EFFECTS OF SELECT PARAMETERS ON ELECTRON BEAM WELDING OF AL6061-T6 ALLOY

by

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ABSTRACT

Electron beam welding was used for joining Al6061-T6, precision machined, cylindrical sections. The welded assembly exhibited a minimum amount of distortion, but a better understanding of the effects of several key welding parameters on the structural integrity of the weld was required. The contents of this document describe the relative importance and interaction between welding speed, volume of filler, and beam pattern on the microstructural and mechanical properties of the welded joint. Understanding of the relationship between welding parameters and weld properties was accomplished by macrophotography and microstructural examination, microhardness testing, energy dispersive spectroscopy (EDX), and mechanical tensile testing of weld coupons. The results of this study will help quantify the robustness of the EBW process for this common aerospace material and joint geometry and will help determine the impacts of process deviations on weld fidelity in the production environment.
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CHAPTER 1: INTRODUCTION

1.1 ENGINEERING STUDY FLOW

Electron beam welding is widely considered one of the best welding methods in manufacturing. There are two main reasons for this recognition. One of the reasons is the narrow fusion zone (FZ). When less metal is melted shrinkage is less and distortion is also less. Therefore, precision machined components can be welded together with little or no secondary machining requirements. Another reason is the high efficiency of heat utilization. Not only is there less material melted, but significantly less heat is required to melt it. Hence, the solidification rate can be orders of magnitude greater than arc-deposited weld metal. For comparison, the solidification rate for arc-deposited weld metal is orders of magnitude faster than die casting or permanent mold casting. Solidification for electron beam welded material is associated with fast freezing. [1,2,3]

Al6061-T6 is widely used in the aerospace industry because of its characteristic high strength, good corrosion resistance, high heat conductivity and good low temperature properties. Unfortunately, aluminum alloys with small amounts of magnesium like Al6061 or Al5154 are not suitable for standard arc-welding processes without chemical modifications to the weld pool. Incipient cracking is often observed at the fusion boundary leading to lower mechanical properties.[4] Although not a problem in gas shielded welding, EBW is unique in that it is performed in high vacuum where weld pool modifications are not as simple.

This study investigates the effects of chemical modifications to the weld pool, speed of welding, and beam patterns in the electron beam welding environment on the metallurgical and mechanical properties of Al6061-T6 without the benefit of post-weld heat treatment. The macroscopic, metallurgical, and mechanical analyses were carried out in series as shown in Figure 1.1.

Note that many of the units provided in this thesis are non-SI units. The U.S. welding industry still uses many of the English and non-standard units. Some dimensions are in inches where typical of the industry. Another example would be the leak rate of $10^{-4}$ mbar cc/s which corresponds to mbar-l/s in SI units.
Figure 1.1 Electron beam welding engineering study flowchart
1.2 ELECTRON BEAM WELDING PRINCIPLES

The invention of electron beam welding can be directly traced to the needs of the nuclear industry. From approximately 1950 onward, there was interest in reactive materials because of their efficiency in capturing neutrons. Selections included niobium, tantalum, zirconium, vanadium, beryllium, molybdenum, tungsten, and their alloys. These were the potential canning materials for the advanced reactors being developed, but without a suitable joining technology none could be used satisfactorily. All of these materials had one property in common; they were all extremely reactive to oxygen and nitrogen at temperatures in excess of 300°C. The impurity levels introduced where high enough to effect the strength and ductility of the metal. For this reason, operations involving welding needed to be conducted in an inert atmosphere. Gas tungsten arc welding (GTAW) shielded with inert gases was initially used with limited success. In 1954, Dr. J.A. Stohr of the French Atomic Energy Commission initiated his developments which led to the publication of his paper in 1957 outlining the use of an electron beam to perform fusion welding in a vacuum.\[1,2,3,4\]

Modern EBW apparatus involves three main components: the beam generator, the beam manipulation mechanism, and the working chamber. These components may have separate vacuum systems. A schematic representation of an electron beam welding machine is shown in Figure 1.2.

![Figure 1.2 Schematic representation of EBW machine [4]](image-url)

[1,2,3,4]
A tungsten or lanthanum hexaboride (LaB$_6$) filament heated to about 2500°C in a high-vacuum environment ($10^{-5}$ torrs or lower) will produce free electrons with a current density given by the Richardson-Dushman thermionic emission equation, $J=AT^2e^{-W/kT}$. Electrons thermionically emitted from the filament are accelerated by high-voltage towards the anode and a beam of high energy electrons is emitted through the circular hole at its center into the beam manipulation column. The Wehnelt cap, or bias cup, which is positioned between the cathode and anode and is held at a voltage slightly more negative than the filament, regulates the flow of electrons moving through the anode. In principle, the EB generation is identical to the transmission electron microscope (TEM) developed in the late 1930s. Modern TEM and EBW machines use an accelerating voltage of 300kV or more. The EBW gun develops a beam current between 50 to 1000 mA, whereas the TEM employs currents on the order of 1µA, or about 1/1000$^{th}$ that of the EBW. The electron beam passes through the pierced anode and obtains the power density required to weld. It is then passed through an alignment and focusing system to direct the beam. Several electromagnetic focusing lenses bundle the beam onto the work piece. A stigmator coil helps correct aberrations of the lenses. A viewing optic or video system allows the exact positioning of the EB. The beams typically are focused to about 0.025 to 0.064 centimeters in diameter and have a power density of about 155K watts/cm$^2$, which is sufficient to vaporize any metal [1,2,4].

Figure 1.3 illustrates the EB energy transformation inside the work piece. When the highly accelerated electrons impinge upon the work piece they release their kinetic energy through heat dissipation. Some of the primary electrons are subject to backscatter and secondary electrons along with x-rays.

Figure 1.3 EB energy transformation inside work piece [5]
The impact of the tight beam of electrons only penetrates a few microns into the work piece. The kinetic energy is efficiently imparted to the work piece in the form of heat. The high energy density beam at the point of impact causes the metal to vaporize allowing the formation of a keyhole that is surrounded by a shell of fluid metal for the entire weld depth. As the electron beam advances along the joint, a weld is formed by a combination of three effects that occur at the same time: (1) metal on the advancing side of the hole vaporizes and the vaporized metal then condenses to form molten metal on the trailing side of the hole; (2) the molten metal on the leading side of the hole flows to the trailing side of the hole; and (3) the molten metal formed continuously fills the hole and solidifies as the electron beam advances. Penetration depths of 15 cm in aluminum and 7.5 cm in steel are possible with modern high vacuum, high voltage machines.

1.3 STATEMENT OF WORK

Funding for this study was provided by the U.S. Navy. The study determined the impact of several EBW parameters on the metallurgical and mechanical properties of an Al6061-T6 joint. The EBW parameters determined the amount of metal filler shim, travel speed, and beam pattern. The output variables were porosity percentage, solidification cracking, and base metal dilution in the FZ and their effect on the weld metallurgical and mechanical properties. Analytical tools included light optical microscopy (LOM) and scanning electron microscopy (SEM), Knoop hardness testing and mechanical tensile testing. Electron Beam Engineering, Inc. performed the welding and the analysis was performed at the Colorado School of Mines in conjunction with Barber-Nichols, Inc. This thesis provided recommendations for improving Al6061-T6 electron beam welds for use in future naval applications.
CHAPTER 2: EXPERIMENTAL METHOD

2.1 SELECTION OF KEY WELDING PARAMETERS

There are several standard EBW parameters that must be developed for each joint geometry and material. These include the beam current, beam accelerating voltage, spot size, travel speed, filler shim material and volume if required, and beam pattern. The beam current determines how many electrons per second are boiled off the thermionic emitter. Increases to the current increase the weld pool width and depth, but do not alter the weld aspect ratio, defined as the weld width at the crown divided by the weld penetration depth. The beam accelerating voltage determines the velocity to which the electrons are accelerated. This is a key factor in determining the depth of penetration into the work piece. The spot size determines the power density of the beam. By changing the spot size the beam can be used to preheat the joint, cosmetically smooth out the weld bead, or perform anything from a shallow seal weld to a full depth of penetration weld all with the same current and voltage settings. The weld travel speed determines how fast the beam and work piece move relative to one another. The incident beam of electrons hitting the work piece evaporates the underlying material and rapidly forms a metal vapor cavity, or keyhole, which is surrounded by a column of liquid metal. Figure 2.1 illustrates the steps in creating the EBW keyhole.

![Vapor cavity and liquid metal diagram]

Figure 2.1 Steps in creating the EBW keyhole [5]

As the work piece progresses with respect to the beam, the front side of the keyhole melts. The melted material moves around the keyhole and rapidly solidifies at the backside, Figure 2.2.
The keyhole walls remain open due to the vapor pressure of boiling metal. This pressure is constantly being balanced against the hydrostatic pressure and the surface tension of the molten column as illustrated in Figure 2.3.

The equilibrium of the forces from the metal vapor, surface tension and hydrostatic pressure is unstable. The transient nature of the pressures exposes the molten backside of the keyhole to forces that rapidly and erratically change the shape of the liquid film. Pressure pulses create cavities that may or may not collapse depending on the rate of solidification. In some cases, the keyhole may even collapse and be recreated by the beam which will create further turbulence in which vapor pockets are formed. Increasing weld travel speed can lead to turbulent flow and
porosity. Decreasing weld travel speed will increase the heat transferred into the base metal which may cause distortion and increase the weld penetration depth.

