was carried out at the University of Tennessee Space Institute's Center for Laser Applications, Tullahoma, Tennessee and at Argonne National Laboratory, Argonne, Illinois.

CHAPTER II

BACKGROUND

A review of both the physics of conventional aluminum welding techniques and the physics of laser beam welding is helpful to motivate studying the relation between cracking in laser welded aluminum alloys and spectral emissions from the weld plasma. In addition, a review of related research in laser welding and spectral monitoring of welds is offered. With this background, it will be possible to postulate how a correlation between spectral emissions and cracking arises.

A. Conventional Welding of Aluminum Alloys

Welding is a joining process where the “localized coalescence” of materials is achieved by applying heat and/or pressure [7]. Welding processes fall into two categories according to whether they use fusion or solid-state coalescence. In fusion processes, work-piece material is melted, mixed, and resolidified to form a joint, examples being resistance welding, arc welding, oxyfuel gas welding, and laser beam welding. Solid-state processes use mechanisms such as diffusion and plastic deformation to bond materials at temperatures below the melting point. Examples of these processes include ultra-sonic welding, friction welding, forge welding, and hot isostatic pressure welding.

Fusion and solid-state welding processes are common methods for joining most aluminum alloys, including heat treatable systems such as the 6xxx series.

Depending on the application, certain processes are more desirable than others. Two are used more frequently in wider variety of aluminum products than any of the others [8]: gas-tungsten arc welding (GTAW) and gas-metal arc welding (GMAW). Their reliability and versatility have made them “conventional” welding processes for aluminum alloys.

GTAW is a welding process that fuses metals by heating them with an electrical arc generated between a non-consumable tungsten electrode and the work-piece [9]. The arc and weld pool are shielded by an inert gas, typically helium, argon, or a mixture of both to help sustain the arc and to prevent reactive atmospheric gases from interacting with the weld pool. Filler wire may be used, but it is not necessary for maintaining the arc. Advantages of the process include precise control over welding heat input, ability to weld almost all metals, and no spatter as associated with other methods requiring fluxes. Disadvantages are slow welding speeds, erosion of the electrode contributing to weld pool contamination, and a high skill level required of operators.

GMAW is also a fusion welding process. In GMAW, heat is delivered by an electrical arc established between a continuously fed filler-metal electrode and the work-piece [10]. As with GTAW, the arc and weld pool are typically shielded with inert gas, although with special materials, reactive gases such as carbon dioxide serve as shielding [10]. Some of the advantages associated with GMAW are faster welding speeds compared to GTAW, long welds which are not interrupted by discontinuous supply of electrode rods, welding in all positions, and a lower skill level required for

operators. Disadvantages include the necessity for a power supply at each work station, consumable electrodes, and high levels of radiated heat and arc intensity which hinder operators.

Flaws in fusion welds can appear in the fusion zone or in the heat affected zone (HAZ). Figure 2 is a schematic showing these areas in a transverse cross-section of a typical weld. In the case of welding 6xxx series aluminum alloys, three flaws are inherent to fusion joining methods and are typical in GTAW and GMAW: *porosity*, *HAZ degradation*, and *cracking* [1].

Porosity

Porosity occurs in the fusion zone and is attributed primarily to hydrogen gas. Hydrogen has a high solubility in molten aluminum and is readily absorbed from moisture in the atmosphere or from hydrated oxides and organic compounds that appear on aluminum surfaces. Since hydrogen is practically insoluble in solid aluminum, it is rejected at the solidification front, often forming bubbles that are trapped in the fusion zone. The relation between the solubility of hydrogen in aluminum and temperature is presented in Figure 3 which demonstrates the significant drop in hydrogen solubility when the temperature is decreased below the aluminum melting point. Porosity is reduced by removing as much hydrogen as possible from the welding environment. Using dry shield gas, cleaning excess oxides from weld areas, and storing welding stock in a warm, dry place help prevent hydrogen contamination.

HAZ degradation

HAZ degradation in 6xxx series welds is a result of microstructure changes associated with elevated temperatures in the base material surrounding a weld [1]. Typically, an alloy contains as much as 1.5% magnesium by weight along with silicon in the ratio of approximately 1.7:1. The two alloying elements combine to form Mg_2Si , which has a maximum solubility of 1.85% (by weight) and decreases with lower temperatures [11]. Controlled precipitation of Mg_2Si during heat treatment creates metastable phases which increase the hardness and strength of the alloy. During welding, however, elevated temperatures in areas around the weld cause the metastable phases to transform into non-strengthening phases [2] and precipitates to grow in excessive size, resulting in a weak grain structure surrounding the fusion zone. Post heat treatment can correct the problem, except in the case where magnesium has been lost through overheating of the melt pool. This may lower the maximum amount of Mg_2Si that can be formed and limit the effectiveness of post weld heat treatment. Strength of welds can be improved by reducing the size of the HAZ where the strengthening effects of precipitation hardening are reversed and also by avoiding magnesium losses.

Cracking

Cracking may be seen either in the fusion zone or in the HAZ. It is a metallurgical problem caused by thermophysical properties inherent to aluminum alloys: a large coefficient of thermal expansion, a wide solidification temperature

range, and a large change in volume upon solidification [1]. These properties lead to solidification cracking and liquation cracking. Solidification cracks occur in the fusion zone when high thermal stresses act in conjunction with solidification shrinkage to split the weld as it solidifies. The effects are believed to be more severe for high heat inputs, for example, slow high power welds [1]. Figure 4 shows a solidification crack which is visible in the top surface of an aluminum arc-weld bead.

In contrast, liquation cracks form when eutectic phases with melting temperatures less than the melting temperature of the base material liquate at grain boundaries [1]. This is typically seen at the edges of the fusion zone. As with solidification cracks, thermal stresses and solidification shrinkage cause the liquid regions between the grain boundaries to widen, forming cracks. Figure 5 illustrates an extreme case of liquation cracking in an Al 6061 weld.

For both solidification and liquation cracking, material may be added to modify the alloy composition and lower solidification temperatures, allowing the cracks to heal before solidification is complete [12]. This is typically accomplished through the addition of an aluminum-silicon system with high silicon content, for example, a 4xxx series aluminum alloy. Adding too much silicon, on the other hand, will lead to dilution of the Mg_2Si precipitate along with excessive precipitation of primary silicon and result in a weak weld. An alternate approach is to fill with a 5xxx series alloy which contains magnesium. The liquation temperature is not suppressed as well, but cracking may be adequately controlled while weld strength is improved. Determining the appropriate filler additions for maximizing weldability and strength has been the

object of numerous works as reviewed by Davis [1]. Some of the results from these studies are summarized in Figures 6 and 7.

Carefully controlled GTAW and GMAW produce high quality 6xxx series welds. A minimal amount of porosity is present in welds made from clean, dry, well-shielded work-pieces. While autogenous welds (those made between similar alloys without the use of filler metal to modify the alloying) almost always have cracks, a filler can be used to lower sensitivity to weld cracking and improve other material properties such as strength. Arc welding of aluminum alloys, however, requires highly skilled labor and is still prone to quality control problems. Plus, it is a relatively slow process with high heat input, and so even the best arc weld techniques produce a large HAZ. Although post heat treatment reduces the severity of the latter problem, it is certainly not a desirable secondary operation. While the end product may be acceptable, a better alternative is to make welds with a limited HAZ and use more automated process controls where possible. In this work, laser beam welding is examined as a possible process which offers these improvements.

B. Laser Beam Welding of Aluminum Alloys

Laser beam welding (LBW) uses coherent, high-energy-density (10^5 to 10^7 W/cm²) laser light to fuse materials [13]. The physics of LBW differ from conventional arc welding. As a result, the process has its own advantages and disadvantages over GTAW or GMAW. Advantages include [14] [15]:

1. *High energy density heat input.* Rapid heating and cooling results in a minimal HAZ size, less distortion of the work-piece, and faster welding speeds compared to conventional techniques. Deep, narrow welds can be made in one pass where multiple passes would be required of arc processes.
2. *No electrode.* Contamination of the weld due to electrode erosion is completely absent. Likewise, heat input is more consistent.
3. *Optical delivery of the beam.* Fast start/stop motions are possible as well as manipulation of the beam into otherwise inaccessible areas. Time sharing of the laser between work stations is also possible with optical delivery of the beam, making LBW a flexible welding process that can increase production efficiency.

Though LBW offers many attractive advantages over arc welding, it is not a process without difficulties. If these drawbacks are to be overcome, an understanding of the unique physics of LBW is necessary. The following discussion describes some of the process's physics in order to address problems encountered during laser welding. Thus, a description of some of the important aspects of LBW physics is included.

1. Physics of Laser Beam Welding

The term *laser* is an acronym for *light amplification by stimulated emission of radiation*. It produces a coherent beam of radiation with a wavelength that is characteristic of the electron energy transition level of the lasing media. For instance, the wavelength produced by CO₂ lasers, which are commonly used for industrial welding, is 10.6 μm . Coherency and monochromaticity of the beam allows optical focusing to a small spot size with an extremely high energy density. Multikilowatt CO₂ lasers can deliver energy at intensities three orders of magnitude higher than arc sources.

The energy density, though, is not uniform across the diameter of a laser beam. A profile of the spatial energy distribution in a transverse cross-section is dependent upon the transverse electromagnetic mode (TEM). It is a result of the arrangement of the laser cavity, the lasing media, the excitation system, and optical feedback. Several common TEM shapes and corresponding plots of relative intensity versus radial position in the beam are given in Figure 8. The plots show that low order modes (for instance TEM₀₀ and TEM₁₀) have higher peak intensities and can be focused to smaller spot sizes, increasing the energy density delivered in welding. For this reason, the TEM can have a significant effect on laser welding.

The energy density absorbed in LBW determines the mode of welding. A low intensity beam that causes melting of the material but little or no vaporization produces a "conduction limited" weld. The result is like an arc weld and requires similar shielding and processing controls. Fusion zones for this mode have a low

depth to width ratio (See Figure 2) which is typical of welds in which heat transfer is dominated by conduction and convection. On the other hand, high intensity beams are capable not only of melting but vaporizing target material, forming a weld pool with a deep surface depression around the point of beam incidence. A schematic diagram illustrating this physical phenomenon is shown in Figure 9. The depression, called the "keyhole," is held open by a balance between ablation pressure and the surface tension pressure, hydrostatic pressure, and pressure due to melt flow (with potentially high velocities) around the cavity [16].

Once the keyhole is formed, the beam is "coupled" to the work-piece. Radiation enters the keyhole and is subject to multiple reflections before escaping, thus the keyhole acts as an optical blackbody. In addition, plasma is generated from the vaporized material in the keyhole as the laser beam continues to heat these gases to extreme temperatures. The plasma may attenuate the laser beam, reducing the effect of coupling, or it may absorb energy from the beam and re-radiate at wavelengths that increase the coupling efficiency [14]. The keyhole mode of welding produces "deep penetration" welds characterized by high depth to width ratios which increase the "joining efficiency" of the process. Joining efficiency is defined as the reciprocal of the specific energy and has the units $\{ \text{mm}^2 \text{ joined} / \text{kJ supplied} \}$ [14]. Typical joining efficiencies for arc welding are 0.8 to 3 mm^2 / kJ while lasers have efficiencies in the range of 15 to 25 mm^2 / kJ .

Several material properties for aluminum alloys may adversely affect the LBW process. These properties are high surface reflectivity, high thermal conductivity,

large differences in vapor pressure between aluminum and many of its alloying constituents, low viscosity, and low surface tension in the molten state [3].

High reflectivity and thermal conductivity, in particular, make conduction limited laser welding nearly impossible, since a beam with insufficient intensity to couple with the aluminum typically reflects from a work-piece and does not deliver enough heat to cause significant melting. On the other hand, if keyhole mode welding is established, high quality, deep penetration welds may be produced. A threshold intensity of 1×10^6 (W / cm²) has been reported necessary for effective coupling of a CO₂ laser beam with aluminum alloys [3].

Coupling requires inducing vaporization of the liquid and is, therefore, affected by the vaporization temperatures and vapor pressures of alloying elements. Some alloying elements such as zinc, magnesium, and lithium have low boiling points and high vapor pressures which help establish and keep the keyhole open. This is beneficial to coupling, but for certain alloys, such as the 6xxx series, resulting losses of magnesium due to vaporization can lead to low weld strength. Careful control of processing parameters is necessary to avoid problems with magnesium loss [17].

Further, the stability of the keyhole depends on, among other things, the surface tension and viscosity of the molten metal in the weld pool. Since aluminum alloys have relatively low surface tension, the vapor pressure inside the keyhole may overcome this retaining force, causing liquid to be expelled from the weld pool and a subsequent collapse of the keyhole. In addition, low viscosity of aluminum makes

splashing even more likely. As a consequence, a laser weld may have spatter, vapor cavities, voids, and inconsistent penetration (spiking).

Cracking in laser welded aluminum alloys is problematic for the same reasons as given for arc welding. Lasers, though, may offer an advantage over arc techniques in reducing crack sensitivity. Large heat inputs, like those from high current and slow speed arc welds, appear to increase cracking. It follows that processes -- such as laser welding -- which lower the heat input by using high energy density heating and faster welding speeds reduce crack sensitivity [1]. This is a potentially significant benefit in choosing laser welding over arc processes. Therefore, cracking in laser welds is deserving of further investigation.

2. Experimental Research in Laser Beam Welding Using Wire Fillers

One method for overcoming some of the laser welding difficulties which are related to metallurgical properties is to modify weld alloys by adding filler metals in the form of, for example, wire feed. However, research in the area of LBW in conjunction with wire fillers is limited [3] [18] [19]. Several significant findings were made by Martukanitz and Smith [9] as well as Berkmanns (et al) [18]; still, the complexity of LBW physics has proven that more investigations are necessary to understanding of the effects wire fill has on controlling weld quality, cracking in particular.

Martukanitz and Smith studied the effects of filler metal additions on CO₂ laser beam welded aluminum alloys. Butt welds were made with two aluminum-copper-

magnesium systems and two aluminum-magnesium-silicon systems. Al 4047 and Al 5554 filler wires that were 0.9 mm and 0.8 mm in diameter were fed at rates ranging from 5100 mm/min to 7620 mm/min. Welding velocities ranged from 6360 mm/min to 7620 mm/min. A helium cross jet was used for plasma suppression and shielding. Welds were made parallel to the roll direction of the samples with laser beam powers between 6 kW and 7 kW with the beam in TEM₀₁* mode and focused approximately 9.5 mm above the sample surface. Mechanical testing to determine yield strength, tensile strength, and fatigue behavior was used to characterize welds. Fillers were found to have the following effects: "improved reinforcement of the weld profile," reduced sensitivity to solidification cracking, moderately increased joint strength in the heat treatable alloys, and slightly improved joint strength in non-heat treatable alloys. No analysis was performed to quantify the effects of fillers on cracking in the fusion zone or HAZ.

Berkmanns investigated the weldability of Al 5082 and Al 6016 using aluminum-magnesium and aluminum-magnesium-manganese systems for fillers. Several of his experimental conditions differed from those used by Martukanitz and Smith. First, a mixture of argon and helium was used for cover gas. The mix ratio was found to have a significant effect on weld quality. For Al 5082, a 1:1 ratio of argon and helium produced the best welds, while Al 6016 required a 2:1 mixture. Also, Berkmanns began trial welds using large diameter wires up to 2.0 mm in diameter, reasoning that large diameter wires have lower surface area to volume ratios and thus would carry less moisture-containing oxide into the weld pool. He reported

the feed rates required to deliver appropriate filler additions were slow enough that the radiated heat from the plasma caused the wires to melt and drop short of the weld pool. Better results were achieved with 0.8 mm wires fed at rates between 6000 mm/min and 12000 mm/min for weld velocities in the range of 1980 mm/min to 10200 mm/min. Mechanical testing was used to characterize the welds. It was found that filler additions improved yield strength and tensile strength, plus fatigue behavior improved except in the case where so much filler was added that notch action was created by a severe overbead. Again, no analysis was performed to quantify the effects of fillers on cracking.

Cracks can cause devastating failures in aluminum alloy welds since they act as severe stress concentration points. Often, cracks are not detectable except by destructive testing. This can pose serious quality control problems in industrial applications. Investigating the effects of filler additions on the sensitivity of aluminum alloys to cracking during LBW is essential to improving the process. In addition, a means of monitoring -- during welding -- the conditions which lead to cracking would certainly be beneficial. Therefore, the present work has made use of wire filler additions to address the difficulties of determining the degree of cracking in laser welded Al 6061.

3. Experimental Research in Spectral Monitoring of Laser Weld Plasma

Since recent investigations have shown that valuable information about weld quality can be obtained by monitoring spectral emissions from the plasma generated

during welding [4] [5] [6], the present work seeks to study how spectroscopy may be used as a monitoring tool for processing parameters that affect cracking. In light of this, the following section reviews experimental work in spectral monitoring of laser weld plasma.

The plasma generated during welding, whether from an arc process or a laser, emits radiation at specific wavelengths and intensities which are related to the atomic structure of the ions in the plume as well as the number of ions, their level of excitation, and the electron temperature. Since the plume is generated from heat input and the material in the area where heat interaction occurs, its spectral emission is characteristic of welding process parameters including the power density delivered to the weld, travel speed, constituents in the base material, constituents in fillers, and contaminants in the cover gas [5] [6].

Spectral emissions from weld plasmas have been studied as an in-process monitoring tool by McCay (et al) [6]. Spectral intensity and temperature of CO₂ laser weld plasma were measured as functions of the type of shield gas and its flow rate. Representative alloys from the aluminum 5xxx series served as weld materials. A narrow cross section of the plasma, 6 mm in height, was focused onto the entrance slit of a 0.25 m spectrometer that used a diffraction grating with 300 grooves per mm. Samples of spectral emissions in the 370 nm to 430 nm wavelength range were captured by an optical multi-channel analyzer (OMA) which stored 40 spectra for each weld sample at an integration time of 20 ms per spectra. Using ratios of line intensities from two different wavelengths emitted by the same element, temperature was found.

Likewise, relative amounts of alloy constituents in the plume were determined by calculating the area under the line profile. For the characterization of welds, transverse cross sections were mounted and polished to produce metallographs from which depth, width, and area of the fusion zone were measured. Results indicated that weld quality and plasma temperature are greatly affected by shield gas flow rates. Plasma temperature, in addition, depended largely on the volatility and ionization potential of alloy elements. Alloying elements for the welding material were positively identified in the plasma. As expected, large quantities of magnesium were found in the plume, indicating the element volatilized more readily than other alloy constituents, and its presence apparently had a significant affect on the plasma temperature. Alloys with higher magnesium content had hotter plasma temperatures which correlated to greater depth to width ratios in welds, hence, greater joining efficiencies.

C. Qualitative Correlation Between Cracking and Spectral Output

It is known that the plasma generated during laser welding contains elements present in the materials interacting with the laser beam, including those from the alloy being welded and the shielding gas [4] [5] [6]. The plasma emits radiation with specific wavelengths and intensities which are indicative of the population density and temperature of the excited elements [20]. These emissions have been shown to vary with laser weld processing parameters and different alloys [6], suggesting that such variations are related to the elemental content of material interacting with the beam and factors such as beam power density, cover gas flow, travel speed, etc. It follows

that resulting characteristics of welds may be correlated with "finger print" spectral emissions.

Cracking is a characteristic in laser welded aluminum alloys under many processing conditions. Susceptibility to cracking may be controlled by modifying the alloy with filler metals. Since the plasma emissions change for different alloys, it may be possible to monitor emissions while changing the alloy with filler additions and correlate recorded spectra with the cracking that results in the welds. This offers a possible means to monitor welding via the weld plume.

D. Rationale for the Experiment

In the present work, spectral sampling of emissions from the weld plasma was investigated as a technique for monitoring conditions which affect cracking in laser welded Al 6061. The approach was to study the effect of Al 4043 wire filler additions on weld cracking, as the wire feed rate was varied, and to correlate cracking with the ratio of intensities from two atomic spectral emission lines radiating from the weld plasma.

Al 6061 was selected for this study because it is an especially popular aluminum alloy which might be used even more extensively if the welding process can be improved. Furniture frames, automobile bodies, pipelines, trailer trucks, and bicycles are common applications where Al 6061 is welded [11]. Like most of the 6xxx series alloys, however, Al 6061 has a relatively low weldability. Other welding

difficulties include distortion of the work-piece and high residual stresses. A need to investigate ways of improving the weldability of Al 6061 is evident.

Previously referenced studies [3] [18] have shown LBW in conjunction with wire feed has the potential to improve welding of many aluminum alloys, including those belonging to the 6xxx series. The importance of choosing the correct filler alloy and quantity of filler additions was also demonstrated in these works. However, parameters were not established for Al 6061. Therefore, based on recommended fillers for conventional welding along with the results from Berkmanns' study involving laser welding with various sizes of feed wire [18], 0.76 mm (0.030 inch) diameter Al 4043 wire filler was chosen to be used with LBW for this investigation. The nominal compositions of the two alloys are given in Table 1. Comparing compositions to the data presented in Figures 6 and 7, the sensitivity to cracking in laser welded Al 6061 should be largely reduced or eliminated with increased additions (faster feed rates) of the filler wire.

Spectral monitoring was selected as a diagnostic for this study because it offers a means of determining the relative quantity of elements which exist as excited atoms in the weld plasma. This, in turn, may be correlated to process parameters such as the addition of filler metals. For this experimental study, the quantity of magnesium relative to aluminum in the plasma is expected to be an indicator of the Al 4043 filler additions necessary to control cracking. Spectral monitoring, where the intensity of a magnesium emission line is compared to an aluminum line, should indicate a change in the ratio of magnesium to aluminum content in the plasma. This relation is explained

more thoroughly in subsequent chapters. Most importantly, this change should correlate to the degree of cracking seen in Al 6061 as filler additions are increased.

An important consideration when monitoring spectra is choosing the appropriate lines. They must have intensities which are distinguishable from surrounding emissions and are within the wavelength window of the spectrometer. Silicon lines, although important to the constituencies of Al 6061 and Al 4043, are not readily visible under most welding conditions and are not easily monitored. Thus, they were not selected for monitoring in this study. The magnesium 383.8 nm line and the aluminum 396.2 nm line met the above criteria and were, therefore, chosen for monitoring. In addition an aluminum 309.3 nm line was selected since it was required in an intermediate step to analyze data. Analysis procedures are given in the following chapter.

CHAPTER III

EXPERIMENTAL PROCEDURE

A. Overview of Work

The experimental work for this project entailed making bead-on-plate laser welds in Al 6061-T4 (solution heat treated and naturally aged) using Al 4043 wire filler. Feed rates for the filler were varied while other processing parameters including travel speed, laser power, and cover gas flow were held constant. During welding, emissions from the weld plasma were sampled using a spectrometer with an optical multi-channel analyzer (OMA). Afterwards, the weld tracks were cross sectioned and examined metallographically to determine the degree of cracking for each wire feed rate. OMA data was converted to a format suitable for analysis on a personal computer (PC) where peak transmission intensities for the magnesium 383.8 nm wavelength and the aluminum 396.2 nm wavelength were extracted from the spectral data. The ratio of the two intensities was determined for each weld track to correlate with the degree of cracking for a given wire feed rate.

In the remaining portion of this chapter, complete descriptions of the equipment, procedures, and data reduction methods for the experiment are given.

B. Equipment

A Rofin-Sinar RS3000 CO₂ laser was used for all welding. The RS3000 design uses radio frequency (27.12 MHz) excitation and has a fast axial-flow cavity

configuration. It may be configured to produce TEM₀₀, TEM₁₀, TEM₂₀, or TEM₀₁* spatial modes in a linearly polarized beam which is circularly polarized with external optics. An optical beam delivery system with a 150 mm focal length copper off-axis parabolic mirror provides focusing of the beam to a 300 μ m diameter spot size. Also, the laser may be operated in one of four temporal modes: full CW, 5 kHz modulated power, pulsed (25 kHz max), and superpulsed (25 kHz max). A computer numeric controlled (CNC) five-axis Aerotech workstation is used to translate the work-piece during welding while also providing control of the laser and associated equipment such as flow valves for cover gas.

Wire feed was delivered by a Jetline CWF-20B industrial wire feeder. The CWF-20B has variable feed rate. It holds 30.5 cm (12 inch) wire spools (approximately 2.7 kg or 6 lb. of aluminum filler wire), and can be configured to feed standard wire diameters 0.51 - 2.36 mm (0.020 - 0.093 inches).

For the plasma emission measurements, a 0.25 m Jarrel-Ashe spectrometer with an OMA 1420 detector was used. Diffraction gratings with 300 grooves/mm and 1200 grooves/mm made it possible to scan a wide window of wavelengths (200 nm across) at low resolution or a narrow window (80 nm across) at a higher resolution. A quartz fiber optic cable with an entry angle of 12 degrees served as the optical system for transferring light from the plasma onto the spectrometer opening slits.

Analysis of alloy constituencies was performed using an International Scientific Instruments ISI Super III A scanning electron microscope (SEM) with a Noran

Instruments Series II X-Ray Analyzer which quantifies elemental contents based on the principle of energy dispersion spectroscopy (EDS).

Additional equipment used in the course of the experiment included a Scientech 390 water cooled calorimeter, a 10 kW laser beam power meter, and a Buehler Micromet II microhardness test machine.

C. Procedures

1. Preparing Aluminum Alloys Prior to Welding

Welding coupons, 38 by 51 mm (1.5 by 2.0 inch) rectangular pieces, were shear cut from 1.6 mm (1/16 inch) thick Alcoa Al 6061-T4 sheet metal. The coupons were cleaned with propanol and stored in dry, open-air conditions before welding.

The diamond-drawn 0.76 mm (0.030 inch) diameter Al 4043 wire filler was stored on a wire feed spool in a sealed plastic bag with silica packs for reducing moisture contamination which can lead to weld porosity. Once loaded in the feeder, the wire was protected from dust and moisture by a plastic shield surrounding the spindle. The wire traveled through a protective cable from the spindle shield to the delivery point. Wire that was handled during loading of the feeder was purged before welding.

2. Calibrating the Spectrometer and Setting OMA Sampling

A wavelength calibration of the spectrometer was performed using a mercury calibration lamp for the 300 groove/mm grating and a copper vapor calibration lamp

for the 1200 groove/mm grating. In both cases, a cubic spline fit was applied to extrapolate a wavelength calibration based on the wavelengths of five known emission lines identified in the emissions from each of the calibration lamps. The coarse grating was aligned to scan a spectral window between 268 nm and 468 nm, covering several significant emission lines for both magnesium and aluminum which are listed in Table 2. The maximum possible resolution for this arrangement was 0.3 nm. In order to identify two significant emission lines (at 383.8 nm and 396.2 nm), a spectral sample with higher resolution was required. Thus, the coarse grating was exchanged for the 1200 groove/mm grating which was aligned to scan between 381 nm and 402 nm, providing a maximum resolution of 0.1 nm. Figures 10 and 11 show calibration lamp emission samples taken for the two gratings. Figures 12 and 13 show weld plasma samples with the lines listed in Table 2 identified.

Relative (weld-to-weld) spectral intensity measurements were made during the experiment. An absolute intensity calibration was not conducted. However, a deuterium lamp was used to compensate for sensitivity variations across the 1024 separate detectors in the OMA linear array. To do this, a spectral sample was taken with the lamp in place of a weld plume. Figure 14 shows the detector array response.

The intensities for each spectral sample recorded during welding were subsequently divided by intensities corresponding to the same wavelengths from the deuterium lamp. For every weld a total of 20 samples were taken, each at 100 ms intervals. With the given travel speed (3000 mm/min), the sampling covered twice the coupon length to give time to trigger manually the OMA. Thus, there were 10

samples which were taken either before or after crossing the coupon. Figure 15 shows a typical recording of the spectral intensity for the 383.8 nm magnesium line versus time. An initial low value occurs during the period before the laser strikes the coupon. During this period, wire filler was fed into the laser beam. A plasma was generated as the filler interacted with the beam, but since the wire contained extremely small amounts of magnesium (0.05 % by weight is a specified maximum amount of magnesium contamination in Al 4043), there was no significant source for the plasma to acquire large amounts of magnesium and emit strong intensities at its characteristic wavelengths. The sudden rise to a peak intensity indicates laser interaction with the weld coupon which contains a nominal 1% magnesium and can provide the element to the plasma. Another peak exists later in the sampling. These peaks may be a result of edge conditions where less material is available as a heat sink and "over heating" of the weld may affect the plasma emissions. Between the intensity peaks lie about seven data points of relatively constant values. These seven points in the constant regime were used for each weld.

With the spectrometer slits at a nearly closed position, the OMA exposure time was adjusted between 25 ms and 50 ms to minimize noise while avoiding saturation of the detectors. For all samples, background emissions from lighting in the laboratory were taken with the fiber optic cable in place for welding. The background was automatically subtracted from all weld spectral samples using the OMA.

3. Calibrating the Wire Feeder

Feed rates for the CWF-20B are set by adjusting a potentiometer which must be calibrated according to the diameter of wire being fed. In this instance, the device was configured for 0.76 mm (0.030 inch) diameter wire. A spool of wire was loaded, and start/stop triggering was controlled by CNC. The feeder was run for 2.2 seconds at five potentiometer settings ranging from 200 to 600 scale units. For each setting, the length of delivered wire was measured and used to determine wire speed. A linear relation between feed rate and the potentiometer dial reading was found such that the feed rate (ipm) corresponded to the potentiometer reading multiplied by a proportionality constant of 0.82.

4. Welding the Coupons

Figure 16 gives a schematic of the experimental apparatus. Positioning of the wire feed delivery tube and the fiber optic cable was constrained by the dimensions of the optical delivery system and the weld fixturing. The laser beam was focused on the surface of the weld coupon, and the copper hold-down fixture was tilted 10 degrees from the travel axis to avoid back reflection into the laser. The fixture was translated relative to the beam, making welds along the roll direction of the coupon. Coupons were fixed by loosely clamping two sides with copper pinch-plates to hold the pieces level and in place as shown in the photograph of the fixturing arrangement in Figure 17. Stand-off for the assist gas nozzle was 8 mm with helium supplied at 7 liters /

minute. Helium was also used as a shroud gas supplied from below the weld coupon at a rate of 15 liters / minute.

The laser processing parameters are listed in Table 3. All parameters were held constant while wire feed rate was varied at 500 mm/min increments from 0 - 11500 mm/min to cover the maximum range of possible wire delivery speeds. Power was set using the RS3000 internal calorimeter. A Scientech 390 calorimeter and a 10 kW laser power meter were used as well to check laser power externally.

For each weld, a new coupon was clamped to the hold-down fixture, and the surface was cleaned with propanol. A different wire feed rate was selected for all welds. Triggering of the laser, helium flow valves, fixture translation, and wire feed was managed by CNC while triggering of the OMA was handled manually. Prior to each weld, the helium gas lines were purged for four seconds and the wire feeder was allowed a half second delay to reach operation speed before translating the work-piece. A total of 18 welds were made using this procedure.

5. Characterizing the Welds

Overview photographs of welded coupons were made, and any apparent surface cracks or inconsistencies in the bead were noted. Subsequently, five transverse cross sections were cut from each weld track. The pieces were mounted in bakelite to be polished using 600 grit grinding paper followed by lapping with 0.3 μm and 0.05 μm alumina polishing slurries and etching with Keller's agent. From micrographs printed off of 35 mm film images, the length of the fusion zone perimeter, p , and total

crack length, l , of each cross-section were measured by means of a compass and knowledge of the magnification. On the photographs, which were enlarged to give a magnification of 28X, point-to-point measurements were made with the compass spread to 3 mm. A typical microphotograph of a cross section with l and p labeled is given in Figure 18. The ratio of l/p was determined for the five cross sections of each weld, and the average of the five ratios was tabulated as a dimensionless representation of the cracking.

A quantitative elemental analysis of several etched cross-sections was performed using the SEM X-ray analyzer. The base alloy was tested as well as the filler wire and fusion zones of welds with feed rates 0 mm/min, 5000 mm/min, 6500 mm/min, and 11500 mm/min. In each case, element content was measured in three locations. All data was normalized by dividing with the average of the base alloy content for each element.

6. Reducing Spectral Sample Data

In analyzing spectral data, the plasma was modeled assuming a simple, uniform slab with local thermodynamic equilibrium conditions so a line ratio method for determining relative changes in temperature and ion densities could be used. These assumptions were based on the fact that the spectral samples were not spatially resolved when recorded and, since the weld plume is near atmospheric pressure, its temperature is relatively insensitive to the equilibrium state for typical plasma atom densities (10^{16} - 10^{18} cm⁻³) [21].