The type, thickness, and the number of metal filler shims can affect the number of defects in the weld zone. Standard filler alloys selected for gas tungsten arc welding (GTAW) of Al6061-T6 are Al4043, Al4346 and Al5356. For this study, Al4047 has been selected. This alloy was originally developed as a brazing alloy (Boron-Aluminum-Silicon-4) for Al6061, taking advantage of its low melting point and narrow freezing range (577°C to 582°C). Table 2.1 provides chemical composition and typical mechanical properties for Al4047 [7]. Note the 4XXX series of alloys is not heat treatable and the ultimate strength even in the post weld heat treated condition is about 28% less than Al 6061-T6. In addition, there is a degradation in the elongation properties. 4XXX alloys (Al-Si) are selected for Al6061-T6 welding because they form a eutectic that helps backfill solidification cracking in the fusion zone and liquation cracking in the HAZ. This characteristic is desirable in GTAW when joints are required to be leak tight. The results of this study are intended for navy applications that require helium leak testing with an acceptance criteria of $10^{-4}$ mbar cc/s. Since Al4047 also doubles as a braze material, it is readily found in very thin sheet stock sizes. Filler wire laid on top of the EBW joint is the most common method of introducing filler material, but this method does not introduce the filler metal to the joint evenly and is difficult to implement in production. For this study, a ‘gasket’ of Al4047 braze material found in the form of shim stock .0075 mm thick was placed in the weld joint. The shim stock was cut to size using a wire electrical discharge machine (EDM). Multiple numbers of shims were used to determine the effects of filler alloy on the mechanical properties of the joint. The effects on weld inclusions and mechanical properties with the addition of two oxide layers per shim gasket were evaluated.

**Table 2.1 Chemical composition in wt. % and typical mechanical properties of Al4047 using GTAW**

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Zn</th>
<th>Be</th>
<th>Other</th>
<th>Alum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11.0-13.0</td>
<td>0.8</td>
<td>0.30</td>
<td>0.15</td>
<td>0.10</td>
<td>0.20</td>
<td>0.003</td>
<td>0.15</td>
<td>REM</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Base alloy properties</th>
<th>As welded</th>
<th>Post HT and age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>UTS (MPa)</td>
<td>YS (MPa)</td>
<td>ELG (%)</td>
</tr>
<tr>
<td>6061-T6</td>
<td>310</td>
<td>276</td>
<td>17</td>
</tr>
</tbody>
</table>

*ELG - elongation
Beam oscillation patterns are unique to electron beam welding. The beam is controlled and manipulated by a magnetic field. By deflecting the beam to a particular pattern, the keyhole size can be enlarged and joints with gap widths up to 0.250 mm can be successfully welded. Beam oscillation is advantageous when stacking tolerances become too large for a straight beam. This process has also been used as a low energy density weld to smooth out undercuts and improve the cosmetic appearance of the top head in a secondary operation after the penetration weld. Figures 2.4 shows several standard beam patterns which include straight, oscillating, double parabola and triangular functions.

![Figure 2.4](image)

Figure 2.4 Top view and profile view of standard electron beam weld patterns [6]

Literature suggests that the larger keyhole created by an oscillating beam may result in more time for metal vapor in the keyhole to rise and escape the FZ [6]. The oscillating beam in this study will effectively increases the keyhole area by a factor of 2.5. The larger volume of molten metal will take longer to cool down, leaving the gas more time to rise and escape. The driving force for pushing out the gas pores is simply the buoyancy forces acting on them. One of the reasons that aluminum has more issues with gas pores is because the buoyancy forces on the pores is not as great as in higher density steel and nickel alloys. The high solubility of hydrogen in molten aluminum also contributes to the increase in porosity in aluminum welds. This investigation will study whether or not a low density, low melting temperature alloy will see the the same benefits from an oscillating beam.
2.2 MATERIALS, FIXTURING, EQUIPMENT, PROCESSES, AND TESTING

The assembled EBW coupon and joint geometry is illustrated in Figure 2.5. The cylindrical weld joint was machined identical to the final product geometry. The assembly provided a butt joint 6.9 mm thick with an integral backing of 2.5 mm. The integral backing provides a pilot to align the joint and an area for the root of the weld to penetrate that is out of the critical stress zone. A predetermined number of shims were placed at the interface based on test requirements. Sketches for the individual weld samples with the integral backing, the filler metal shim, and tensile coupons can be found in Appendix A.

Figure 2.5 Schematic illustration of welded assembly
All welded pieces were cleaned by hand one hour prior to being welded. All components of the welds, including the metal filler shims, were cleaned with 7447 Scotchbrite pads (medium red) and then wiped down with Kimtech wipes wetted in methyl ethyl ketone (MEK). Operators wore sanitized rubber gloves during the cleaning and welding process to prevent contamination. Each welding station was equipped with a stereo microscope capable of 100X magnification and a log to record the procedure and any important events for future reference.

The electron beam welding apparatus used for this study was a Wentgate Frame retrofitted by EB Engineering Inc., Figure 2.6. The Beamer 524 is capable of 3.5 kilowatts, 60 kilovolts, and 50 milliamperes. The Beamer 524 was designed for smaller, thin walled components. The small work chamber combined with a large roughing pump and diffusion vacuum pump pulled the chamber pressure down to $3.0 \times 10^{-5}$ Torr in three minutes. Once the vacuum in the chamber was achieved the gun was opened to the chamber and welding commenced.

![Figure 2.6](image)

**Figure 2.6** The Beamer 524 EBW machine used for this investigation

The chamber was lead lined to protect the operator and those around him from the x-rays produced by the machine during welding, Figure 2.7. The table with the knobs on the door controlled the beam focus parameters. The operator’s computer monitored the vacuum pressure,
Figure 2.7 A view of the EBW machine working chamber, rotating shaft and chuck kilovolts, milliamperes, valve operation, and beam pattern. Inside the chamber was a chuck used to rotate the part with respect to the stationary beam.

Figure 2.8(a) shows a fixtured weld assembly prior to electron beam welding. The round plate at the base of the assembly utilized a lathe turned pilot to position the weldment to the stationary electron beam in a repeatable fashion. Figure 2.8(b) shows the same assembly chucked and ready for electron beam welding.

Figure 2.8  a)  weld assembly in fixturing  b)  weld assembly chucked up inside EB machine
Figure 2.9 Representative EBW on the outer diameter of welded assembly

Figure 2.9 shows the EBW. The spot size of the beam at the surface of the joint was about 0.38 mm so the alignment of the part to the beam was critical. The all-thread, flat upper bar, spring, and nut provided a constant compressive load on the weld joint. Without the compressive spring force, the part could become loose in the fixture due to lateral shrinkage in the weld joint.

Once the part was placed in the fixture, the chamber door was closed and the vacuum was reduced down to $10^{-5}$ Torr. A diffuse beam was used to align the beam and the weld joint. The vacuum hold time prior to welding was increased due to the reactive nature of molten aluminum and the tight joint spaces. The part was electron beam tack welded in four places to ensure that the weld gap did not separate as the weld proceeded. Once electron beam weld tacking was completed and the operator rechecked all the critical parameters and the weld was initiated.

With a circumference of 56 cm and travel speeds of 19 mm to 25 mm/s, the weld was complete in about 25 seconds. The part was left to cool in the chamber for 2 to 3 minutes. The vacuum was broken, the door opened, the welded part removed, and another part loaded for processing. All welding was performed in one ten-hour shift due to production constraints on the machine.

2.3 EXPERIMENTAL DESIGN

Normally in development of the production EB welding process, penetration and weld defects are the key requirements for acceptance. Weld penetration and defects are influenced by six key parameters: accelerating voltage, current, spot size, travel speed, beam pattern and filler material. Cleaning is considered to be essential in any case. The accelerating voltage, current, and spot size are directly responsible for the depth of penetration. The travel speed, beam pattern, and filler indirectly influence the penetration, but have a greater impact on the defects and chemical
composition in the fusion zone that dictate the overall mechanical properties of the weld. Since the depth of penetration had been developed, and the allotted slot on the electron beam welding machine was only one ten-hour shift the three parameters that most influenced the mechanical properties were selected for this investigation. These variables include the travel speed, beam pattern, and the filler shim volume. The accelerating voltage, current, spot size and cleaning methodology were held constant throughout the experiment.

A 2x2x3 full factorial design of experiment (DOE) structure was chosen because it provided a means to optimize and understand the three selected welding parameters fully. Multivariate analysis of variance (ANOVA) and multiple linear regression were used to investigate and model the relationships between many of the response variables and independent variables. Effect plots were used to visualize the impact of each factor combination and identify which factors were most influential. Multivariate ANOVA was used to test simultaneously the null hypothesis thereby determining if any of the effects were significant.

Table 2.2 provides the designed experiment factors and their associated levels. The DOE design test matrix is given in Table 2.3. As mentioned earlier, the factors included in this research were travel speed, number of metal filler shims, and the EBW beam oscillation. The levels for each factor were selected to maximize their impact. The welding speed was set at 19 and 25 mm/s. This range represented the maximum difference that could be attained without adversely affecting the depth of penetration in practice. Weld dilution is defined as the contribution of the base metal into the formation of the weld by melting. The weld dilution was controlled by placing different numbers of 0.0075 mm thick, Al4047 metal filler shims at the joint interface. Zero dilution was represented by no shim material at the joint and the maximum dilution (4 shims) was dictated by the maximum spot size diameter of 0.025 mm. A 0.25 mm diameter oscillating circular beam pattern is a common industry standard outside the straight beam pattern. This beam pattern provided a good indication of the effects of beam oscillation on defect reduction.

All other EBW parameters remained constant throughout the testing. The accelerating voltage, beam current, and focus (spot) size were maintained at 60 kV, 19 mA, and 0.025 mm, respectively. The material for the testing was received as extruded Al6061-T6511 tube stock per
Table 2.2 2X2X3 full factorial DOE factors and associated levels.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel speed</td>
<td>19 mm/s 25 mm/s</td>
</tr>
<tr>
<td>Beam Pattern</td>
<td>Straight Beam (no oscillation)</td>
</tr>
<tr>
<td></td>
<td>Circular Oscillation (0.25mm)</td>
</tr>
<tr>
<td>Filler Shims</td>
<td>No Shims 2 shims 4 shims</td>
</tr>
</tbody>
</table>

Table 2.3 DOE Test Matrix

<table>
<thead>
<tr>
<th>Test #</th>
<th>Travel speed (mm/s)</th>
<th>Beam Pattern Diameter (mm)</th>
<th>Filler Shim (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>Straight (0.000)</td>
<td>0.000</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>Oscillating (0.250)</td>
<td>0.000</td>
</tr>
<tr>
<td>3</td>
<td>19</td>
<td>Straight (0.000)</td>
<td>0.015</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>Straight (0.000)</td>
<td>0.015</td>
</tr>
<tr>
<td>5</td>
<td>19</td>
<td>Straight (0.000)</td>
<td>0.030</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>Straight (0.000)</td>
<td>0.030</td>
</tr>
<tr>
<td>7</td>
<td>19</td>
<td>Oscillating (0.250)</td>
<td>0.015</td>
</tr>
<tr>
<td>8</td>
<td>25</td>
<td>Oscillating (0.250)</td>
<td>0.015</td>
</tr>
<tr>
<td>9</td>
<td>19</td>
<td>Oscillating (0.250)</td>
<td>0.030</td>
</tr>
<tr>
<td>10</td>
<td>25</td>
<td>Oscillating (0.250)</td>
<td>0.030</td>
</tr>
<tr>
<td>11</td>
<td>19</td>
<td>Straight (0.000)</td>
<td>0.000</td>
</tr>
<tr>
<td>12</td>
<td>19</td>
<td>Oscillating (0.250)</td>
<td>0.000</td>
</tr>
</tbody>
</table>

AMS-QQ-200/8. The tube stock had an outer diameter of 7.5 inches and an inner diameter of 5.5 inches. The chemical composition is provided in Appendix A. The machined weld sample measurements are shown in Figure 2.10.
The same electron beam machine was used for all testing. The vacuum level in the EB gun and work chamber was maintained at $10^{-6}$ and $10^{-5}$ Torr, respectively. The same procedure was used for cleaning the wrought cylindrical coupons and metal filler shims. The parts were welded within one hour of cleaning. The same operator performed all the testing over the course of eight hours.

The measured results included: macrophotography and micro examination of the EB weld and associated defects, mechanical testing for yield strength, ultimate tensile strength, and elongation, Knoop microhardness measurements through the weld zone in three locations, and dilution measurements in the weld pool. Figure 2.11 illustrates the location and type of weld.
coupons excised from each weldment. Each of the twelve weldments was cut into four sections, A through D. Each section produced a metallographic and mechanical weld test coupon.

Figure 2.11 Schematic of the EBW weldment sectioned for metallographic and mechanical testing

Forty-eight (12 DOE tests x 4 quadrants) metallographic samples were mounted in Bakelite and polished to one micrometer finished using a suspended diamond solution. Keller’s etchant was prepared, and samples were etched for 8 seconds. These samples were used for
macrophotographs, micrographs, Knoop hardness testing, and XRF dilution testing. Forty-eight (12 DOE tests x 4 quadrants) subsize tensile coupons were prepared per ASTM E8M-04. Figure 2.12 illustrates the tensile sample dimensions and the locations from which they were extracted.

The tensile coupons were pulled using a standard Instron tensile testing machine. The cross head displacement rate was 5 mm/minute. The extensometer gage length was 25 mm. The load-deflection results were used to develop yield strength, ultimate tensile strength and elongation.
Optical and SEM photographs of the fracture zone were used to understand the mode of failure. Section C provided the oversized longitudinal weld coupon. This 30 to 40-degree section of the weldment was milled to within 0.75 mm of the weld centerline and final polished to the electron beam centerline to provide a much larger macroscopic view of the defects.
CHAPTER 3: METALLURGICAL AND MECHANICAL ANALYSIS

3.1 MACROSCOPIC ANALYSIS OF THE WELD ZONE

A thirty to forty-degree section of each welded assembly was cut out, milled, and polished to create a macrostructural view of the EBW centerline. The oversized longitudinal weld samples were separated into groups for a given main factor. The weld samples were then arranged so that a one to one comparison could be made between tests with identical levels. Visual analysis was used to ascertain the impact of the main factors for all the different levels tested. The sections were arranged so that visual comparisons could be made between different travel speeds, beam patterns, and metal filler shim counts. The arrangements are shown in Figures 3.1 – 3.3. Visual predictions of how the welding parameters affected the porosity density were made possible by the large longitudinal cross-section specimens. Figure 3.1 shows that high and low porosity counts were distributed throughout the specimens for either travel speed indicating that travel speed was probably not a main driver in porosity percentage in these experiments. This observation may be because the range of speeds was too close together. The travel speed was constrained by the decision to maintain constant current, accelerating voltage, and spot size which directly effect the weld penetration. Figures 3.2 and 3.3 show that there was a correlation between beam pattern, shim thickness, and porosity percentage. Interactions between the weld parameters were more difficult to assess. A quantitative statistical analysis was required to understand the strength and significance of the EBW factors tested.

The statistical analysis required that the number of defects and size of each defect be mapped for each test. A 50 mm long section with an average porosity percentage was selected from each longitudinal weld specimen. A software program designed to measure digital pictures was used to measure the area and aspect ratio of each defect. From this data the total defect area, porosity percentage, average defect area, and average aspect ratio were calculated. Table 3.1 summarizes the information.

A multiple linear regression model and multivariate ANOVA was developed for the percentage of porosity in the DOE tests. The steps developed for this statistical analysis were identical for the remainder of the work in this study. To ensure the model was useful, certain conditions had
to be met. A linear relationship must exist between the weld parameters and the porosity percentage.

![Figure 3.1 Comparison of defects in longitudinal oversized section welded at different travel speeds: (a) 19 mm/s; (b) 25 mm/s](image)

Figure 3.1 Comparison of defects in longitudinal oversized section welded at different travel speeds: (a) 19 mm/s; (b) 25 mm/s

![Figure 3.2 Comparison of defects in longitudinal oversized section welded with different beam patterns: (a) straight beam; (b) oscillating beam](image)

Figure 3.2 Comparison of defects in longitudinal oversized section welded with different beam patterns: (a) straight beam; (b) oscillating beam
Figure 3.3 Comparison of defects in oversized longitudinal sections welded with different numbers of shims: (a) no shims; (b) 2 shims; (c) 4 shims
Table 3.1 Longitudinal weld specimen defect mapping

<table>
<thead>
<tr>
<th>Test #</th>
<th>Test Parameters (Speed/Pattern/Shim Thickness)</th>
<th>Defect Count</th>
<th>Total Defect Area (mm²)</th>
<th>% Porosity (pore area/area examined)</th>
<th>Average Defect Area (mm²)</th>
<th>Average Aspect Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25/Straight/0.000</td>
<td>24.0</td>
<td>0.40</td>
<td>0.20</td>
<td>0.010</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>25/Oscillating/0.000</td>
<td>27.0</td>
<td>2.4</td>
<td>1.5</td>
<td>0.09</td>
<td>2.1</td>
</tr>
<tr>
<td>3</td>
<td>19/Straight/0.015</td>
<td>60.0</td>
<td>4.5</td>
<td>1.9</td>
<td>0.07</td>
<td>1.9</td>
</tr>
<tr>
<td>4</td>
<td>25/Straight/0.015</td>
<td>24.0</td>
<td>2.6</td>
<td>1.1</td>
<td>0.12</td>
<td>1.8</td>
</tr>
<tr>
<td>5</td>
<td>19/Straight/0.030</td>
<td>40.0</td>
<td>9.0</td>
<td>3.9</td>
<td>0.23</td>
<td>2.8</td>
</tr>
<tr>
<td>6</td>
<td>25/Straight/0.030</td>
<td>63.0</td>
<td>9.7</td>
<td>4.1</td>
<td>0.15</td>
<td>2.0</td>
</tr>
<tr>
<td>7</td>
<td>19/Oscillating/0.015</td>
<td>52.0</td>
<td>12.0</td>
<td>4.8</td>
<td>0.20</td>
<td>2.6</td>
</tr>
<tr>
<td>8</td>
<td>25/Oscillating/0.015</td>
<td>37.0</td>
<td>6.5</td>
<td>2.7</td>
<td>0.17</td>
<td>3.4</td>
</tr>
<tr>
<td>9</td>
<td>19/Oscillating/0.030</td>
<td>54.0</td>
<td>27.0</td>
<td>7.5</td>
<td>0.50</td>
<td>3.6</td>
</tr>
<tr>
<td>10</td>
<td>25/Oscillating/0.030</td>
<td>41.0</td>
<td>18.0</td>
<td>6.6</td>
<td>0.40</td>
<td>2.9</td>
</tr>
<tr>
<td>11</td>
<td>19/Straight/0.000</td>
<td>4.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.05</td>
<td>1.0</td>
</tr>
<tr>
<td>12</td>
<td>19/Oscillating/0.000</td>
<td>40.0</td>
<td>2.1</td>
<td>1.2</td>
<td>0.05</td>
<td>1.8</td>
</tr>
</tbody>
</table>

percentage. Figure 3.4 plots these relationships and shows a general upward or slightly downward linear movement of the data. The data was assumed to be linear with the factors assessed.