To apply the line ratio method, the intensity of underlying continuum radiation in the spectral samples was first subtracted from peak intensity. Next, the volume emission coefficient, ϵ , was determined. The coefficient is given by an integration to obtain the area under the line profile. In this case, the resolution of the spectrometer and the intensities of the emission lines were such that line broadening was assumed to be negligible, so ϵ was taken simply as the maximum relative intensity, I , for a given line emission. Then, the relation between relative intensity (I), plasma temperature (T), and population density of excited atoms (N) is given by [20]

$$\epsilon_{nm} = I_{nm} = g_n N_{\theta} A_{nm} h \frac{c}{\lambda_{nm}} \frac{e^{-E_n/kT}}{U(T)} \quad (1)$$

where n = designation for the upper electron energy transition level

m = designation for the lower electron energy transition level

θ = designation for the total of all possible transitions for the
element

A = Einstein transition probability coefficient

g = statistical weight

h = Planck constant

λ = emission wavelength

k = Boltzmann constant

c = speed of light

T = plasma temperature

E = Electron transition energy

The partition function, $U(T)$, assumes a Boltzmann distribution for the population of excited atoms such that [20]:

$$U(T) = \sum_{x=0}^{\theta} g_x e^{-E_x/kT} \quad (2)$$

Applying the above equations to the ratio of intensities from two different spectral lines yields

$$\frac{I_{nm}}{I_{ji}} = \frac{N_{\theta_a}}{N_{\theta_b}} \frac{A_{nm}}{A_{ji}} \frac{\lambda_{ji}}{\lambda_{nm}} \frac{g_n}{g_j} \frac{U_b(T)}{U_a(T)} e^{-(E_n - E_j)/kT} \quad (3)$$

where i = designation for the upper electron energy transition level of the
second emission line

j = designation for the lower electron energy transition level of the
second emission line

a = designation for the element undergoing the nm transition

b = designation for the element undergoing the ji transition

All of the transition probability properties in Equation 3 are known and constant except for I , N , and T . By inspection, Equation 3 may be simplified to

$$\frac{I_{nm}}{I_{ji}} = C_1 \frac{N_{\theta_a}}{N_{\theta_b}} \frac{U_b(T)}{U_a(T)} e^{-C_2/T} \quad (4)$$

where C_1 and C_2 are constants. Thus, the line ratio is a function of ion densities and plasma temperature. If the temperature can be established, then the line ratio becomes

merely a function of the population densities which, in turn, are related to the percentage of element species in the weld plasma.

Plasma temperature may be determined by a variation of the line ratio method described above. When Equation 3 is used with the ratio of intensities from two spectral lines emitted by the same element, the relation simplifies to

$$\frac{I_{nm}}{I_{ji}} = \frac{A_{nm}}{A_{ji}} \frac{\lambda_{ji}}{\lambda_{nm}} \frac{g_n}{g_j} e^{-(E_n - E_j)/kT} \quad (5)$$

which is easily solved for temperature, T.

Based on this principle, the average ratio of intensities for the 309.3 nm and 396.2 nm aluminum lines were found from the seven spectral samples taken during each of the weld runs and used in determining the variation in plasma temperature as the wire feed rate changed. Having established plasma temperature as a function of line ratios by means of Equation 5, Equation 4 was applied to adjust for temperature effects when using the 383.8 nm magnesium line and the 396.2 nm aluminum line in a ratio to detect, qualitatively, changes in the alloying content of material interacting with the laser beam. Again, average ratios were tabulated from seven spectral samples taken during each of the welds.

CHAPTER IV

RESULTS

A. Weld Characterization

Overviews of typical welds are shown in Figures 19 and 20. The photographs show the top and bottom of two welds. For the weld in Figure 19, the wire feed rate was comparatively slow (5000 mm/min), while for Figure 20 the feed rate was at the upper end of the experimental range (11500 mm/min). Several distinct features were noted in the overviews:

1. *Full penetration was seen in all welds.* That is, the fusion zone extended through the thickness of the 1/16 inch thick coupons.
2. *Variances in the distribution of the filler were observed.* At slow feed rates (up to 3000 mm/min), the Al 4043 filler was deposited sporadically along the weld track in droplets that appeared to solidify before mixing thoroughly with the weld pool. This was similar to the description Berkmanns gave of "wire melt back." As the wire speed increased, filler was deposited more uniformly on the surface of the track but still did not appear to be mixed with the base metal. This occurred over a narrow range of feed rates covering 3000 - 5000 mm/min. In the same range, a transition to a regime of better filler mixing was observed. At feed rates greater than 5000 mm/min up to 10000 mm/min, the filler appeared smoothly blended into the weld track; however, a portion of wire that was

melted before translating the work-piece attached to the weld lead-in. This created an over-sized, distorted bead within the first 0.5 cm section of the weld. Welds with feed rates faster than 10000 mm/min were subject to similar problems with the lead-in; in addition, the filler wire was not always completely melted by the laser and occasionally pushed through the bottom of the weld pool.

3. *Cracks were visible* to the unaided eye in welds with wire feed rates less than 10000 mm/min. Many of the cracks could be seen on both the top and bottom surfaces of the welds. An example is shown in the overview photographs of Figure 19. Cracking was more prominent within in the first 2 cm of each weld track.
4. *Asymmetry of the weld bead was apparent* in welds with wire feed rates greater than 5000 mm/min. A deep crevice, running along the weld track near the interface between the fusion zone and the base material, could be seen in welds with feed rates greater than 5000 mm/min (See Figure 20). As the feed rate was increased, the crevice became less distinguishable in the increasingly high weld bead.

Cross-section views of four welds are shown in Figure 21. The photographs are 28X magnification micrographs. Figure 21a shows a weld made with a relatively slow wire feed rate, 3000 mm/min. Figure 21b shows a weld with wire feed at 4500 mm/min, and Figure 21c shows a weld with a higher feed rate, 6500 mm/min, while Figure 21d shows the highest feed rate weld, 11500 mm/min. The first 0.5 cm of weld

where the bead was distorted by the attachment of excess filler was excluded from cross-sectioning. Cross-sections were taken from the next 1.5 cm of weld, since in the overview examination cracking was noted to be more evident in this region and the bead shape was more representative of the remaining weld track. A schematic showing the orientation of cross section slices is given in Figure 22. Again, several characteristic features were observed in the welds:

1. *Cracks were clearly visible in the fusion zone.* Typically, the cracks were near the centerline of the weld and often split the joint into two pieces. Occasionally, smaller secondary cracks appeared to have initiated from centerline fracture and extended transversely. Others appeared to have initiated at the surface of the weld and extended a relatively short distance into the fusion zone. All appeared to be the result of solidification cracking.
2. *No cracks were visible in the HAZ or base material.* The absence of cracks in these areas indicates liquation cracking may not occur for the given experimental conditions. However, a more thorough metallographic analysis at higher magnifications would be necessary to completely rule out the presence of liquation cracks.
3. *The HAZ was less than 0.1 mm wide.* In comparison, the width of the fusion zones at their narrowest were from approximately 2.9 mm to 3.4 mm. The extent of the HAZ was estimated by measuring the distance from the fusion zone perimeter to the closest region in the base alloy where

grains were consistent with the size and color of grains in unwelded Al 6061. To confirm this measurement, a microhardness test was performed on a weld cross-section for which the wire feed rate was 10000 mm/min. Vicker scale microhardness was measured at the weld center line and at 14 other points spaced incrementally away from the centerline using a Buehler Micromet II and a diamond point Vickers indenter. The results are given in Table 4. The average microhardness of the fusion zone was 65 while the average for the base material was 74 (which when converted by extrapolating to the Brinell scale, is typical of Al 6061). The width of the HAZ was taken to be the distance between the point closest from the weld centerline with a microhardness of 65 and the point farthest to the centerline with a microhardness of 74. The HAZ width was found to be 0.06 mm.

4. *The crevices noted in overviews were clearly visible in cross-sections.*
Some extended to a depth of 0.7 mm from the surface of the base material.
5. *The fusion zone was hour-glass shaped* with the neck near the middle of the cross-section.

Measurements of total crack length (l) and length of the fusion zone perimeter (p) are given in Table 5. Ratios of the averages for the five l and p values found for each weld were used to provide a dimensionless representation of the cracking. Figure 23 shows the relationship between these ratios and the wire feed rate. The

graph indicates that cracking decreases as the amount of filler additions increases. Also, a significant amount of scatter is seen in the data, indicating that the degree of cracking is not entirely consistent. Scatter is worse for data in the range of 0 - 5500 mm/min wire feed rate where inconsistencies in the depositing and mixing of the filler were observed. Excluding this range, a linear curve fit can be applied to the remaining data. The curve fit is also shown in Figure 23.

EDS testing was performed to confirm constituency changes in the fusion zones after welding. The base alloy was tested as well as the filler wire and fusion zones of welds with feed rates 0 mm/min, 5000 mm/min, 6500 mm/min, and 11500 mm/min. In each case, element content was measured in three locations to check for variations. All data was normalized by dividing with the average of the base alloy content for each element. Results from the tests are given in Figure 24 which graphically shows normalized contents of the major alloying constituents (aluminum, silicon, and magnesium) in each of the tested cross-sections. The results indicate that the magnesium content of the fusion zones dropped to approximately half the amount present in the base alloy, and no magnesium was detectable in the filler wire. Significant variations were seen in the magnesium, possibly due to the alloy percentage of magnesium being below accurate detection limits for the X-ray analyzer. The apparent drop in magnesium may have been partially the result of vaporization during welding. Silicon content increased with higher feed rates as would be expected since the filler contains large amounts of the element. Likewise, aluminum content dropped

as feed rate increased. Trends were consistent with expected alloy changes due to welding with filler additions.

B. Spectral Monitoring

The average ratio of intensities for the 309.3 nm and the 396.2 nm aluminum lines was found from seven spectral samples taken during each of the weld runs. Standard deviation was also calculated and the results are given in Table 6. Figure 25 shows the ratio of intensities versus wire feed rate. It indicates that the line intensity ratio was approximately constant at 0.48 over the range of wire feed rates, and therefore the plasma temperature, was approximately constant. Using Equation 5 along with the intensity ratio and the values listed in Table 7, the effective temperature of the plasma was determined to be 5700 K.

In the same manner, the average ratio of intensities for the 383.8 nm magnesium line and the 396.2 nm aluminum line was tabulated. The results are given in Table 8. The relationship to wire feed rate is shown in Figure 26. The data followed 4 distinct behaviors depending on the wire feed rate. These are designated I, II, III, and IV:

1. *Range I* -- For wire feed rates of 0 - 4500 mm/min, the line intensity ratio decreases as the wire feed rate increases.
2. *Range II* -- For wire feed rates of 4500 - 6000 mm/min, a transition occurs and the line intensity ratio suddenly jumps to a higher value.

Correspondingly, a transition from inconsistent delivery of the wire feed to a smoother deposition of the filler was also seen in this range.

3. *Range III* -- For wire feed rates of 6000 - 9700 mm/min, the line intensity ratio again decreases as the wire feed rate increases.
4. *Range IV* -- For wire feed rates of 9700 - 11500 mm/min, the line intensity ratio continues to decrease as wire feed rate increases but at a slower rate.

Linear curve fits over these ranges are shown in the graph.

CHAPTER V

DISCUSSION

A. Qualitative Correlation of Results

In the results from weld characterizations and spectral monitoring corresponding trends were observed over four wire feed rate ranges. These ranges are labeled as I, II, III, and IV in Figure 26.

Range I covered rates 0 - 4500 mm/min. At these speeds, filler wire was not deposited evenly along the weld track, and it did not appear to mix completely with the melt pool. Also, the degree of cracking was inconsistent. The line intensity ratio, however, was very consistent and decreased steadily as wire feed rate increased. For range I, changes in the wire feed rate appear to be detectable with spectral monitoring, but the filler wire is apparently delivered too slowly to be evenly distributed and have a reliable effect on cracking. It should be noted that Al 4043 controls cracking sensitivity by adding silicon to the base alloy thus suppressing the solidification temperature of the weld pool and allowing more time for cracks to "heal" before the weld completely solidifies [12]. The solidification temperature of Al 6061 is 582 deg C, while Al 4043 solidifies at 575 deg C. As more Al 4043 is added to a weld pool, the solidification temperature approaches 575 deg C. Uneven distribution of the filler, as seen with the welds in range I, may not adequately suppress the solidification temperature over the entire weld and also contributes to variances in heat input. Under these conditions, filler does not reduce susceptibility to cracking.

Range II spanned feed rates of 4500 - 6000 mm/min. A transition occurred over this range. Filler was deposited more evenly, although it still did not mix well with the base material for all welds in this range. With the spectral monitoring, a sudden jump was seen in the line intensity ratio, indicating a possible threshold for wire feed rates that results in consistent delivery of the filler. Cracking, still, was sporadic and inconsistent. It is possible that for ranges I and a portion of II, melting of the filler wire was slow enough that surface tension was capable of preventing the filler from flowing into the weld pool until a large, heavy droplet formed at the tip of the wire and fell into the weld. For the higher feed rates in range II, wire may have been delivered fast enough that the weight of melted filler was able to continually overcome surface tension effects. In this case, melted wire would constantly flow into the weld pool rather than collect and fall sporadically. A physical phenomena of this sort agrees with the transitions seen in results of both the degree of cracking and the spectral emission analysis for range II.

Range III covered rates 6000 - 9700 mm/min. Smooth blending of the filler was observed for these wire speeds, and the degree of cracking became more uniform. Improved mixing of the filler seemed to result in better conditions for controlling cracks. Cracking, however, seemed to be influenced by another factor. A portion of melted wire, that was fed into the laser beam just before translating the work-piece, attached to the front edge of the weld coupon. This created an over-sized, distorted bead within the first 0.5 cm of the weld. Evidence points towards the degree of cracking being adversely affected by large heat inputs and unusually steep thermal

gradients caused by the attachment of excess filler. Use of a weld lead-in tab is a common method of alleviating similar problems in conventional welding [23]. A lead-in tab is additional material inserted ahead of the work-piece for initiating the weld and allowing it to stabilize before crossing the work-piece. It is likely that a weld tab would decrease the susceptibility to cracking in the laser welds as well. Despite adverse lead-in effects, the degree of cracking steadily decreased as the wire feed rate increased. Correspondingly, the line intensity ratio also steadily decreased with filler additions.

Range IV included the remaining feed rates, 9700 - 11500 mm/min. It was distinguishable from range III in two ways. First, an apparent upper limit to the rate at which wire could be delivered was observed. In some welds, the filler wire was not always completely melted by the laser and occasionally pushed through the bottom of the weld pool. Second, the line intensity ratio stopped decreasing with filler additions and remained near constant.

In light of the above observations, the data trends in Figure 26 become more meaningful with further analysis. Since the temperature was experimentally established as constant, Equation 4 was simplified to

$$\frac{I_{nm}}{I_{ji}} = C_3 \frac{N_{e_2}}{N_{e_1}} \quad (6)$$

where the following substitutions can be made:

$$I_{nm} = \text{intensity of the 383.8 nm magnesium line}$$

I_{ji} = intensity of the 396.2 nm aluminum line

$N_{\theta a}$ = population density of magnesium specie

$N_{\theta b}$ = population density of aluminum specie

C_3 = a constant

Applied to the data in the figure, Equation 6 shows for this experiment changes in the line intensity ratio are directly related to the population density of excited atoms in the weld plume. It can be inferred that the population densities of different elements in the plasma are dependent on the alloy constituency of material interacting with the laser beam. Alloy constituency varies with the wire feed rate. With no wire feed, the percentage of magnesium in material interacting with the laser beam is at its highest. When Al 4043 is added, the magnesium is diluted with aluminum and silicon (the filler contains no magnesium), lowering the alloy percentage of magnesium. This appears to correspond with an increase in the population density of aluminum relative to magnesium in the plasma and can be seen when comparing intensity ratios in ranges III and IV of Figure 26; as the wire feed rate increases, the line ratios fall. Range I demonstrates a similar trend. However, the distribution and mixing of filler for Ranges I and II appeared to be inadequate to control the degree of cracking (l/p), suggesting that spectral monitoring is useful for detection of feed rate changes for wire interacting with the laser beam, yet the technique seems to be effective for monitoring the degree of cracking only after a certain lower threshold is reached with the wire feed rate. For the given welding conditions, the feed rate threshold is approximately 5000 mm/min.

Other results were noted as being common to all or several of the four wire feed rate ranges, suggesting that they are dependent on other processing parameters such as laser beam intensity, location of the beam focus, translation speed, cover gas conditions, and alignment of the wire feed. The results include:

1. Full penetration welds
2. Asymmetry of weld beads
3. Hour-glass shape of fusion zones
4. No cracking in the HAZ or base material
5. Small HAZ width.

B. Quantitative Correlation of Results

While results for ranges I and II are inconsistent and do not correlate well, the trends in ranges III and IV warrant a more quantitative comparison since linear (least-square) curve fits were applied to data that fell in these ranges. Correlating the curves in Figures 24 and 26, a relation between the line intensity ratio versus the degree of cracking was found. The line intensity ratio varied from a low of 1.26 to a high of 2.17, while the degree of cracking (l/p) was from 0.05 to 0.38. Between the extremes, slope is constant over two intervals divided at the 0.16 value for degree of cracking. Figure 27 shows this relation.

The figure suggests that, for the wire feed rates between 6000 mm/min and 11500 mm/min, a one-to-one correspondence exists for the line intensity ratio and the degree of cracking. A relation of this type can be used as the basis for monitoring the

amount of filler additions necessary to control cracking. For feed rates outside of this range, a correlation is not established.

CHAPTER VI

CONCLUSIONS

For this work, a 3 kW CO₂ laser and a wire feeder were used to produce bead on plate welds while a 0.25 m spectrometer with an optical multi-channel analyzer (OMA) was used to sample spectral emissions from the weld plasma. The feed rate of 0.76 mm (0.030 inch) diameter filler wire was varied over a range of 0 - 11500 mm/min while other welding parameters were held constant. The degree of cracking in welds was determined by an average ratio of the total crack length (l) to the length of the fusion zone perimeter (p) for five transverse cross sections. Also, the average ratio of intensities for the 383.8 nm magnesium line to the 396.2 nm aluminum line was found. The line intensity ratio was correlated with l/p . The following conclusions can be made from the results of the work:

1. The intensity ratio of the 383.8 nm magnesium line and the 396.2 nm aluminum line can be correlated to the degree of cracking. As filler wire is added, the ratio drops reflecting the addition of Al 4043 filler and, consequently, lowered sensitivity to the formation of cracks. X-ray quantitative elemental analysis of fusion zones appears to confirm expected alloy changes resulting from laser welding with Al 4043 filler. Likewise, the degree of cracking in the welds, when quantified as the total crack length (l) divided by the length of the fusion zone perimeter (p) for a transverse cross-section, decreased with filler additions.

2. For wire feed rates in the range of 6000 - 11500 mm/min, the line intensity ratio varies linearly with the degree of cracking (l/p) when curve fits are applied to the data. A relation of this type can be used as the basis for monitoring the amount of filler additions necessary to control the degree of cracking. Outside of this range, changes in the wire feed rate are detectable using spectral monitoring; however, the distribution and mixing of filler are sporadic and cracking is too inconsistent to be used for correlation.
3. Solidification cracking is more prominent than liquation cracking. Cracks are limited to the fusion zone and, at 28 X magnification, are not seen in the HAZ or base material where only liquation cracks typically emerge.
4. High heat inputs and steep thermal gradients caused by the attachment of a portion of melted filler wire that was fed into the laser beam just before translating the work-piece appear to increase cracking in the welds. Lead-in tabs which allow the welding to stabilize before crossing the work-piece are commonly used to solve similar problems in conventional welding [23] and would likely improve laser welds also.
5. Other processing parameters, such as laser beam intensity, location of the beam focus, translation speed, cover gas conditions, and alignment of the wire feed, appear to affect weld characteristics. This is indicated by results common to all or most of the wire feed rates tested. The results include full penetration of welds, asymmetry of weld beads, hour-glass shape of

fusion zones, no cracking in the HAZ or base material, and a small HAZ width.

Results from this work justify further investigation into LBW with wire filler and spectral monitoring. Recommended directions for continued research towards improving the system and finding other applications for its use are

1. Improving sampling and measuring techniques used in this study, for instance, an automatic triggering system for the OMA.
2. Studying the response time of the system to wire feed rate changes
3. Correlating line intensity ratios with alloying constituencies in welds
4. Varying other processing parameters including translation speed, cover gas conditions, laser beam focus, and beam intensity
5. Using weld tabs
6. Determining weld quality by other means. (For instance, magnesium content in welds, porosity, tensile strength, or microhardness might be correlated with line intensity ratios.)
7. Incorporating other, more practical joint configurations such as butt welds, lap welds, and edge welds
8. Automating the spectral monitoring system so that results are provided as the weld is made.

LIST OF REFERENCES

- [1] J. R. Davis (ed.), "Welding," *ASM Specialty Handbook Aluminum and Aluminum Alloys*, ASM International, OH, 1993, pp. 376-419.
- [2] D. Houser, E. A. Metzbower, "Failures of Weldments," *ASM Metals Handbook Ninth Edition Volume 11 Failure Analysis and Prevention*, ASM International, USA, 1987, p. 437.
- [3] R. P. Martukanitz, D. J. Smith, "Laser Beam Welding of Aluminum Alloys," *Proceedings of the Sixth International Conference on Aluminum Weldments*, American Welding Society, FL, 1995, pp. 309-323.
- [4] R. Mueller, "Development of Spectral Weld Monitoring Phase I Report for Bendix-Atlantic Inflator Company," CSTAR, UTSI Research Park, TN, 1994.
- [5] "Measuring Weld Parameters by Spectroscopy," *NASA Tech Briefs*, MFS-26206.
- [6] M. H. McCay et al, "Correlation of Plasma Characteristics with Weldment Properties for Laser Welded Aluminum Alloys," *Metals Abstracts*, MA90-551625, 1989, pp. 107-122.
- [7] J. R. Davis (ed.), "Glossary of Terms," *ASM Metals Handbook Tenth Edition Volume 6 Welding, Brazing, and Soldering*, ASM International, USA, 1993, pp. 1206-1215.
- [8] J. Knight, *Welding Kaiser Aluminum*, Kaiser Aluminum & Chemical Sales, Inc, CA, 1967.
- [9] G. Hickson, "Gas-Tungsten Arc Welding," *ASM Metals Handbook Tenth Edition Volume 6 Welding, Brazing, and Soldering*, ASM International, USA, 1993, pp. 190-194.
- [10] D. B. Holliday, "Gas Metal Arc Welding," *ASM Metals Handbook Tenth Edition Volume 6 Welding, Brazing, and Soldering*, ASM International, USA, 1993, pp. 180-185.
- [11] R. B. C. Cayless, "Alloy and Temper Designation Systems for Aluminum and Aluminum Alloys," *Metals Handbook Volume 2 Properties and Selection: Nonferrous Alloys and Special Purpose Materials*, 10th ed., ASM International, USA, 1990, pp. 15-61.
- [12] M. Gittos, M. Scott, "Cracking in the Heat Affected Zone (HAZ) of Al-Mg-Si Alloys -- A Review," *Welding Institute Bulletin*, Cambridge, UK, 1990, pp. 100-102.

- [13] J. Mazumder, "Laser-Beam Welding," *ASM Metals Handbook Tenth Edition Volume 6 Welding, Brazing, and Soldering*, ASM International, USA, 1993, pp. 262-269.
- [14] W. M. Steen, "Laser Welding," *Laser Material Processing*, Springer-Verlag, London, 1991.
- [15] C. Dawes, "Principles of Laser Welding and It's Characteristics," *Laser Welding*, McGraw-Hill, New York, 1992.
- [16] V. Semak, et al, "Weld Pool Oscillations in Laser Welding," *Proceedings of ICALEO*, 1995.
- [17] A. Blake, J. Mazumder, "Control of Magnesium Loss During Laser Welding of Al-5083 Using a Plasma Suppression Technique," *Journal of Engineering for Industry*, August 1985, Volume 107, pp. 275-280.
- [18] J. Berkmanns et al, "Laser Welding of Aluminum," *University of Michigan 1995 Automotive Laser Applications Workshop*, 1995.
- [19] J. Mazumder, "Laser Welding: State of the Art Review," *Journal of Metals*, July 1982, pp. 16-24.
- [20] T. L. Eddy and A. Sedghinasab, "The Type and Extent of Non-LTE in Argon Arcs at 0.1-10 Bar," *IEEE Transactions on Plasma Science*, Vol. 16, 1988.
- [21] W. L. Wiese et al, *Atomic Transition Probabilities Volume II Sodium Through Calcium*, United States Department of Commerce, National Bureau of Standards, 1969, pp. 47-49.
- [22] A. P. Thorne, *Spectrophysics*, Chapman and Hall, London, 1974, pp. 285-286 and 374-379.
- [23] D. Olson, "Submerged Arc welding," *ASM Metals Handbook Ninth Edition Volume 6 Welding, Brazing, and Soldering*, ASM International, USA, 1983, p.135.

APPENDICES

APPENDIX A: Tables

Table 1. Nominal composition of alloying elements in Al 6061 and Al 4043 based on weight % [2].

Alloy	Cu	Si	Mn	Mg	Zn	Cr	Al	others
Al 6061	0.28	0.6	...	1.0	...	0.20	rem	...
Al 4043	...	5.25	...	...	...	...	rem	...

Table 2. Significant spectral lines identified between 268 nm and 468 nm using a 300 groove/mm diffraction grating.

Wavelength (nm)	Element
309.2	aluminum
359.3	chromium
383.8	magnesium
394.4	aluminum
396.2	aluminum

Table 3. Laser processing parameters.

-
- **Laser Power**
3 kW (focused at the sample surface)
 - **Laser Spatial Mode**
TEM_{01*}
 - **Laser Temporal Mode**
5 kHz Pulse Width Modulated
 - **Weld Travel Speed**
3000 mm/min
 - **Wire Feed Rate**
 - With 300 grooves/mm Spectrometer Grating
0 mm/min to 11500 mm/min (at 500 mm/min increments)
 - With 1200 grooves/mm Spectrometer Grating
0 mm/min
 - **OMA**
20 Samples per Weld
100 ms intervals
25-50 ms Exposure Time
-

Table 4. Results of microhardness testing.

Point Number	Distance from Center Line of Weld (mm)	Vickers Scale Microhardness
1	0.09	61
2	0.27	65
3	0.49	65
4	0.73	66
5	0.93	66
6	1.03	65
7	1.12	65
8	1.18	74
9	1.22	73
10	1.30	73
11	1.34	74
12	1.55	74
13	∞	74
14	∞	71
15	∞	77

Table 5. Crack length and fusion zone perimeter measurements from weld cross-sections. Incomplete data indicated by *.

Wire Feed Rate (mm/min)	Cross-section #	p (mm)	l (mm)	l/p
0	1	6.86	1.61	0.23
	2	6.64	0.86	0.13
	3	6.64	3.00	0.45
	4	6.64	1.07	0.16
	5	6.32	0.43	0.07
2000	1	7.61	2.57	0.34
	2	7.29	2.36	0.32
	3	7.50	2.57	0.34
	4	7.82	3.64	0.47
	5	8.57	2.04	0.24
3000	1	7.29	2.36	0.32
	2	7.39	1.82	0.25
	3	7.18	2.79	0.39
	4	7.82	3.86	0.49
	5	*	*	*
4500	1	7.93	1.71	0.22
	2	8.36	2.89	0.35
	3	*	*	*
	4	8.14	3.00	0.37
	5	8.25	1.61	0.19
5000	1	9.75	3.96	0.41
	2	8.89	2.57	0.29
	3	7.61	3.43	0.45
	4	7.29	2.25	0.31
	5	6.96	2.14	0.31
5500	1	10.07	4.07	0.40
	2	8.79	3.64	0.41
	3	8.89	3.64	0.41
	4	9.32	3.54	0.38
	5	*	*	*

Table 5. (Continued).

6000	1	8.68	3.64	0.42
	2	7.71	3.43	0.44
	3	7.29	2.25	0.31
	4	7.07	2.46	0.35
	5	7.29	2.57	0.35
6500	1	8.57	3.00	0.35
	2	9.32	3.43	0.37
	3	8.57	2.57	0.30
	4	8.89	3.11	0.35
	5	8.79	4.50	0.51
7000	1	8.36	2.36	0.28
	2	8.68	3.43	0.40
	3	8.36	2.79	0.33
	4	8.68	3.96	0.46
	5	9.21	2.89	0.31
7500	1	9.00	2.57	0.29
	2	9.11	2.25	0.25
	3	8.57	2.14	0.25
	4	9.11	2.46	0.27
	5	9.43	2.14	0.23
8000	1	8.57	2.04	0.24
	2	8.36	2.14	0.26
	3	7.61	2.25	0.30
	4	8.25	1.82	0.22
	5	8.14	2.36	0.29
8500	1	9.64	0.00	0.00
	2	9.54	1.50	0.16
	3	9.00	2.25	0.25
	4	9.00	1.82	0.20
	5	9.75	1.93	0.20

Table 5. (Continued).

9000	1	8.68	1.82	0.21
	2	8.14	2.14	0.26
	3	8.46	2.46	0.29
	4	9.43	2.25	0.24
	5	8.68	2.36	0.27
9700	1	9.11	1.61	0.18
	2	9.21	1.93	0.21
	3	9.11	0.00	0.00
	4	9.43	2.46	0.26
	5	9.21	0.00	0.00
10000	1	8.89	1.93	0.22
	2	8.68	2.14	0.25
	3	8.57	2.57	0.30
	4	9.32	1.61	0.17
	5	8.57	2.25	0.26
10500	1	10.71	0.00	0.00
	2	9.75	0.00	0.00
	3	10.07	0.00	0.00
	4	9.86	0.00	0.00
	5	8.79	0.00	0.00
11000	1	7.71	0.00	0.00
	2	7.93	1.07	0.14
	3	7.93	1.18	0.15
	4	8.04	0.00	0.00
	5	7.82	0.00	0.00
11500	1	8.25	0.64	0.08
	2	8.14	1.39	0.17
	3	8.04	0.00	0.00
	4	9.11	0.00	0.00
	5	8.36	2.36	0.28

Table 6. Spectral data for intensity ratios of the 309.3 nm and 396.2 nm aluminum lines.

Wire Feed Rate	Line Intensity Ratios for Sequential Sampling Intervals							Sum of ratios	Standard Deviation	Average of Data Set
	mm/min	0 ms	100 ms	200 ms	300 ms	400 ms	500 ms	600 ms		
	0	0.51	0.44	0.43	0.44	0.48	0.52	0.54	3.38	0.05
	2000	0.48	0.71	0.51	0.48	0.47	0.61	0.58	3.84	0.09
	3000	0.54	0.53	0.53	0.50	0.62	0.55	0.64	3.91	0.05
	4500	0.59	0.60	0.51	0.49	0.49	0.50	0.52	3.70	0.05
	5000	0.56	0.59	0.53	0.55	0.59	0.53	0.57	3.93	0.03
	5500	0.52	0.54	0.54	0.47	0.51	0.51	0.53	3.61	0.02
	6000	0.47	0.52	0.58	0.51	0.57	0.60	0.55	3.80	0.05
	6500	0.57	0.46	0.49	0.49	0.55	0.45	0.50	3.52	0.04
	7000	0.47	0.47	0.49	0.53	0.47	0.50	0.44	3.37	0.03
	7500	0.51	0.58	0.54	0.52	0.58	0.51	0.48	3.71	0.04
	8000	0.50	0.45	0.45	0.50	0.38	0.42	0.44	3.15	0.04
	8500	0.56	0.46	0.56	0.52	0.48	0.60	0.50	3.68	0.05
	9000	0.49	0.54	0.55	0.55	0.52	0.45	0.52	3.61	0.04
	9700	0.53	0.51	0.41	0.22	0.33	0.65	0.63	3.27	0.16
	10000	0.27	0.26	0.28	0.33	0.32	0.33	0.34	2.12	0.03
	10500	0.58	0.67	0.57	0.56	0.49	0.42	0.51	3.80	0.08
	11000	0.42	0.37	0.38	0.36	0.38	0.46	0.39	2.75	0.03
	11500	0.38	0.34	0.34	0.34	0.31	0.25	0.23	2.19	0.06

Table 7. Atomic transition probability data used to calculate plasma temperature [22].