The variables tested must remain independent of one another. The metal filler shim from test X cannot influence the metal filler shim from test Y, thereby influencing the porosity percentage. To ensure this did not happen the tests were run in a randomized pattern. In this manner, the independence assumption was satisfied. The equal distribution and normality conditions were checked after the linear regression model was developed.

Since there were three main welding process factors tested: travel speed, beam pattern, and shim thickness, three second order interactions were needed to determine if the main welding process factors influenced each other. Table 3.2 lists the main welding process factors and their interactions.

Main effect plots were used to visualize the impact of each welding parameter on the percentage of porosity. Figure 3.5 shows the main effect plots for this DOE. The average result was represented by end points for each factor level. Factors with steeper slopes had larger effects and provided larger impacts on the results. Therefore travel speed had very little impact on porosity percentage. The beam pattern and shim thickness provided greater impact.
Figure 3.4 Linear relationships between the % porosity and select weld parameters: (a) beam pattern versus; (b) weld speed; (c) shim thickness

Table 3.2 List of main welding process factors and their interactions

<table>
<thead>
<tr>
<th>Factor</th>
<th>Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel speed</td>
<td>Travel speed*Beam Pattern</td>
</tr>
<tr>
<td>Beam Pattern</td>
<td>Travel speed*Shim Thickness</td>
</tr>
<tr>
<td>Shim Thickness</td>
<td>Beam Pattern*Shim Thickness</td>
</tr>
</tbody>
</table>

Figure 3.5 Main effects plots for the percentage of porosity versus select electron beam welding parameters: (a) travel speed; (b) beam pattern diameter; (c) shim thickness

Interactions plots were used to determine the size of the interactions. The graph in Figure 3.6 shows that as the thickness of the metal filler shim increased, the impact of the beam pattern increased. When the graphed lines are parallel, the interaction effect is zero. More variance between the slopes means the interaction has a greater impact on the results.
Multiple regression analysis was used to determine if the factors were significant to the model. This study used backward selection regression to determine the statistical significance of the factors. Using this method all the factors and second-order interactions were initially included in the model, and then they are removed as they become unnecessary or unhelpful to the model. Table 3.3 gives a summary of how the data fits the model when all the welding process factors and interactions are included in the analysis.

Rsquare represents the amount of variability accounted for by the linear regression model. This model accounted for 96.6% of the variability. Rsquare adjusted took into account that there were several factors. Notice the adjusted value is slightly less than Rsquared meaning it is slightly more conservative estimate of the variability. This analysis used the Rsquared adjusted term.

Table 3.3  Summary of fit and p-values for all welding process factors and interactions

<table>
<thead>
<tr>
<th>Term</th>
<th>Coefficients</th>
<th>t Ratio</th>
<th>p-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1.2</td>
<td>0.92</td>
<td>0.40</td>
</tr>
<tr>
<td>Travel speed</td>
<td>-0.03</td>
<td>-1.3</td>
<td>0.23</td>
</tr>
<tr>
<td>Beam Pattern</td>
<td>218</td>
<td>5.6</td>
<td>0.00*</td>
</tr>
<tr>
<td>Shim Thickness</td>
<td>160.</td>
<td>10.</td>
<td>0.00*</td>
</tr>
<tr>
<td>(Travel speed)*(Beam Pattern)</td>
<td>-5.0</td>
<td>-0.97</td>
<td>0.37</td>
</tr>
<tr>
<td>(Travel speed)*(Shim Thickness)</td>
<td>-1.2</td>
<td>-0.61</td>
<td>0.56</td>
</tr>
<tr>
<td>(Beam Pattern)*(Shim Thickness)</td>
<td>5900.</td>
<td>1.8</td>
<td>0.11</td>
</tr>
</tbody>
</table>
0.05, the null hypothesis was rejected. The null hypothesis was, ‘the factor or interaction had an effect on the model’. For this model, there were only two factors, the beam pattern and shim thickness, that accepted the null hypothesis and therefore influenced the percent porosity. These p-values are shown in Table 3.4 with asterisks. The t-ratio determines how valid our statistic is. The larger t-ratio, the more valid is the p-value.

Table 3.4 shows the data summary for the regression model run only with the beam pattern and shim thickness factors. It shows the beam pattern and shim thickness were both significant, and since the Rsquared adjusted value only changed by 2.3%, the model still predicted the variability extremely well.

Table 3.4 Summary of fit using only beam pattern and shim thickness

<table>
<thead>
<tr>
<th>Term</th>
<th>Coefficients</th>
<th>Std Error</th>
<th>t Ratio</th>
<th>p-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-0.54</td>
<td>0.41</td>
<td>-1.3</td>
<td>0.22</td>
</tr>
<tr>
<td>Beam Pattern</td>
<td>218</td>
<td>4.4</td>
<td>4.9</td>
<td>0.00*</td>
</tr>
<tr>
<td>Shim Thickness</td>
<td>160</td>
<td>1.8</td>
<td>8.9</td>
<td>0.00*</td>
</tr>
</tbody>
</table>

To check whether this model provided more information than standard summary statistics (means and averages) another null hypothesis was developed. In this case the null hypothesis stated that the model was no better than summary statistics in explaining the increase or decrease in the porosity percentage. The alternative hypothesis, F-test, demonstrated that the model was useful and valid. This was accomplished by the F-test. The F-test for this model is shown in Table 3.5.

Table 3.5 F-Test p- Values to validate model viability

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>6</td>
<td>63.10</td>
<td>10.23</td>
<td>23.00</td>
</tr>
<tr>
<td>Error</td>
<td>5</td>
<td>2.18</td>
<td>0.45</td>
<td>p-Value</td>
</tr>
<tr>
<td>C. Total</td>
<td>11</td>
<td>65.28</td>
<td>0.00*</td>
<td></td>
</tr>
</tbody>
</table>

Since the p-value was lower than 0.05 the null hypothesis was rejected and the model was viable. The coefficients for the linear model are found in Table 3.6. Using these coefficients the linear equation for the percent porosity in the weld FZ can be written as: % porosity = 160* shim
thickn ess (mm) - 8.8* beam pattern (mm) at a voltage of 60 kV and an amperage of 19 mA. The beam pattern diameter represented the amount of circular oscillation. This weld parameter varied from a no oscillation (0.000 mm straight beam) to a 0.250 mm fully oscillating beam. The shim thickness represents the shim thickness of 0.000 mm, 0.015 mm, and 0.030 mm. The equation states that at a given voltage and amperage setting the only significant factors were the amount of shim material and beam pattern, and that as these variables tended to zero so did the percentage of porosity. There were no significant interactions between the test variables. The interaction shown previously in the Figure 3.6 between the beam pattern and the shim thickness had too high a p-value to be significant. Within the limits tested the travel speed had no impact on porosity.

There were two final conditions that had to be satisfied. The data must exhibit a normal distribution and equal spread conditions. The nearly normal conditions states that the residuals must be distributed in a fashion that is close to normal. The residuals are the difference between what the model predicts and what the actual values were. Table 3.6 gives these values. By plotting the distribution of residuals, it became clear that the model was near normal, Figure 3.7. The distribution tailed off in either direction with no major lean to the left or right. All the

Table 3.6 Residual % Porosity

<table>
<thead>
<tr>
<th>Test #</th>
<th>Test Parameters ( mm/s, pattern, mm)</th>
<th>% Porosity</th>
<th>Residual % Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25/Straight/0.000</td>
<td>0.20</td>
<td>0.70</td>
</tr>
<tr>
<td>2</td>
<td>25/Oscillating/0.000</td>
<td>1.5</td>
<td>-0.14</td>
</tr>
<tr>
<td>3</td>
<td>19/Straight/0.015</td>
<td>1.9</td>
<td>0.03</td>
</tr>
<tr>
<td>4</td>
<td>25/Straight/0.015</td>
<td>1.1</td>
<td>-0.76</td>
</tr>
<tr>
<td>5</td>
<td>19/Straight/0.030</td>
<td>3.9</td>
<td>-0.36</td>
</tr>
<tr>
<td>6</td>
<td>25/Straight/0.030</td>
<td>4.1</td>
<td>-0.16</td>
</tr>
<tr>
<td>7</td>
<td>19/Oscillating/0.015</td>
<td>4.8</td>
<td>0.75</td>
</tr>
<tr>
<td>8</td>
<td>25/Oscillating/0.015</td>
<td>2.7</td>
<td>-1.3</td>
</tr>
<tr>
<td>9</td>
<td>19/Oscillating/0.030</td>
<td>7.5</td>
<td>1.0</td>
</tr>
<tr>
<td>10</td>
<td>25/Oscillating/0.030</td>
<td>6.6</td>
<td>0.14</td>
</tr>
<tr>
<td>11</td>
<td>19/Straight/0.000</td>
<td>0.0</td>
<td>0.54</td>
</tr>
<tr>
<td>12</td>
<td>19/Oscillating/0.000</td>
<td>1.2</td>
<td>-0.44</td>
</tr>
</tbody>
</table>

values were centered around the middle, and there was no evidence of bimodality. In this manner, the normality condition was satisfied.
Figure 3.7 Distribution of % porosity residuals is normal

The final condition was the equal variance assumption or the equal spread condition. This condition stated there could be no discernable pattern when the residuals as a function of the predicted values were plotted. Table 3.7 gives the predicted % porosity values.