Variable Name	Value	Unit
I_{nm}/I_{ji}	0.52	(unity)
A_{nm}	0.73	s^{-1}
A_{ji}	0.98	s^{-1}
E_n	32437	cm^{-1}
E_j	25348	cm^{-1}
g_n	6	(unity)
g_i	2	(unity)
λ_{nm}	309.27	nm
λ_{ji}	396.15	nm
k	$1.381 \cdot 10^{-23}$	J/K

Table 8. Spectral data for intensity ratios of the 383.8 nm magnesium line and the 396.2 nm aluminum line.

Wire Feed Rate	Line Intensity Ratios Sequential Sampling Interval							Sum of ratios	Standard Deviation	Average of Data Set
	mm/ min	0 ms	100 ms	200 ms	300 ms	400 ms	500 ms	600 ms		
0		2.58	2.89	2.83	2.72	2.73	2.57	2.71	19.02	0.12
2000		2.16	2.30	2.40	2.16	2.04	2.27	2.33	15.66	0.12
3000		2.07	2.14	2.08	2.05	1.99	1.95	2.16	14.44	0.08
4500		1.81	1.85	1.80	1.76	1.72	1.68	1.69	12.31	0.06
5000		2.57	2.58	2.58	2.72	2.66	2.60	2.57	18.29	0.06
5500		1.48	1.52	1.53	1.52	1.64	1.62	1.59	10.90	0.06
6000		2.20	2.22	2.34	2.45	2.48	2.44	2.08	16.21	0.15
6500		1.90	1.88	1.90	1.92	1.93	2.11	2.53	14.18	0.24
7000		1.89	2.01	2.01	1.97	1.94	2.11	2.03	13.96	0.07
7500		1.48	1.57	1.43	1.64	1.52	1.61	1.52	10.78	0.07
8000		1.67	1.73	1.68	1.64	1.64	1.58	1.86	11.78	0.09
8500		1.40	1.37	1.40	1.56	1.50	1.53	1.53	10.29	0.08
9000		1.72	1.56	1.62	1.56	1.77	1.80	1.73	11.76	0.10
9700		1.27	1.24	1.23	1.27	1.31	1.27	1.25	8.84	0.02
10000		1.35	1.35	1.40	1.43	1.31	1.39	1.39	9.61	0.04
10500		1.49	1.38	1.39	1.25	1.48	1.38	1.37	9.76	0.08
11000		1.30	1.20	1.23	1.22	1.21	1.24	1.30	8.69	0.04
11500		1.26	1.28	1.25	1.25	1.25	1.25	1.16	8.71	0.04

APPENDIX B: Figures

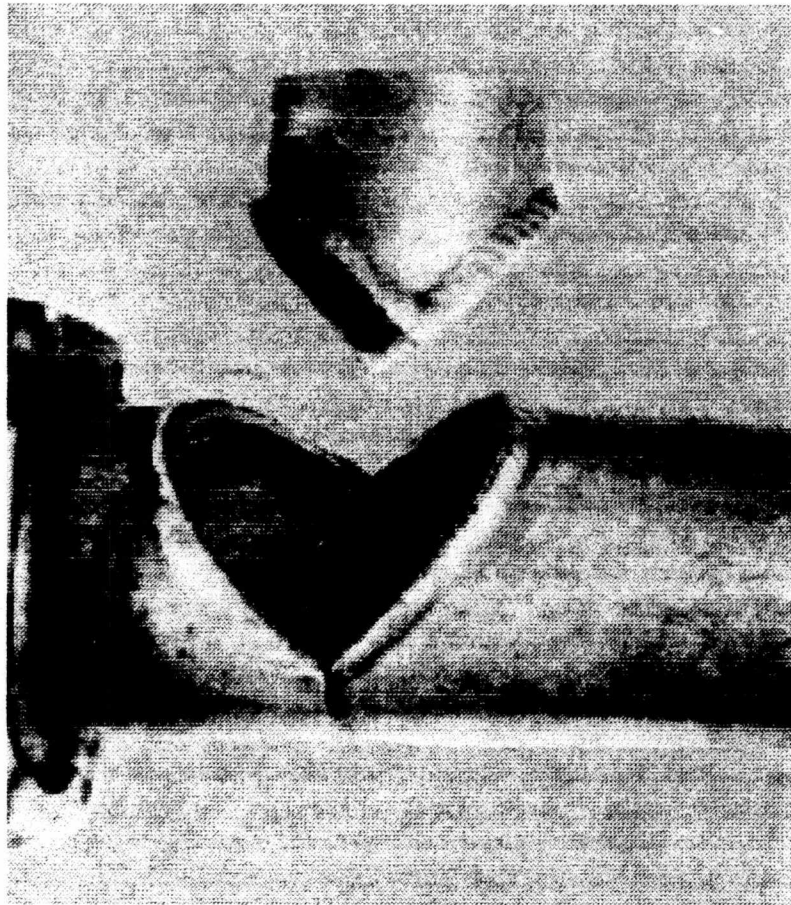


Figure 1. An Al 6061-T6 aircraft-engine oil-line failure caused by welding flaws.
(Source) D. Houser, E. A. Metzbower, "Failures of Weldments," *ASM Metals Handbook Ninth Edition Volume 11 Failure Analysis and Prevention*, ASM International, USA, 1987, p. 437.

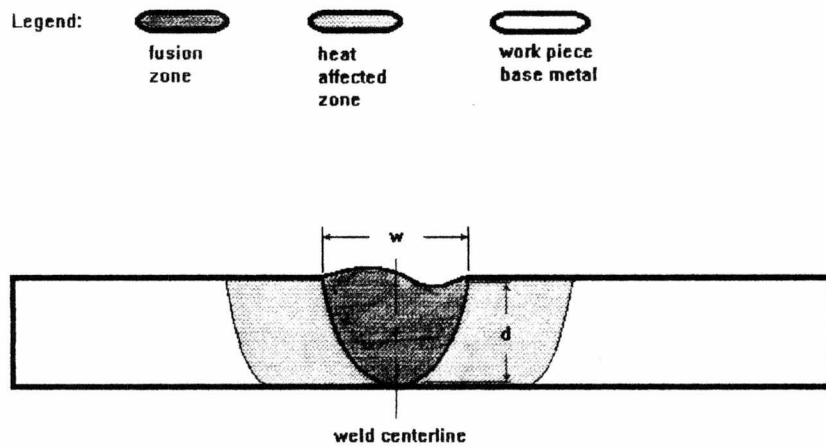


Figure 2. Schematic of a fusion weld transverse cross-section. The depth to width ratio is given by d/w .

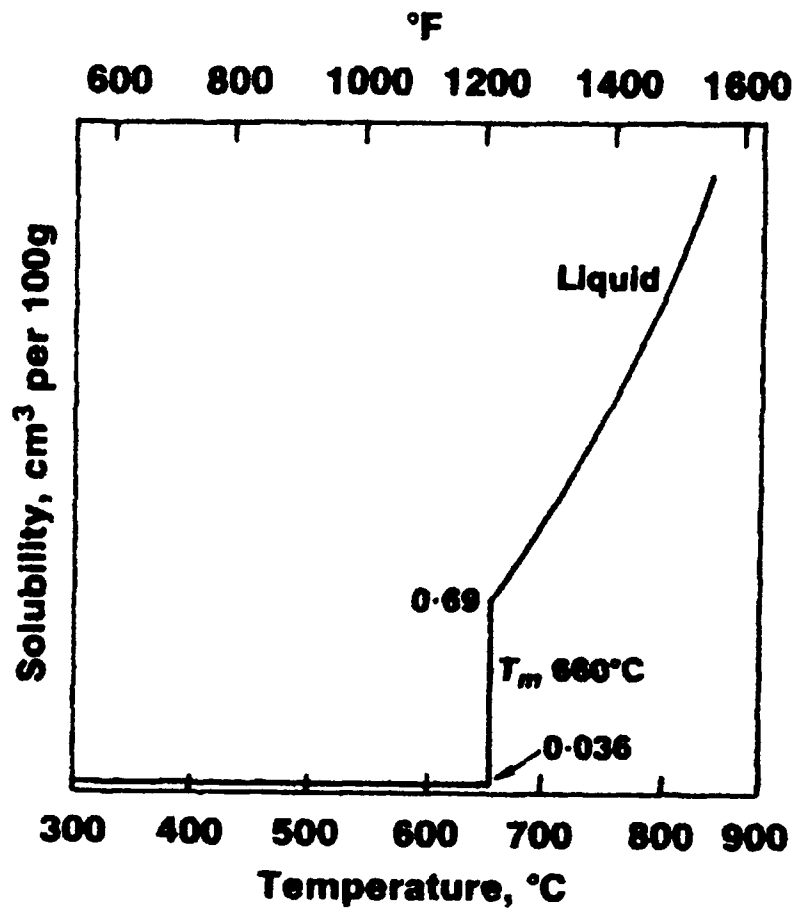


Figure 3. Hydrogen solubility in pure aluminum. The step change at 660 deg C corresponds to the solidification of aluminum. (Source) J. R. Davis (ed.), "Welding," *ASM Specialty Handbook Aluminum and Aluminum Alloys*, ASM International, OH, 1993, pp. 376-419.



Figure 4. An example of solidification cracking in arc welded aluminum. (Source) J. Knight, *Welding Kaiser Aluminum*, Kaiser Aluminum & Chemical Sales, Inc, CA, 1967.

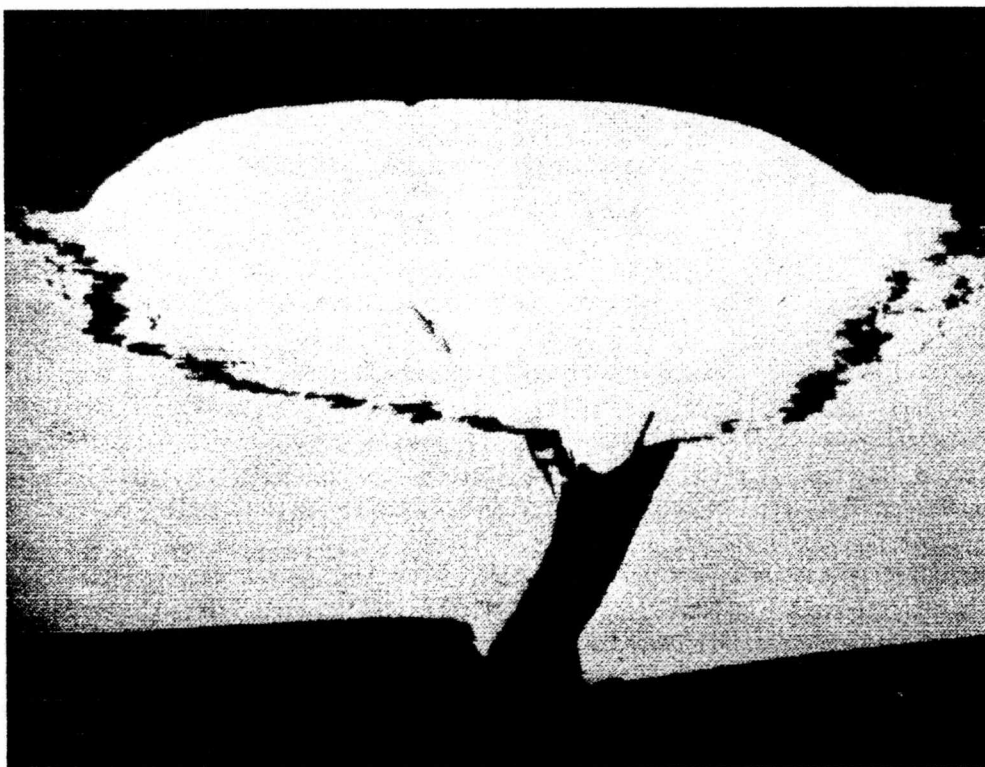


Figure 5. An example of liquation cracking in a badly overheated oxyacetylene weld in 6061-T6. (Source) J. Knight, *Welding Kaiser Aluminum*, Kaiser Aluminum & Chemical Sales, Inc, CA, 1967.

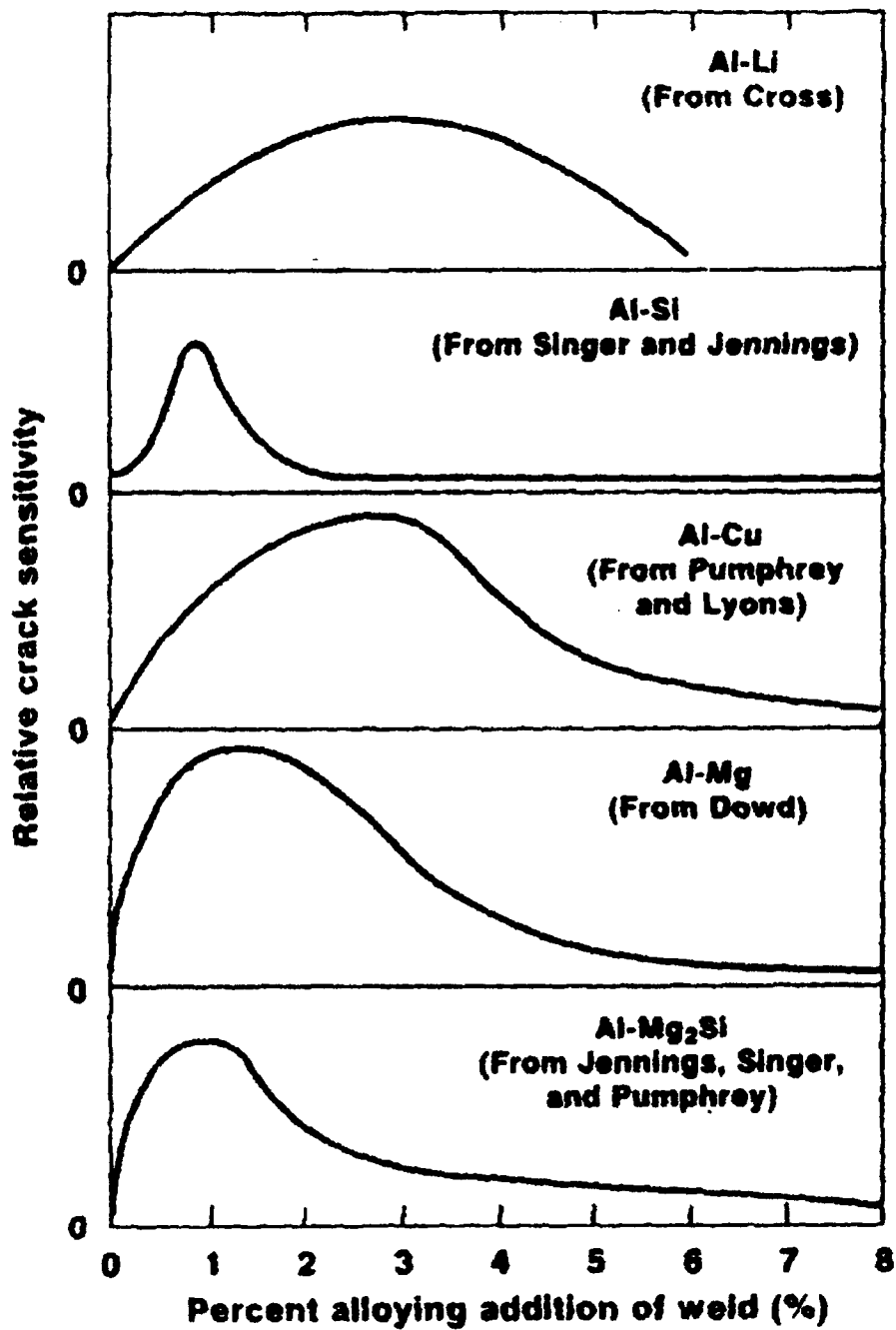


Figure 6. Relative crack sensitivity versus weld composition for various binary aluminum systems. (Source) J. R. Davis (ed.), "Welding," *ASM Specialty Handbook Aluminum and Aluminum Alloys*, ASM International, OH, 1993, pp. 376-419.