Table 3.7 Predicted % porosity

<table>
<thead>
<tr>
<th>Test #</th>
<th>Test Parameters (mm/s, pattern, mm)</th>
<th>% Porosity</th>
<th>Residual % Porosity</th>
<th>Predicted % Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25/Straight/0.000</td>
<td>0.2</td>
<td>0.70</td>
<td>.50</td>
</tr>
<tr>
<td>2</td>
<td>25/Oscillating/0.000</td>
<td>1.5</td>
<td>-0.14</td>
<td>1.6</td>
</tr>
<tr>
<td>3</td>
<td>19/Straight/0.015</td>
<td>1.9</td>
<td>0.03</td>
<td>1.9</td>
</tr>
<tr>
<td>4</td>
<td>25/Straight/0.015</td>
<td>1.1</td>
<td>-0.76</td>
<td>1.9</td>
</tr>
<tr>
<td>5</td>
<td>19/Straight/0.030</td>
<td>3.9</td>
<td>-0.36</td>
<td>4.2</td>
</tr>
<tr>
<td>6</td>
<td>25/Straight/0.030</td>
<td>4.1</td>
<td>-0.16</td>
<td>4.2</td>
</tr>
<tr>
<td>7</td>
<td>19/Oscillating/0.015</td>
<td>4.8</td>
<td>0.75</td>
<td>4.1</td>
</tr>
<tr>
<td>8</td>
<td>25/Oscillating/0.015</td>
<td>2.7</td>
<td>-1.3</td>
<td>4.1</td>
</tr>
<tr>
<td>9</td>
<td>19/Oscillating/0.030</td>
<td>7.5</td>
<td>1.0</td>
<td>6.5</td>
</tr>
<tr>
<td>10</td>
<td>25/Oscillating/0.030</td>
<td>6.6</td>
<td>0.14</td>
<td>6.5</td>
</tr>
<tr>
<td>11</td>
<td>19/Straight/0.000</td>
<td>0.0</td>
<td>0.54</td>
<td>.50</td>
</tr>
<tr>
<td>12</td>
<td>19/Oscillating/0.000</td>
<td>1.2</td>
<td>-0.44</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Figure 3.8 shows the plotted values of residual % porosity as a function of predicted % porosity.
The scatter plot shows that the points do not have any form or shape. They were not arranged linearly or exponentially or in any other pattern. In this manner, the equal spread condition was satisfied. All the conditions were satisfied, so equation (1) was considered a good model to predict the percentage of porosity in a Al6061-T6 weld under the conditions set forth in this test. In a similar fashion, models were developed for each of the values measured in this study.

The number of defects in the weld could not be modeled accurately with the data collected. The model accounted for less than 35% of the variability. The total defect area, average defect area, and average aspect ratio provided models that accounted for nearly 90% of the variability, had low enough F-factors to be deemed statistically useful, and statistically significant p-values for beam pattern and shim thickness. Table 3.8 provides the output for the weld defect ANOVA analysis. The p-values with asterisks are statistically significant.

Table 3.8 ANOVA table for longitudinal weld sample weld defects

<table>
<thead>
<tr>
<th>Weld Defect</th>
<th>Rsquared adjusted</th>
<th>F-factor</th>
<th>p-value for travel speed</th>
<th>p-value for beam pattern</th>
<th>p-value for shim thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Defect Count</td>
<td>0.87</td>
<td>0.00</td>
<td>-</td>
<td>0.00*</td>
<td>0.00*</td>
</tr>
<tr>
<td>Porosity Percent</td>
<td>0.92</td>
<td>0.00</td>
<td>-</td>
<td>0.00*</td>
<td>0.00*</td>
</tr>
<tr>
<td>Average Defect Area</td>
<td>0.89</td>
<td>0.00</td>
<td>-</td>
<td>0.00*</td>
<td>0.00*</td>
</tr>
<tr>
<td>Average Aspect Ratio</td>
<td>0.87</td>
<td>0.00</td>
<td>-</td>
<td>0.00*</td>
<td>0.00*</td>
</tr>
</tbody>
</table>

*-denotes that p-value is statistically significant
Interaction plots for the DOE factors with high Rsquared adjusted values greater than 0.85 are shown in Figures 3.9-3.12. The blue dotted curves on either side of the main line are the 95% confidence interval limits. The main effect plots were produced with the statistical software program JMP®.

Figure 3.9 Main effects plots for the total defect area found in the longitudinal weld sections: (a) beam pattern; (b) shim thickness

Figure 3.10 Main effect plots for the percentage porosity found in the longitudinal weld sections: (a) beam pattern; (b) shim thickness

The porosity percentage, average area, and aspect ratio of the defects were influenced by the electron beam weld pattern and thickness of the filler metal Al4047 metal shims. The travel speed had no bearing on the defects. The shim thickness was the most influential factor, but the beam pattern played an important role. There were no significant interactions between the factors.
Figure 3.11 Main effect plots for the average defect area found in the longitudinal weld sections: (a) beam pattern; (b) shim thickness

Figure 3.12 Main effect plots for the average aspect ratio of the defects in the longitudinal weld samples: (a) beam pattern; (b) shim thickness

The strong correlation between the shim thickness and defects may mean that the oxide coating was not fully removed before welding. Since the shim thickness was produced by multiple shims of the same thickness (.0075 mm) the number of surfaces with oxide increased by two every time a shim was introduced into the system. Another possibility was that air trapped between the shims not fully evacuated by the vacuum pumps prior to welding. This air was then entrained in the FZ during the welding process. A final possibility was that the compressive spring force that was meant to provide for contraction during welding did not compress the shims together and provided voids that were entrained in the FZ. Figure 3.13 illustrates the difference in void formation between no shims, two shims, and four shims for a straight beam and a travel speed of 19 mm/s. Perhaps the most striking difference between the samples was the absence of defects in the straight beam sample with no shims.
The increase in size and aspect ratio of the defects with an oscillating beam was easily detectable with the naked eye. The oscillating beam puts more heat into the system and slows the solidification rate. The increased evolution of gas may be linked to the increased time to solidify the weld pool. A magnified comparison of the straight and oscillating beams for welds made with four shims traveling at 19 mm/s are shown in Figure 3.14.

The literature suggests that high melting temperature materials with deep welds have less porosity when an oscillating beam is used. The theory is that the voids have more time to escape from the fusion zone before solidifies. This is not the case with aluminum Al6061-T6. Perhaps the lower density provides less buoyancy to force the voids upward and the lower melting point provides less time before solidifying.
Two sections were measured for each test to determine the bead consistency as a function of cylinder position. Dimensional measurements for sections A and C previously described in Figure 2.11 are provided in Table 3.9 and 3.10.