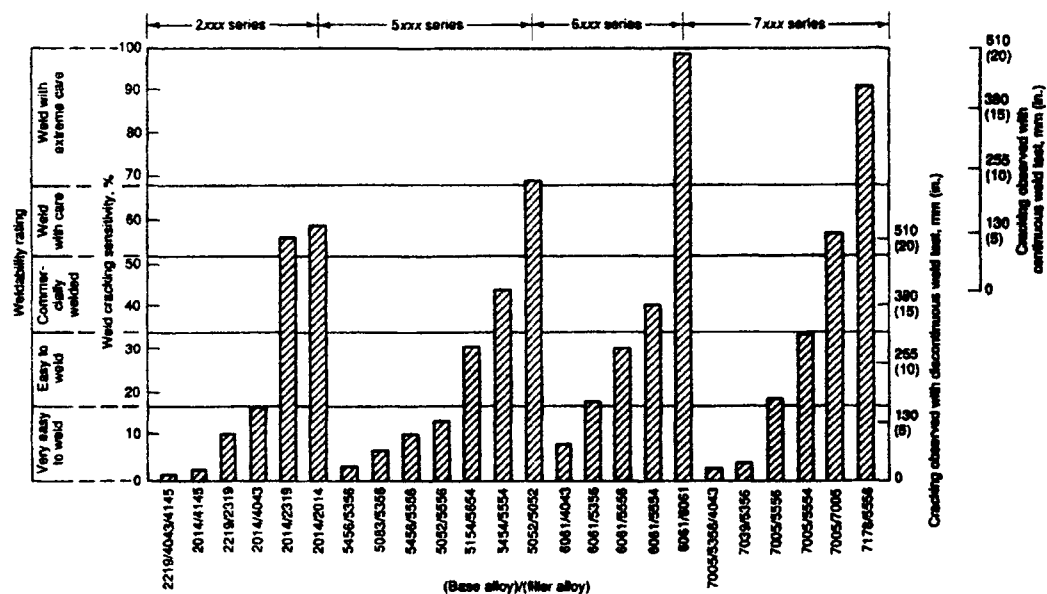


Figure 7. Relative crack sensitivity ratings of selected aluminum (base alloy/filler alloy) combinations. (Source) J. R. Davis (ed.), "Welding," *ASM Specialty Handbook Aluminum and Aluminum Alloys*, ASM International, OH, 1993, pp. 376-419.

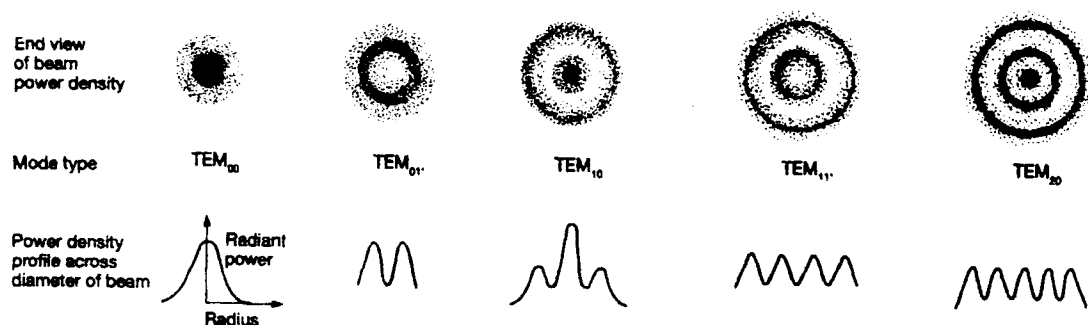


Figure 8. Common TEM shapes and corresponding plots of relative intensity versus radial position in the beam. (Source) C. Dawes, "Principles of Laser Welding and It's Characteristics," *Laser Welding*, McGraw-Hill, New York, 1992.

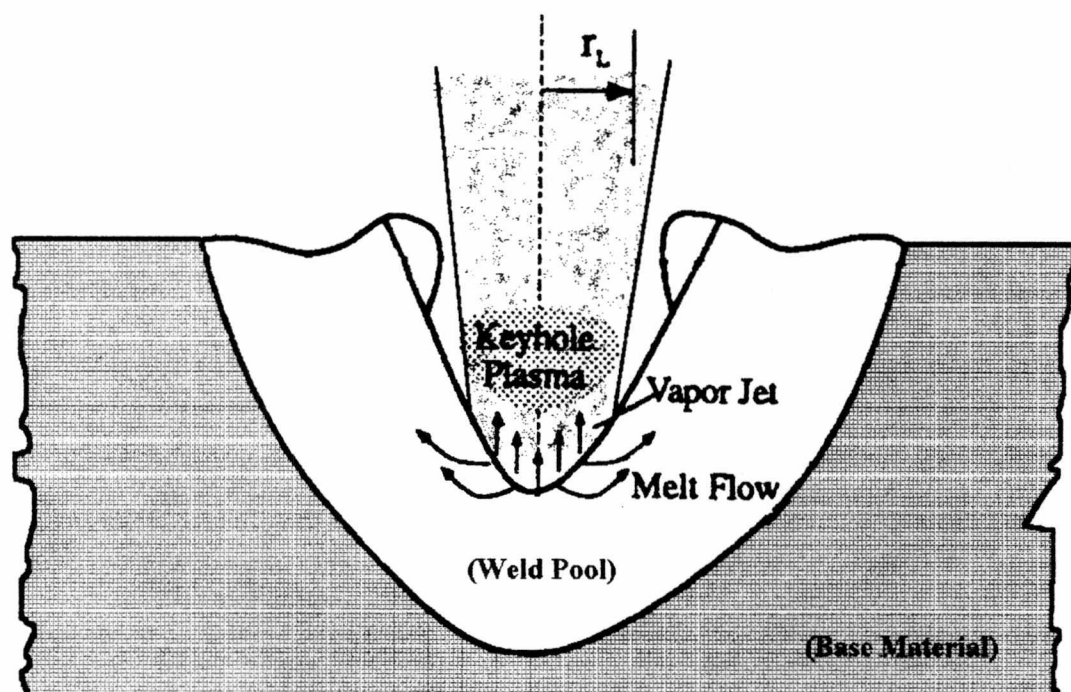


Figure 9. Schematic of a transverse cross-section of keyhole mode welding showing the melted alloy pool with a coincident laser beam and resulting keyhole. The laser beam radius is given by r_L .

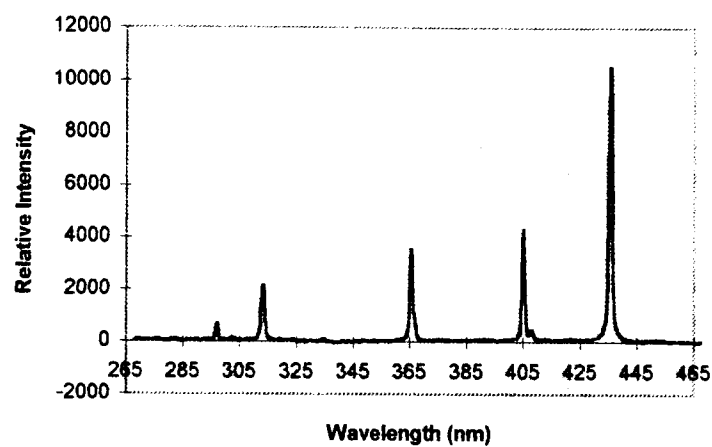


Figure 10. Mercury calibration lamp emission sample taken with the 300 grooves/mm diffraction grating.

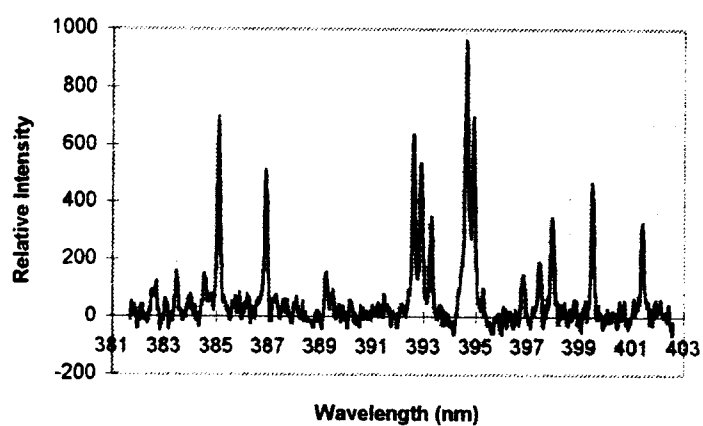


Figure 11. Copper vapor calibration lamp emission sample taken with the 1200 grooves/mm diffraction grating.

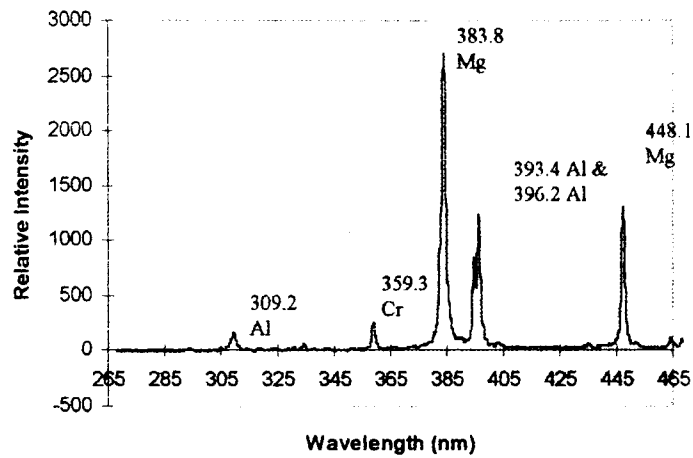


Figure 12. Weld plasma plume emission sample taken with the 300 grooves/mm diffraction grating.

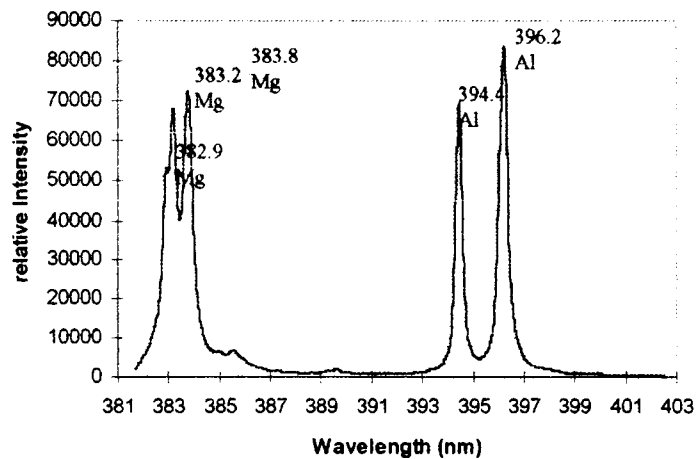


Figure 13. Weld plasma plume emission sample taken with the 1200 grooves/mm diffraction grating.

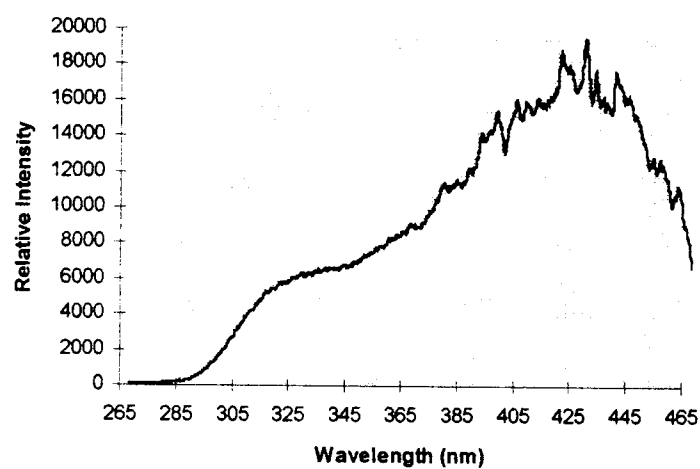


Figure 14. Deuterium calibration lamp emission sample taken with the 300 grooves/mm diffraction grating.

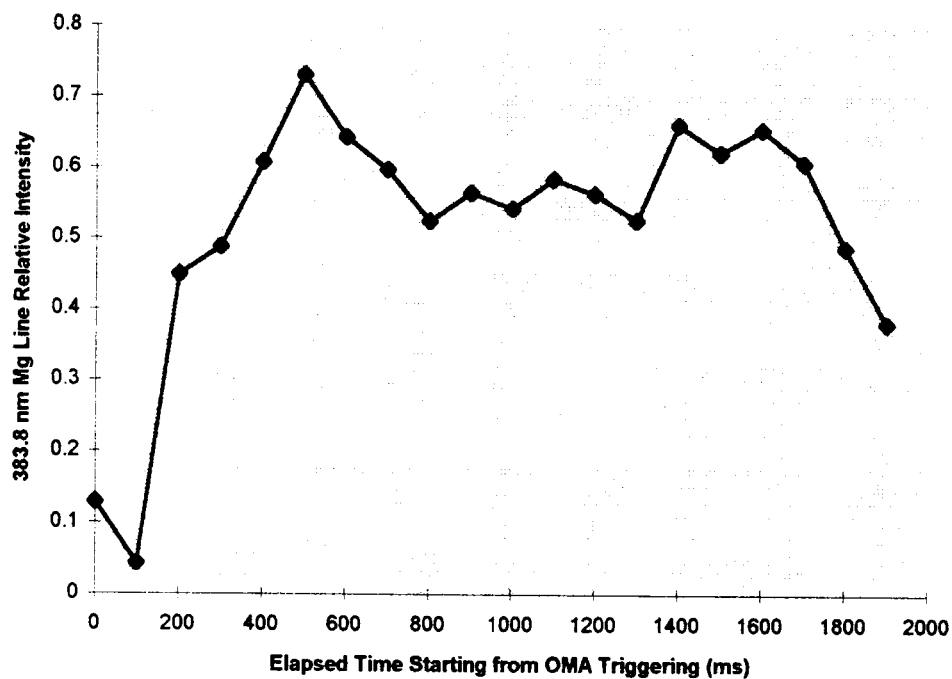


Figure 15. Relative intensity of the 383.8 nm magnesium line versus the elapsed time (ms) from the moment of triggering the OMA for 5500 mm/min wire feed rate. Travel speed was 3000 mm/min and the sample length was 51 mm giving a total weld time of 1 second. Spectral samples were taken every 100 ms for a total of 2 seconds so that a possible 10 samples could be taken during the weld time and an additional second was allowed for timing a manual trigger of the the OMA.

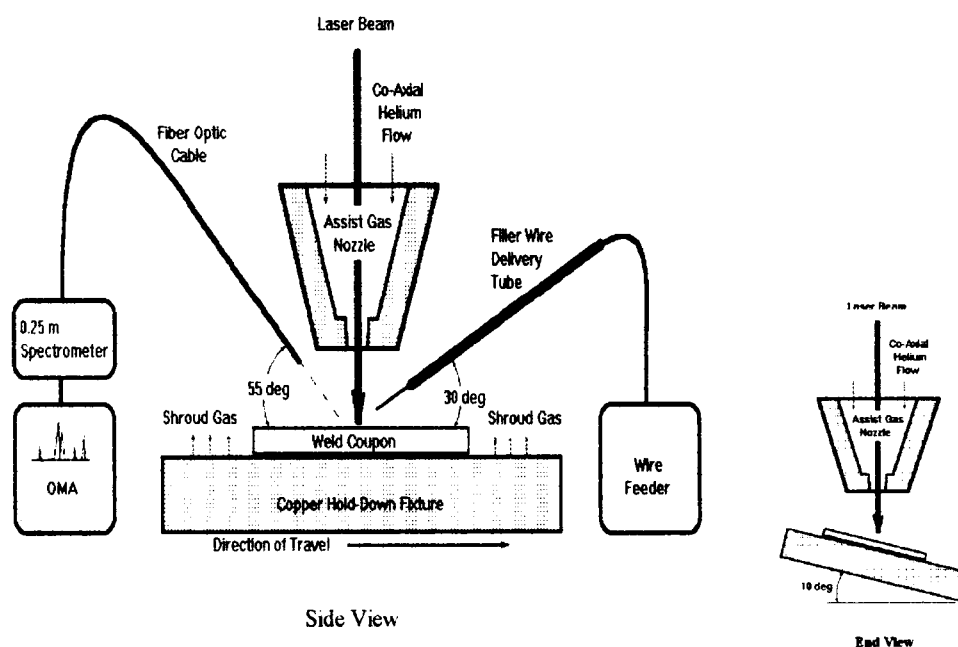


Figure 16. Schematic of experimental set-up. The entrance of the fiber optic cable was approximately 15 cm from the laser focus, and the tip of the wire delivery tube was approximately 3 mm from the focus.