Table 3.9 Measurements of weld FZ in section A

<table>
<thead>
<tr>
<th>Test #</th>
<th>Speed mm/s</th>
<th>Beam Pattern</th>
<th>Thickness mm</th>
<th>Crown A (mm)</th>
<th>Mid A (mm)</th>
<th>Root A (mm)</th>
<th>Weld Depth A (mm)</th>
<th>Aspect Ratio A</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.0</td>
<td>Straight</td>
<td>0.000</td>
<td>2.0</td>
<td>0.76</td>
<td>0.43</td>
<td>7.7</td>
<td>3.5</td>
</tr>
<tr>
<td>2</td>
<td>25.0</td>
<td>Oscillating</td>
<td>0.000</td>
<td>2.2</td>
<td>0.86</td>
<td>0.51</td>
<td>8.6</td>
<td>3.2</td>
</tr>
<tr>
<td>3</td>
<td>19.0</td>
<td>Straight</td>
<td>0.015</td>
<td>2.1</td>
<td>0.71</td>
<td>0.36</td>
<td>8.3</td>
<td>3.9</td>
</tr>
<tr>
<td>4</td>
<td>25.0</td>
<td>Straight</td>
<td>0.015</td>
<td>1.9</td>
<td>0.74</td>
<td>0.43</td>
<td>8.1</td>
<td>4.2</td>
</tr>
<tr>
<td>5</td>
<td>19.0</td>
<td>Straight</td>
<td>0.030</td>
<td>1.7</td>
<td>0.56</td>
<td>0.38</td>
<td>8.3</td>
<td>4.7</td>
</tr>
<tr>
<td>6</td>
<td>25.0</td>
<td>Straight</td>
<td>0.030</td>
<td>1.9</td>
<td>0.64</td>
<td>0.38</td>
<td>9.4</td>
<td>4.7</td>
</tr>
<tr>
<td>7</td>
<td>19.0</td>
<td>Oscillating</td>
<td>0.015</td>
<td>2.0</td>
<td>0.69</td>
<td>0.36</td>
<td>7.8</td>
<td>3.9</td>
</tr>
<tr>
<td>8</td>
<td>25.0</td>
<td>Oscillating</td>
<td>0.015</td>
<td>2.0</td>
<td>0.71</td>
<td>0.51</td>
<td>8.3</td>
<td>4.0</td>
</tr>
<tr>
<td>9</td>
<td>19.0</td>
<td>Oscillating</td>
<td>0.030</td>
<td>2.1</td>
<td>0.64</td>
<td>0.53</td>
<td>9.1</td>
<td>4.3</td>
</tr>
<tr>
<td>10</td>
<td>25.000</td>
<td>Oscillating</td>
<td>0.030</td>
<td>2.1</td>
<td>0.84</td>
<td>0.58</td>
<td>9.65</td>
<td>4.6</td>
</tr>
<tr>
<td>11</td>
<td>19.000</td>
<td>Straight</td>
<td>0.000</td>
<td>2.3</td>
<td>0.79</td>
<td>0.46</td>
<td>8.13</td>
<td>3.4</td>
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<tr>
<td>12</td>
<td>19.000</td>
<td>Oscillating</td>
<td>0.000</td>
<td>2.4</td>
<td>0.76</td>
<td>0.46</td>
<td>7.62</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Table 3.10 Measurements of weld FZ in section C

<table>
<thead>
<tr>
<th>Test #</th>
<th>Speed mm/s</th>
<th>Beam Pattern</th>
<th>Thickness mm</th>
<th>Crown C (mm)</th>
<th>Mid C (mm)</th>
<th>Root C (mm)</th>
<th>Weld Depth C (mm)</th>
<th>Aspect Ratio C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.0</td>
<td>Straight</td>
<td>0.000</td>
<td>2.1</td>
<td>0.74</td>
<td>0.46</td>
<td>7.7</td>
<td>3.5</td>
</tr>
<tr>
<td>2</td>
<td>25.0</td>
<td>Oscillating</td>
<td>0.000</td>
<td>2.3</td>
<td>0.84</td>
<td>0.58</td>
<td>8.1</td>
<td>3.2</td>
</tr>
<tr>
<td>3</td>
<td>19.0</td>
<td>Straight</td>
<td>0.015</td>
<td>2.0</td>
<td>0.58</td>
<td>0.41</td>
<td>8.3</td>
<td>4.1</td>
</tr>
<tr>
<td>4</td>
<td>25.0</td>
<td>Straight</td>
<td>0.015</td>
<td>1.9</td>
<td>0.61</td>
<td>0.41</td>
<td>8.1</td>
<td>4.3</td>
</tr>
<tr>
<td>5</td>
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<td>Straight</td>
<td>0.030</td>
<td>1.8</td>
<td>0.61</td>
<td>0.33</td>
<td>8.3</td>
<td>4.6</td>
</tr>
<tr>
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<td>25.0</td>
<td>Straight</td>
<td>0.030</td>
<td>2.0</td>
<td>0.66</td>
<td>0.38</td>
<td>9.4</td>
<td>4.7</td>
</tr>
<tr>
<td>7</td>
<td>19.0</td>
<td>Oscillating</td>
<td>0.015</td>
<td>2.0</td>
<td>0.64</td>
<td>0.36</td>
<td>7.8</td>
<td>3.9</td>
</tr>
<tr>
<td>8</td>
<td>25.0</td>
<td>Oscillating</td>
<td>0.015</td>
<td>2.1</td>
<td>0.64</td>
<td>0.43</td>
<td>8.3</td>
<td>4.0</td>
</tr>
<tr>
<td>9</td>
<td>19.0</td>
<td>Oscillating</td>
<td>0.030</td>
<td>1.8</td>
<td>0.56</td>
<td>0.56</td>
<td>7.8</td>
<td>4.4</td>
</tr>
<tr>
<td>10</td>
<td>25.000</td>
<td>Oscillating</td>
<td>0.030</td>
<td>2.1</td>
<td>0.84</td>
<td>0.61</td>
<td>9.40</td>
<td>4.3</td>
</tr>
<tr>
<td>11</td>
<td>19.000</td>
<td>Straight</td>
<td>0.000</td>
<td>2.3</td>
<td>0.76</td>
<td>0.46</td>
<td>7.62</td>
<td>3.3</td>
</tr>
<tr>
<td>12</td>
<td>19.000</td>
<td>Oscillating</td>
<td>0.000</td>
<td>2.3</td>
<td>0.76</td>
<td>0.46</td>
<td>7.37</td>
<td>3.1</td>
</tr>
</tbody>
</table>

The results of the ANOVA analysis for the EBW bead dimensions are presented in Table 3.11. ANOVA analysis revealed that for a given current, voltage, and spot size the travel speed influenced the penetration depth and aspect ratio. The relatively high p-value for both show that the influence was not as significant as other factors. Voltage, current and shim thickness played larger roles.
The beam pattern influenced the bead width at the mid-point and root of the weld. Figure 3.15 illustrates the difference between test #5 and #9. Both tests were run at 19 mm/s and had four shims in the joint. Test #5 was run with a straight beam and test #9 was run with an oscillating beam. The gas holes in the fusion zone were typical for welds made with four shims. Measurements of the two weld beads indicate the difference between the oscillating and straight patterns was about 0.18 to 0.22 mm indicating that the main difference was due to the oscillation diameter of 0.25 mm. The low Rsquared adjusted values for the root width indicated this model does not satisfactorily take into account many variables in this section of the weld. Stated differently, it is difficult to predict whether an oscillating beam can consistently fuse together larger joint gaps at the root of the weld. Incomplete fusion can lead to potential crack initiation sites.

Figure 3.15  Macrophotographs illustrating the difference in bead width for weld produced with four shims at 19 mm/s: (a) straight beam; (b) oscillating beam
For a given current, voltage, and spot size, the shim thickness was the most influential of the three weld parameters studied. The shim thickness had a significant influence on weld bead dimensions at the crown and mid-point, and was highly influential to the weld penetration depth and aspect ratio. Figure 3.16 illustrates the variation that was directly influenced by the shim thickness. It was clear from the macrophotographs that the weld with no shims on the left provided less penetration and a higher aspect ratio. The weld with four shims (0.030 mm thick) was significantly deeper and had a lower aspect ratio. The porosity in the four shim weld was typical. The ratio of weld width-to-shim thickness was about 65 at the crown, 20 at the mid-point, and ten at the root. The difference cannot be attributed solely to the lower melting point and beam penetrating ability into the filler metal alloy. Another possibility was the air gap between the shims increased as the number of shims increased, effectively reducing the composite density of the weld joint. The relatively high Rsquared values and extremely low p-values provided strong evidence that the number of shims had a strong influence on the penetration depth and must be accounted for in the EB weld development process.

Figure 3.16 Optical micrographs illustrating the difference in penetration depth for a weld produced by a straight beam at a travel speed of 19 mm/s: (a) no shims; (b) four shims

3.2 METALLURGICAL ANALYSIS OF THE WELD ZONE

The classical nail shape weld geometry was the most noticeable feature found in the EB welds produced in this study. This shape is related to the high-density energy and low heat input that results in a deep weld penetration and narrow HAZ region. Typical weld bead profiles are given
in Figures 3.17-3.20. Macrophotographs for all experiments can be found in Appendix B. The small pinhole porosity shown in the macrophotograph is quite normal in the FZ of EB welds of aluminum alloys. The larger elongated holes are indicative of a more serious problem with the beam pattern combined with retained oxides on the surface of the shims. These same indications were seen with more clarity in the oversized longitudinal weld sections. The photographs show that the 0.50 mm chamfer at the base of the weld had a significant impact on the root of the weld joint. In some instances, the gap created by the chamfer was not filled by fused material and became an in situ crack. Root porosity was evident in every weld test due to metal vapor generated at the center of the molten column that became buried in the backup material. Upon condensation and solidification, a void formed. When the backing material is machined away, the gas and root porosity could become centerline crack initiation sites. Table 3.12 lists these flaws by test from least to most critical to mechanical properties.