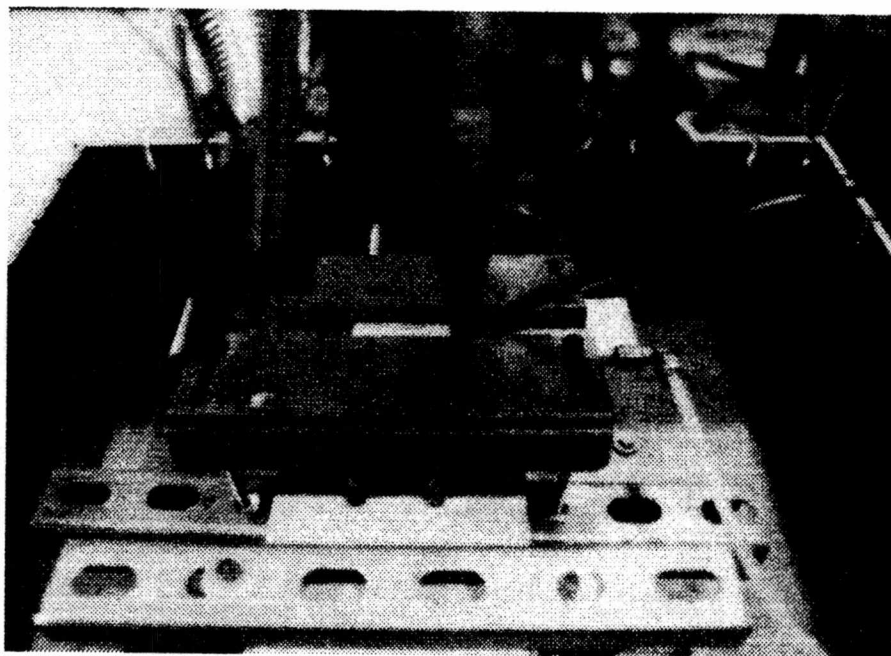


Figure 17. Photograph of fixturing with weld coupon, fiber optic cable, wire feeder, and laser head in position for welding.

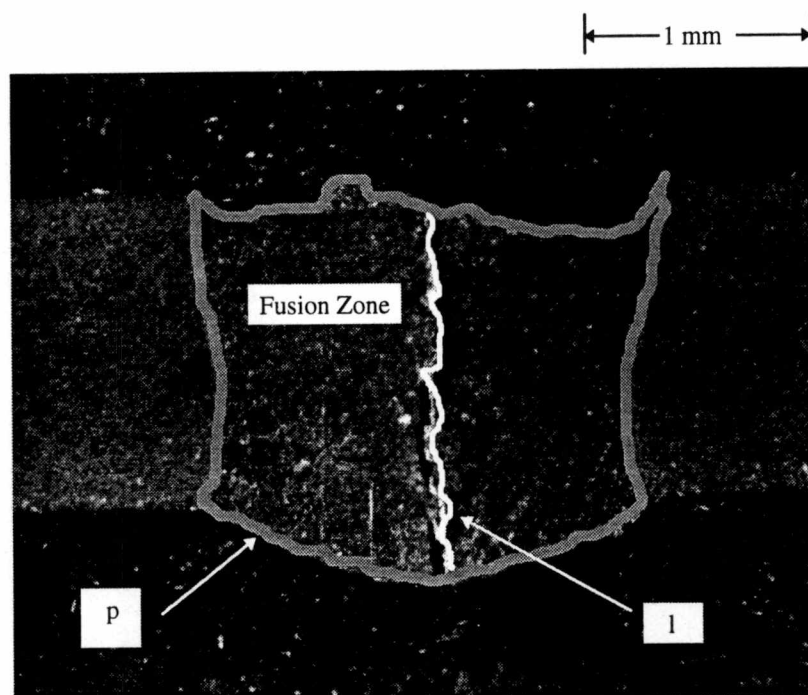


Figure 18. Weld cross-section with the crack length (l) and the fusion zone perimeter (p) labeled.

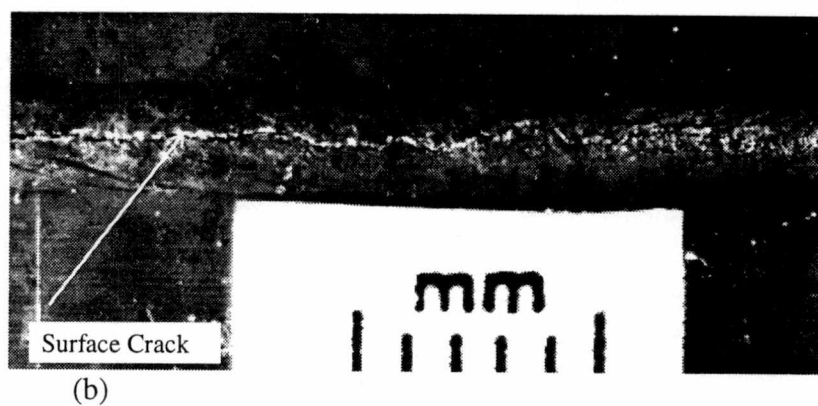
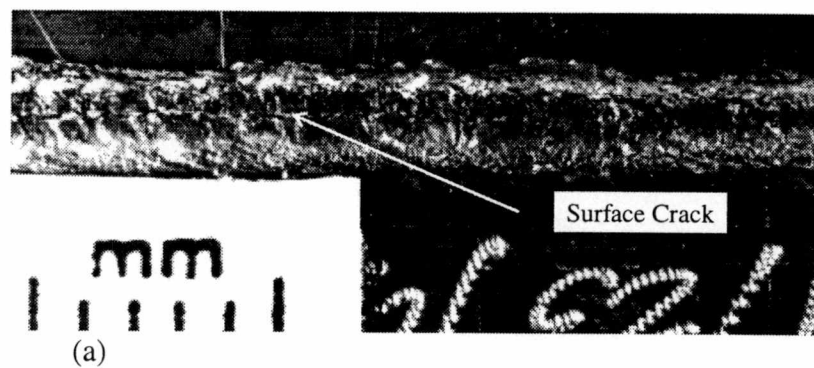


Figure 19. Overviews showing the top surface (a) and the bottom surface (b) of a weld made with the wire feed rate at 5000 mm/min.

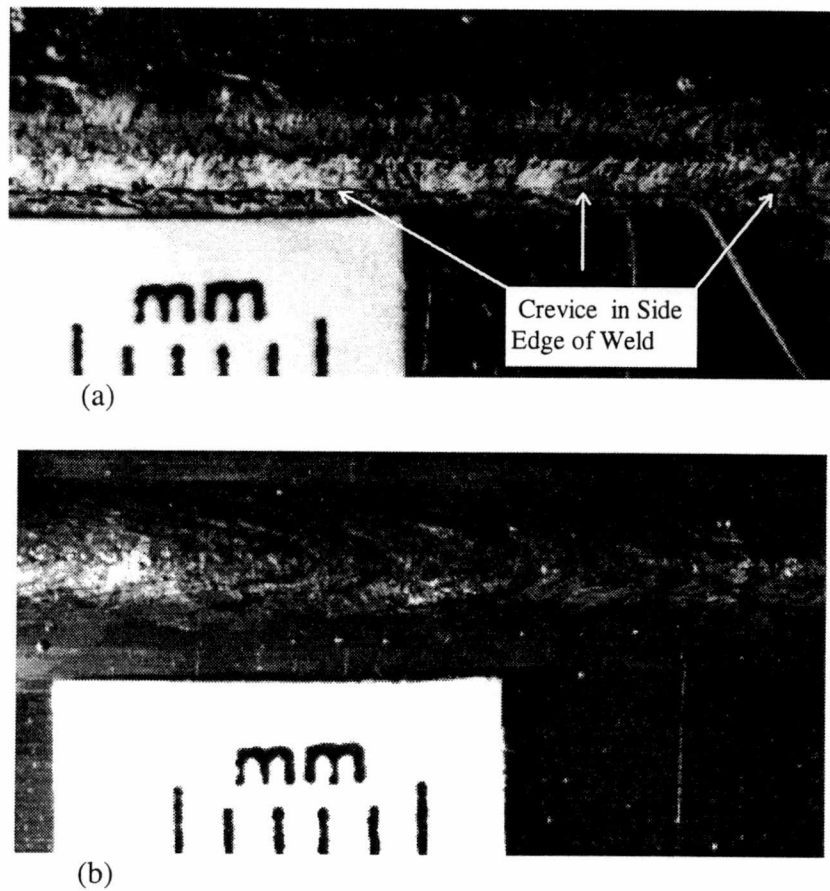


Figure 20. Overviews showing the top surface (a) and the bottom surface (b) of a weld made with the wire feed rate at 11500 mm/min.

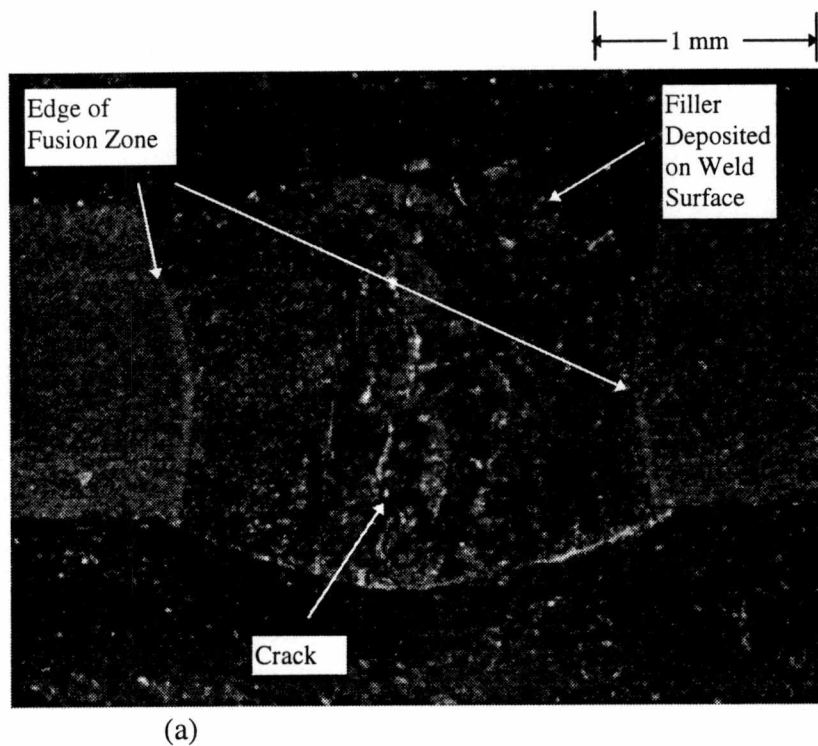
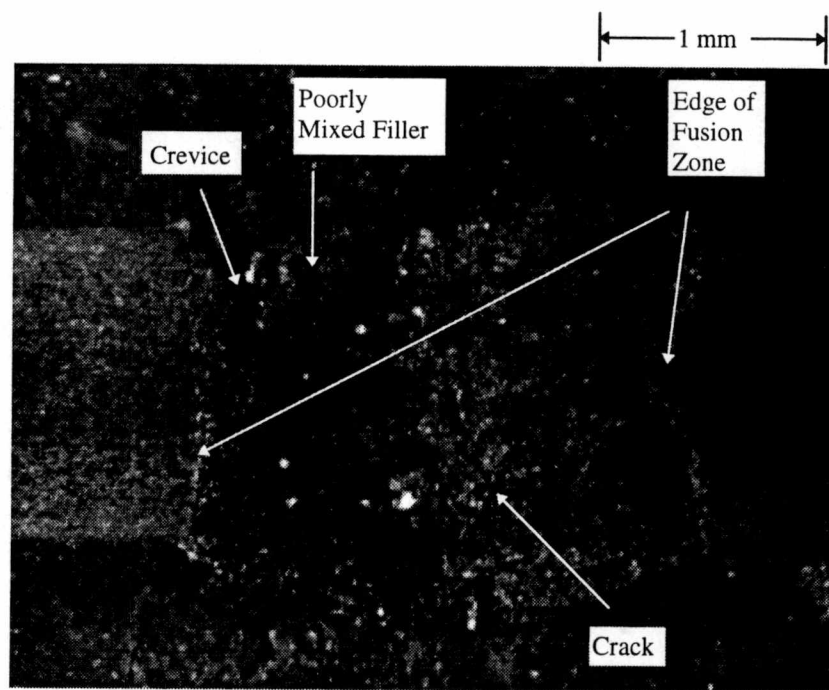


Figure 21. Cross-section views of welds made with wire feed rates of (a) 3000 mm/min, (b) 4500 mm/min, (c) 6500 mm/min, (d) 11500 mm/min.



(b)

Figure 21 (continued).

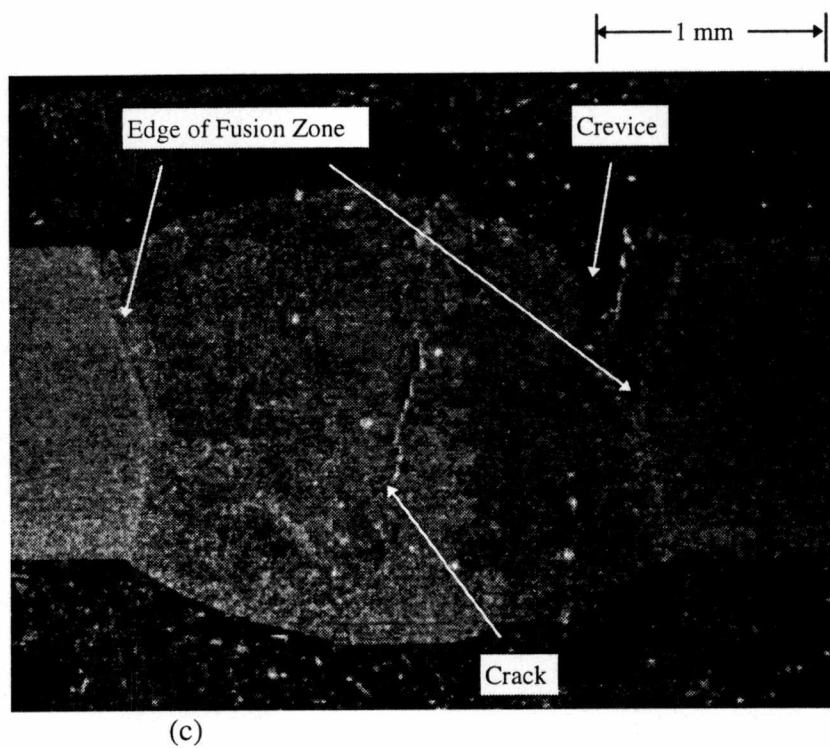


Figure 21 (continued).

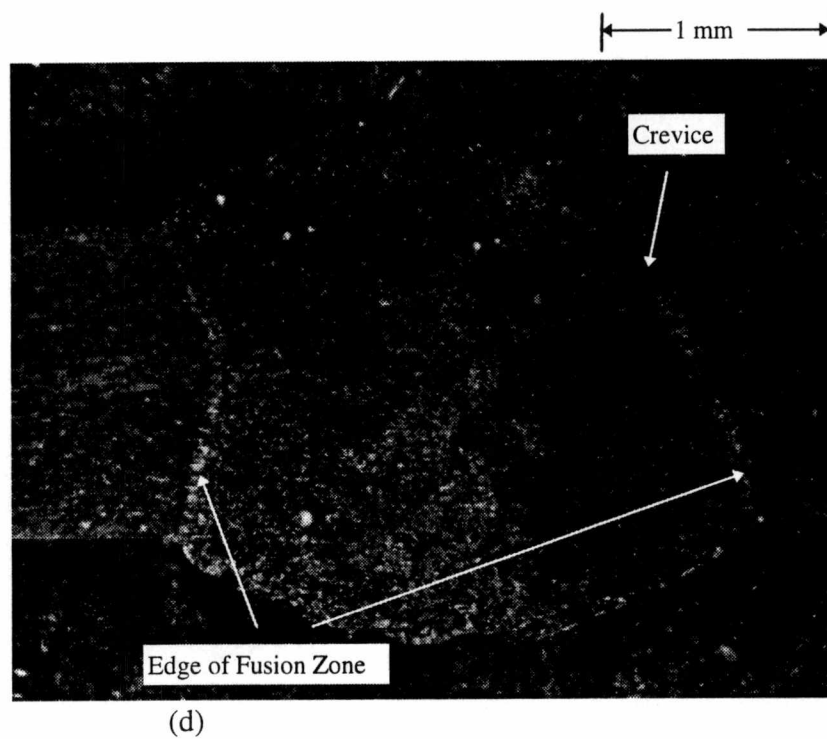


Figure 21 (continued).