Table 3.12 Listing of defects in the FZ

<table>
<thead>
<tr>
<th>Test #</th>
<th>Test Parameters*</th>
<th>Porosity in FZ &lt;100μm</th>
<th>Large Gas Pockets in FZ &gt;100μm</th>
<th>Lack of Penetration into Backing</th>
<th>Unconsumed Chamfer</th>
<th>Gas/Root Porosity at Machining Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25/STR/0.000</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>25/OSC/0.000</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>19/STR/0.015</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>25/STR/0.015</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>5</td>
<td>19/STR/0.030</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>6</td>
<td>25/STR/0.030</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>7</td>
<td>19/OSC/0.015</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>8</td>
<td>25/OSC/0.015</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>9</td>
<td>19/OSC/0.030</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>10</td>
<td>25/OSC/0.030</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>11</td>
<td>19/STR/0.000</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>12</td>
<td>19/OSC/0.000</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

*Test parameters are set up as follows (mm/s / beam pattern / filler shim thickness mm) X- FLAWS OBSERVED
Figure 3.17 Test #1 weld bead geometry with no filler shims (25/STR/0.000): (a) weld bead profile; (b) close up of root porosity

Figure 3.18 Test #6 weld bead geometry with four filler shims (25/STR/0.030): (a) weld bead profile; (b) close up of root porosity

Figure 3.21 shows optical micrographs of the fusion zones and HAZs in the crown, mid-section, and root of the welds when no Al4047 metal filler shims were used. Centerline solidification cracks were evident in the mid-section and weld root of the autogenous welds. Solidification cracking always occurs in the fusion zone and is mainly due to a lack of molten metal needed to backfill areas being strained by thermal contraction. Liquidation cracking was evident in the HAZ of the autogenous welds. Liquidation cracking always occurs in the HAZ, more specifically
partially melted zone (PMZ), and is due to chemical composition fluctuations and local eutectic melting at the grain boundaries.

Figure 3.19 Test #9 weld bead geometry with four filler shims (19/OSC/0.030): (a) weld bead profile; (b) close up of root porosity
Figure 3.20 Test #12 weld bead geometry with no filler shims (19/OSC/0.000): (a) weld bead profile; (b) close up of root porosity

Figure 3.22 shows optical micrographs of the fusion and HAZs in the crown, mid-section, and root of the welds when two Al4047 metal filler shims were used. Similar results are present when four shims were placed in the joint. Figure 3.23 shows micrographs of what may be healed liquation cracks in areas of the PMZ when two or four shims were used. The increase in metal filler shims reduced the liquation cracks in the crown and mid-sections and reduced the solidification cracking in the root. This crack healing is mainly attributed to an increase in alloy fluidity when higher amounts of the Al-Si eutectic are present. More EDX analysis would be required to confirm the chemical composition showing the Al-Si eutectic required for this to occur. Furthermore, the PMZ of autogenous welds did not show signs of healing in the liquation cracks.

Table 3.13 outlines the number of liquation and solidification crack occurrences as a function of the number of alloy Al4047 metal filler shims used in the FZ. The number and overall length of the occurrences increased significantly when metal filler alloy was not used.

Table 3.13  Number and length of liquation occurrences as a function of shim thickness

<table>
<thead>
<tr>
<th>Al4047 Alloy Filler Thickness (mm)</th>
<th>Total Number of Cracks / Area Analyzed (mm$^2$)</th>
<th>Total Crack Length (mm) / Area Analyzed (mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>0.65</td>
<td>55.</td>
</tr>
<tr>
<td>0.015</td>
<td>0.03</td>
<td>5.0</td>
</tr>
<tr>
<td>0.030</td>
<td>0.04</td>
<td>5.5</td>
</tr>
</tbody>
</table>
Figure 3-21 Microstructure showing liquation and solidification cracking in various areas of the weld HAZ and FZ with no metal filler shim.
Figure 3.22 Microstructure showing little or no liquation or solidification cracking with the addition of two Al4047 metal filler shims.
Figure 3.23 High magnification images of areas presumed to be healed liquation cracking in the HAZ. Both welds were produced with a straight beam at 19 mm/s: (a) two shims; (b) four shims.
Knoop microhardness was measured at the upper, mid, and lower sections for all EB welds tests. The secondary electron imaging (SEI) photograph shown in Figure 3.24 illustrates indentions and location for the upper and mid-section.

![Secondary electron image (SEI) of the Knoop hardness indentation locations](image)

Figure 3.24 Secondary electron image (SEI) of the Knoop hardness indentation locations

Figures 3.25-3.27 present the average microhardness profiles as a function of the main parameters in this study; travel speed, beam pattern, and filler shim thickness. Knoop microhardness profiles for all the tests performed in this study can be found in Appendix C. As illustrated, a significant hardness decrease (strength undermatching) was observed in the FZ and HAZ, the hardness minimum lying in the FZ in contrast to arc welding, where the hardness minimum lies in the overaged HAZ [32,33]. The reason for this is the rapid cooling involved in the EB welding process. This leads to a less pronounced particle growth in the HAZ due to shortened time for over aging, in comparison, conventional arc welding of this alloy would result in the formation of a wider HAZ with coarser particles and consequently a hardness loss in the HAZ due to prolonged over aging [7]. GTAW data suggests that for the same material and wall thickness the HAZ is an order of magnitude greater than the EB weld [31].

Faster travel speeds resulted in slightly harder Knoop microhardness readings in the FZ. This
increase may be due to a lower heat input and slightly less over aging. ANOVA analysis of the data shows the difference is statistically insignificant.

Figure 3.25 Average Knoop microhardness profile in the as welded condition for travel speeds of 19 and 25 mm/s

The overall average Knoop hardness for straight and oscillating beam patterns was not statistically significant.

Figure 3.26 Average Knoop microhardness profile in the as-welded condition for straight and oscillating beam patterns

Figure 3.27 shows the average Knoop microhardness as a function of shim thickness. The difference in hardness produced by different shim thicknesses was the only parameter that produced statistically significant results. The hardness distributions for the autogenous welded
region was in the range of 60-65 HK whereas those with the shim stock was in the range of 78-83 HK respectively. The results indicate that the increased Si-content in the Al4047 alloy has increased the solid solution strengthening in the FZ.

![Graph showing microhardness profile](image)

Figure 3.27 Average microhardness profile of the weld joint in as-welded condition for each of the Al4047 metal shim thicknesses tested

OES (Optical Emission Spectrometry) and EDX (Energy Dispersive X-ray) analysis results are presented in Tables 3.14 – 3-18. The OES analysis shows the wrought Al6061-T6 and Al4047 meet AMS standard chemical composition requirements. Tables 3.16 – 3.18 are the averaged EDX alloy concentrations in the base metal and FZs for all the tests performed for no shims, two shims, and four shims respectively.

Table 3.14 AMS-QQ-A-200 chemical composition requirements for Al6061-T6 and alloy Al4047 in wt. %

<table>
<thead>
<tr>
<th></th>
<th>Si wt.%</th>
<th>Mg wt.%</th>
<th>Mn wt.%</th>
<th>Cu wt.%</th>
</tr>
</thead>
<tbody>
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<td>Al6061-T6</td>
<td>0.40-0.80</td>
<td>0.80-1.2</td>
<td>0.15 max</td>
<td>0.15-0.40</td>
</tr>
<tr>
<td>Al4047</td>
<td>11-13</td>
<td>0.10 max</td>
<td>0.15 max</td>
<td>0.30 max</td>
</tr>
</tbody>
</table>

Table 3.15 OES results for Al6061-T6 baseline and Alloy Al4047 filler material in wt.%

<table>
<thead>
<tr>
<th></th>
<th>Si wt.%</th>
<th>Mg wt.%</th>
<th>Mn wt.%</th>
<th>Cu wt.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al6061-T6</td>
<td>0.52</td>
<td>0.89</td>
<td>0.08</td>
<td>0.32</td>
</tr>
<tr>
<td>Al4047</td>
<td>12</td>
<td>0.06</td>
<td>0.09</td>
<td>0.28</td>
</tr>
</tbody>
</table>
Table 3.16  EDX results for the autogenous EBW in wt.%

<table>
<thead>
<tr>
<th></th>
<th>Si wt.%</th>
<th>Mg wt.%</th>
<th>Mn wt.%</th>
<th>Cu wt.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>0.48</td>
<td>0.83</td>
<td>0.08</td>
<td>0.31</td>
</tr>
<tr>
<td>Fusion</td>
<td>0.36*</td>
<td>0.71*</td>
<td>0.08</td>
<td>0.29</td>
</tr>
<tr>
<td>% Change</td>
<td>-25%</td>
<td>-15%</td>
<td>0.0%</td>
<td>-6.4%</td>
</tr>
</tbody>
</table>

*-below AMS-QQ-A-200 standards

Table 3.17  EDX results when two, 0.0075mm shims of Alloy Al4047 filler shim were inserted into the EB weld joint in wt.%

<table>
<thead>
<tr>
<th></th>
<th>Si wt.%</th>
<th>Mg wt.%</th>
<th>Mn wt.%</th>
<th>Cu wt.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>0.48</td>
<td>0.94</td>
<td>0.15</td>
<td>0.23</td>
</tr>
<tr>
<td>Fusion</td>
<td>1.7***</td>
<td>0.68*</td>
<td>0.11</td>
<td>0.25</td>
</tr>
<tr>
<td>% Change</td>
<td>+260%</td>
<td>-28%</td>
<td>-27%</td>
<td>8.7%</td>
</tr>
</tbody>
</table>


Table 3.18  EDX results when four, 0.0075 mm shims of Alloy Al4047 filler shim were inserted into the EB weld joint

<table>
<thead>
<tr>
<th></th>
<th>Si wt.%</th>
<th>Mg wt.%</th>
<th>Mn wt.%</th>
<th>Cu wt.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>0.50</td>
<td>0.88</td>
<td>0.16</td>
<td>0.25</td>
</tr>
<tr>
<td>Fusion</td>
<td>3.1**</td>
<td>0.53*</td>
<td>0.14</td>
<td>0.21</td>
</tr>
<tr>
<td>% Change</td>
<td>+520%</td>
<td>-40%</td>
<td>-13%</td>
<td>-16%</td>
</tr>
</tbody>
</table>


Figures 3.28 – 3.30 are bar charts illustrating the dilution of the Mg and Si in the fusion zone. Dilution charts for all the tests performed can be found in Appendix D. The horizontal red line indicates the amount of Si required to meet AMS QQ-A-200 for Al6061-T6. The horizontal blue line indicates the amount of Mg required to meet AMS QQ-A-200 for Al6061-T6. The two vertical black lines indicate the EDX measurements taken within the fusion zone. The green dashed line in Figures 3.29 and 3.30 shows the solubility limit of Si in Al in a binary system. Figure 3.28 clearly illustrates the reduction in Si and Mg in the autogenous weld due boiling off in the high vacuum electron beam welding environment. Both elements are below the requirements set for in AMS QQ-A-200 for Al6061.
Figure 3.28 SEI mode x-ray map of Si and Mg dilution for a travel speed of 25 mm/s, a straight beam, and no Al4047 metal filler shim taken at the upper section of the weld (Test #1).