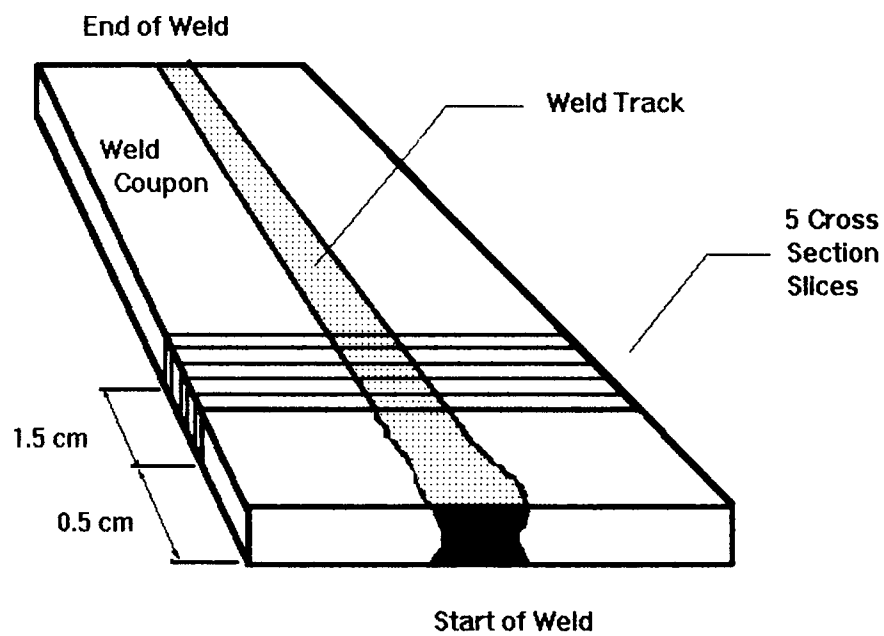


Figure 22. Schematic of a weld coupon showing the orientation of transverse cross-section slices.

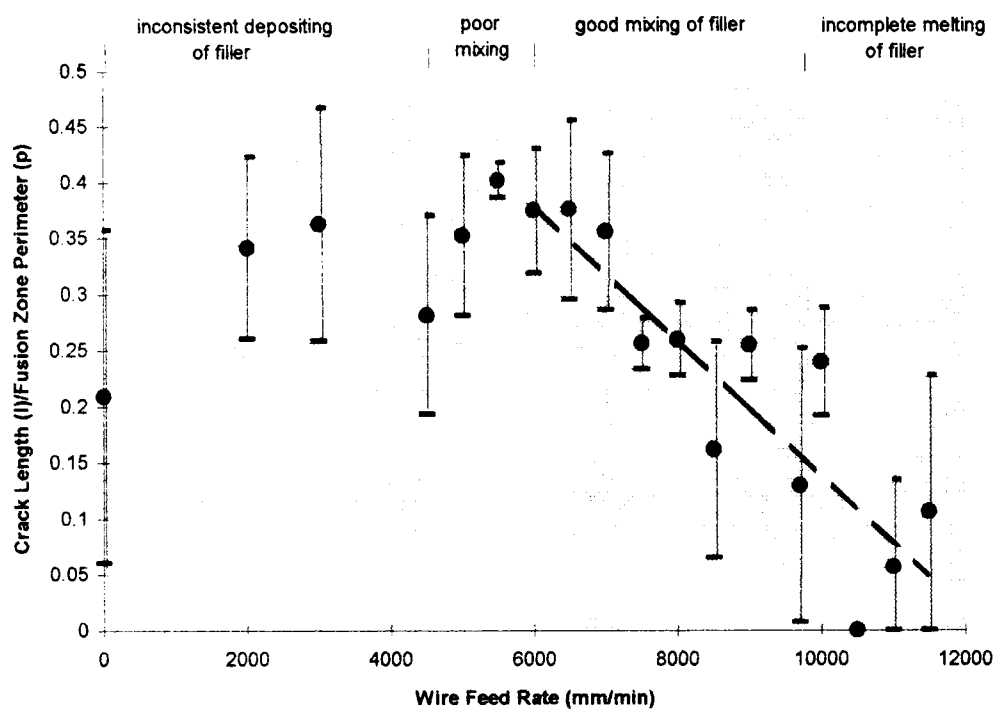


Figure 23. Total crack length (l) divided by the length of the fusion zone perimeter (p) versus wire feed rate. Error bars indicate standard deviation of data.

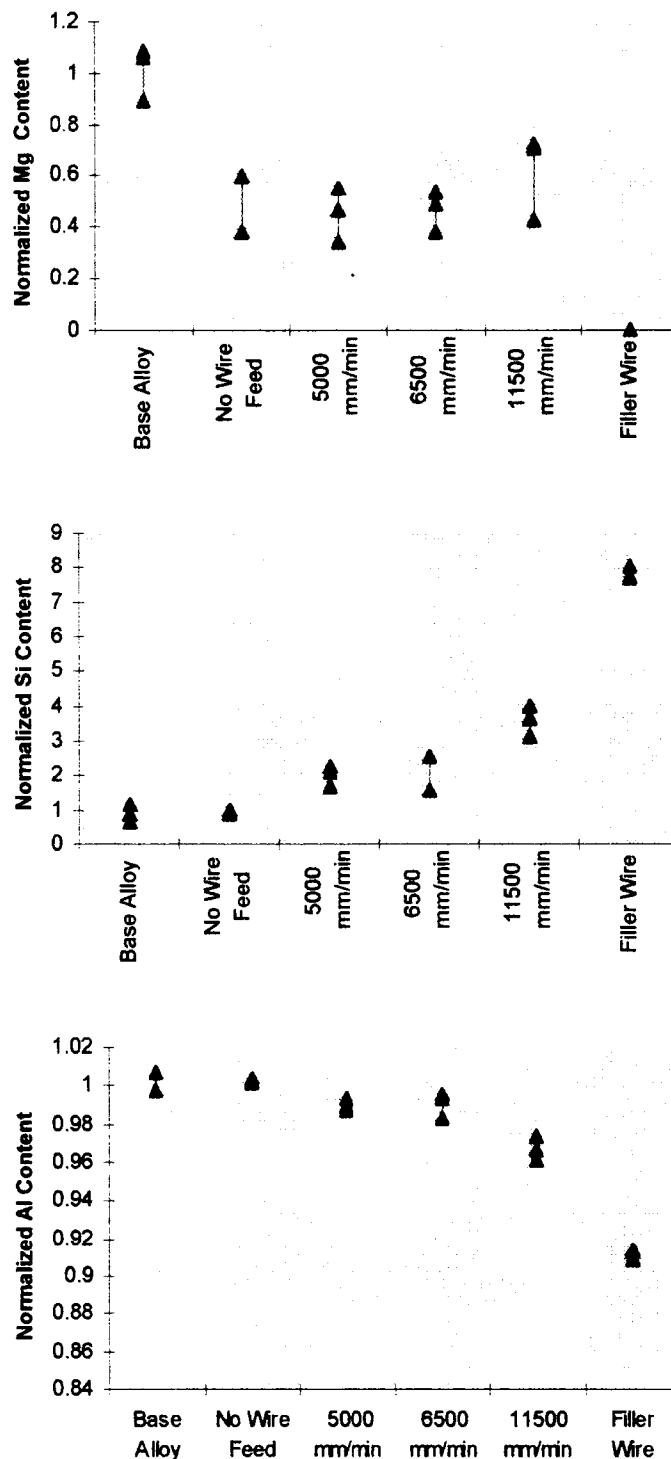


Figure 24. SEM/EDS results from quantitative analysis of the element content in the base alloy, the wire filler, and the fusion zones of welds with wire feed rates 0 - 11500 mm/min. All data is normalized by dividing with the average of the base alloy content for each element.

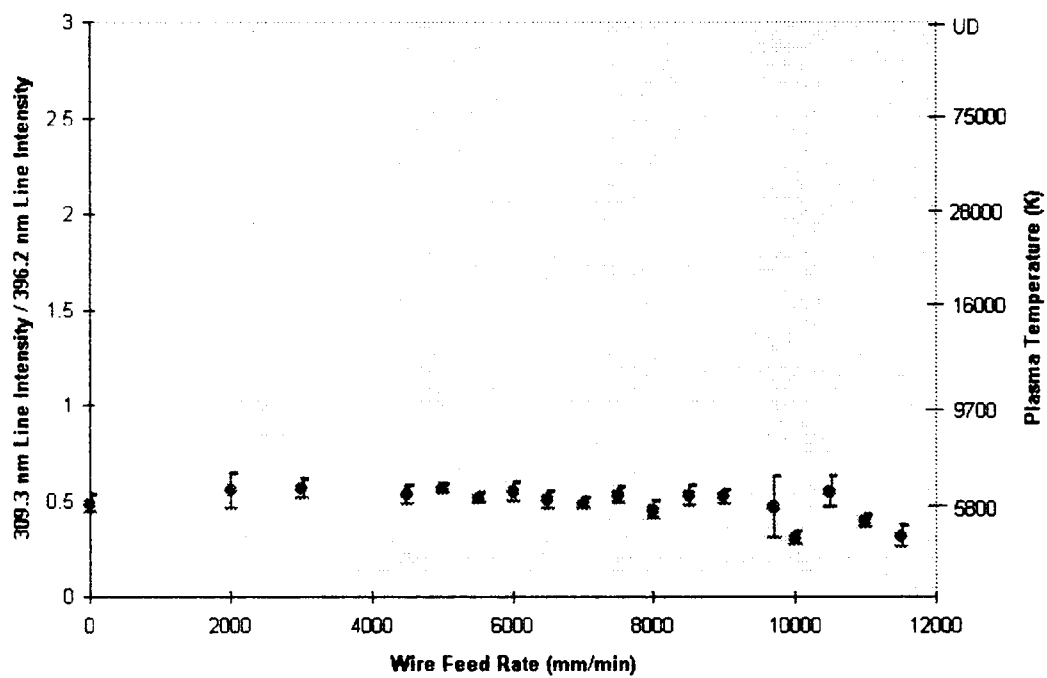


Figure 25. Ratio of 309.3 nm aluminum line intensity to 396.2 nm aluminum line intensity versus wire feed rate (mm/min). The plasma temperature, calculated from Equation 5, is given on the secondary axis. Error bars indicate standard deviation of data.

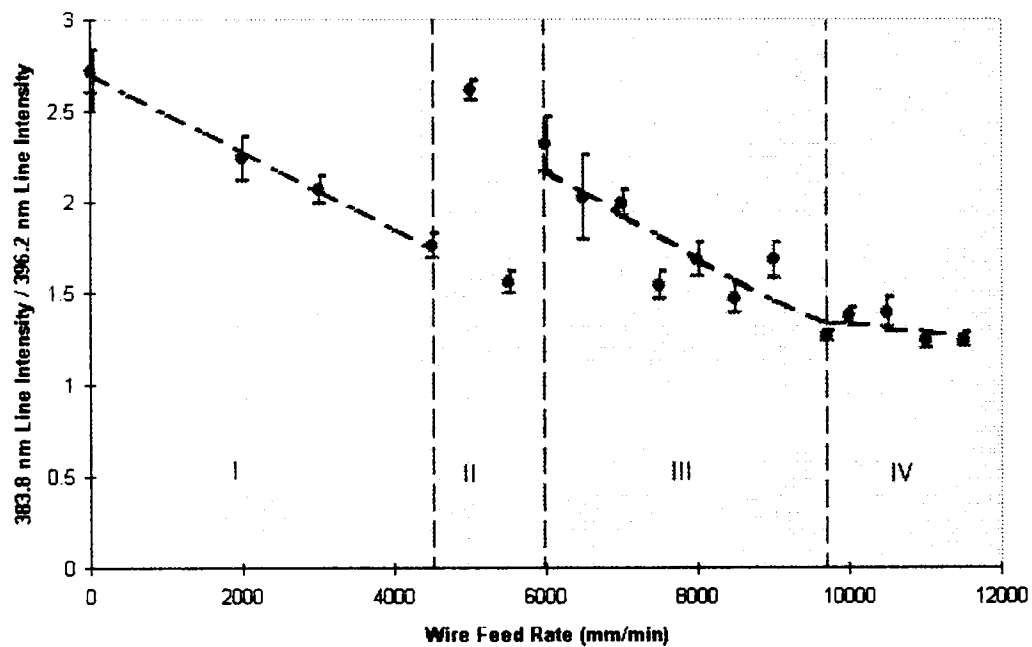


Figure 26. Intensity ratio of the 383.8 nm magnesium line and the 396.2 nm aluminum line versus wire feed rate (mm/min). Linear curve fits are shown for data in the I, III, and IV feed rate ranges. Error bars indicate standard deviation of data.

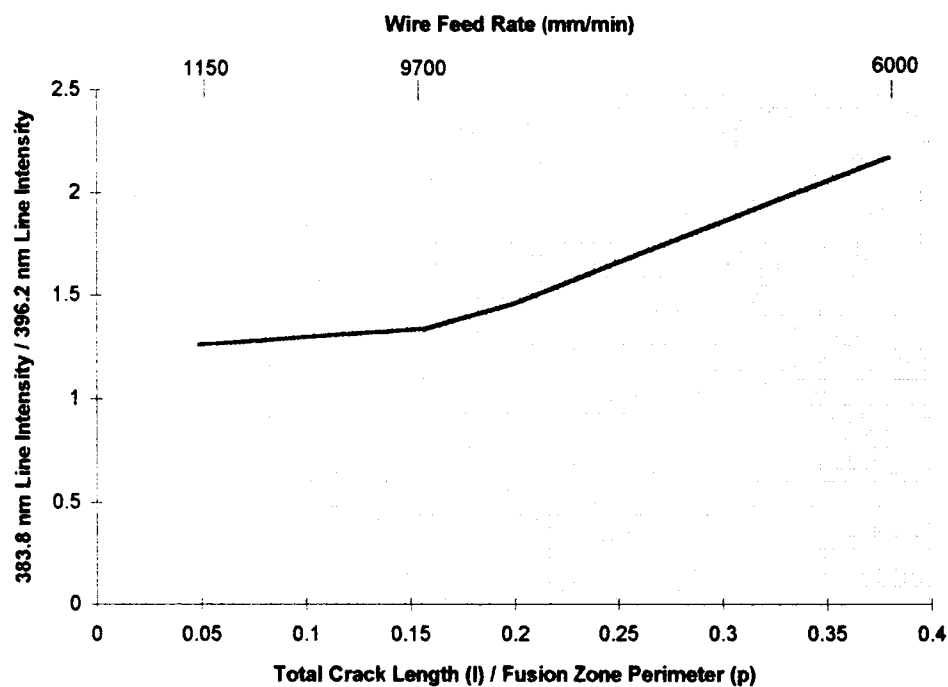


Figure 27. Intensity ratio of the 383.8 nm magnesium line and the 396.2 nm aluminum line versus total crack length (l) divided by the length of the fusion zone perimeter (p). The relation is found from correlated curve fits.

VITA

Ms. West is a native of Cookeville, Tennessee. She worked for her father's motorcycle import company as a mechanic and parts manager before entering Tennessee Technological University to pursue a degree in engineering. As an undergraduate, she participated in the co-operative education program, becoming an employee of Lockheed Aeronautical Systems Company in Marietta, Georgia. Having completed her bachelor's in mechanical engineering, Ms. West entered the University of Tennessee Space Institute (UTSI) in the fall of 1994 for master's studies in engineering science and mechanics. She spent her first year as a research assistant in the UTSI Center for Laser Applications. The following summer, she interned at Argonne National Laboratory, returning to complete her degree at the Institute as a part of the Argonne Graduate Research Program. Outside of her academic and career activities, Ms. West is an avid photographer, enjoys riding motorcycles, is a student pilot, and studies ballet.