Figure 3.29 illustrates the large infusion of Si in the fusion zone from the two shims. Since the shim material does not contain Mg its weight percentage continues to decrease due to dilution and boil off. The excess amount of silicon is expected to help heal solidification cracking in the FZ and liquation cracking in the PMZ by forming a eutectic with Al. Eutectic liquids exhibit great fluidity that can backfill cracks before solidification is complete. Although the Mg has been depleted the amount available to produce Mg₂Si is still adequate for good strength.

Figure 3.29 SEI mode x-ray map of Si and Mg dilution for a travel speed of 19 mm/s, a straight beam, and two, .0075mm thick Al4047 metal filler shims taken at the upper section of the weld (Test #3).

Figure 3.30 illustrates the continued infusion of Si and dilution of Mg when four shims are used. The wt. % of Mg is now below the requirements needed to produce an adequate amount of Mg₂Si for strength. An adequate amount of Mg₂Si is based upon minimum values of Mg and Si.
required per AMS-QQ-200/8. The excess Si forms a eutectic with Al and helps to heal hot cracking.

Figure 3.30 SEI mode x-ray map of Si and Mg dilution for a travel speed of 19 mm/s, a straight beam, and four, .0075 mm thick Al4047 metal shims (Test #5)

Table 3.19 provides the amount of Mg and Si available and used to create the equilibrium phase Mg$_2$Si in the fusion zone as a function of the shim count. For example, if 2 shims are used the available amount of Si and Mg is 0.68 wt.% and 1.7 wt.%, respectively. Based on the optimal weight percentage of Mg to Si 1.73:1 only 0.39 wt. % of the Si can be used to create Mg$_2$Si (0.68:0.39 = 1.73:1). The amount of Mg$_2$Si created is the the sum of the Mg and Si used, which in this case is 1.1%. This is the minimum amount of Mg$_2$Si required to meet the strength requirements for Al 6061-T6 per AMS-QQ-200/8. Excess amounts of Mg and Si stay in solution or precipitate out depending on their concentration. Excess Si is beneficial in the correct amount to backfill solidification cracks in the FZ and liquation cracks in the HAZ. [3] In addition, Table 3.19 provides the extrapolated equilibrium phase results for the current production process which uses 1 shim. The comments in the table provide insight into the expected outcome based on the amount of alloying elements in the fusion zone.

It is the reduction in Si in the autogenous weld that prevents the required amount of Mg$_2$Si from forming. The addition of two shims provides an infusion of Si which helps bring up the amount of Mg$_2$Si produced even though the Mg is diluted. The continued dilution of Mg with four shims reduces the amount of Mg$_2$Si available for strengthening below the required limits. The expectation is that the mechanical strength of the autogenous and 4 shim weldments will suffer as a consequence of the lack of Mg$_2$Si.
Table 3.19 Analysis of Mg, Si, and Mg_{2}Si in Fusion Zone

<table>
<thead>
<tr>
<th>Mg Avail. (wt. %)</th>
<th>Si Avail. (wt. %)</th>
<th>Mg Used (wt. %)</th>
<th>Si Used (wt. %)</th>
<th>Mg_{2}Si Created (wt. %)</th>
<th>Excess Mg (wt. %)</th>
<th>Excess Si (wt. %)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 shims</td>
<td>0.71</td>
<td>0.36</td>
<td>0.62</td>
<td>0.36</td>
<td>0.98</td>
<td>0.09</td>
<td>0.00</td>
</tr>
<tr>
<td>2 shims</td>
<td>0.68</td>
<td>1.7</td>
<td>0.68</td>
<td>0.39</td>
<td>1.1</td>
<td>0.00</td>
<td>1.3</td>
</tr>
<tr>
<td>4 shims</td>
<td>0.50</td>
<td>3.1</td>
<td>0.50</td>
<td>0.29</td>
<td>0.79</td>
<td>0.00</td>
<td>2.8</td>
</tr>
<tr>
<td>1 shim</td>
<td>0.70</td>
<td>1.3</td>
<td>0.70</td>
<td>0.40</td>
<td>1.1</td>
<td>0.00</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Mg_{2}Si → Adequate for strength
No excess Si → cracking is likely to occur in FZ and HAZ

Mg_{2}Si → Adequate for strength
Excess Si → Adequate to heal cracks

Low Mg_{2}Si → Not enough precipitate to allow strengthening
High excess Si → Adequate for cracking.

Mg_{2}Si → Adequate for strength
Excess Si → cracking is likely to occur in FZ and HAZ

Figure 3.31 provides the relative crack sensitivities based on the composition of the weld in weight percent of alloying agent. Superimposed on the figure is the Mg_{2}Si and excess Si amounts for each of the shim counts for the Al-Mg-Si and Al-Si alloys. The figures show peaks which denote the maximum coherence range for each alloy composition represented. The coherence range is the temperature between the formation of coherent interlocking dendrites and the solidus temperature. The wider the coherence range, the more likely hot cracking will occur due to the accumulating strain of solidification between the interlocking dendrites. All the welds produced in this study have their Mg_{2}Si content at or close to the peak of the Al-Mg_{2}Si curve. These welds will incur hot cracking without the help of the liquid Al-Si eutectic. The Al-Si curve shows how the excess Si effects each weld. The autogenous weld has no excess silicon and hence produces little eutectic to prevent hot cracking. The two and four shim welds are off the peak of the Al-Si curve and are expected to provide eutectic to heal hot cracking. The reduction in hot cracking was shown previously in Figures 3.21 - 3.23. Currently, in production, only one shim is used in the weldments. By extrapolating the data for the autogenous and two shim welds we can estimate the amount of excess Si in the fusion zone of the one shim weld. If the results are correct, the one shim weld is close to the peak for both the Al-Mg_{2}Si curve and
Al-Si curves indicating a maximized coherency temperature range. The corresponding chemical composition would indicate the current production process may potentially have hot cracking issues.

Figure 3.31 Alloy content versus crack sensitivity for various shim quantities

Figure 3.32 shows a linear regression plot of the increase in Si concentration in the fusion zone as a function of the shim thickness. The green dashed line is the solubility of Si in Al at 577 °C.

Figure 3.32 Regression plot of Si concentration in the FZ as a function of the shim thickness

The average weight percent of silicon in the fusion zone can be expressed as, \( \% \text{ Si} = 131 \times \text{shim thickness (mm)} + 0.5 \), at a voltage of 60 kV and an amperage of 19 mA. A linear regression plot showing the decrease in Mg as a function of shim thickness is shown in Figure 3.33.
The average weight percent of Mg in the fusion zone can be expressed as, % Mg = -1038* shim thickness(mm) + 0.9, at a voltage of 60 kV and amperage of 19 mA. The measured changes of Mn and Cu in the FZ for the weld parameters investigated was not deemed statistically significant by the ANOVA analysis and were within the AMS QQ-A-200 standard. In all cases, the travel speed and beam pattern had no impact on the final composition of the weld metal. There were no interactions between the weld parameters that affected the final composition of the weld metal.

Figure 3.34 illustrates the grain size in the wrought base alloy. The base metal shows the standard coarse, elongated grains found in wrought Al6061-T6.
Keller’s reagent was used for the developing the microstructure. Better definition for the fusion zone microstructure was developed by heating the Keller’s reagent from 25°C to 38°C and reducing the etching time from 12 seconds to 6 seconds.

Figure 3.35 – 3.38 show the microstructure of the welds produced autogenously and with four, Al4047 shims. An in-depth analysis of the microstructure was not performed for this study, although general observations did not reveal major differences regardless of the tests performed. No discernable correlation between microstructure and mechanical properties were noticed. The epitaxial growth from the base metal is columnar, but quickly becomes equiaxed with a cellular system. The four shim welds show some dendritic growth in the columnar grains. The grain structure is so fine due to the high solidification rates involved in EBW. The fine equiaxed grains tend to reduce solidification cracking and improve the mechanical properties of th re-

Figure 3.35 Autogenous partially melted zone microstructure near crown

Figure 3.36 Microstructure of partially melted zone with four, Al4047 metal filler shims near crown
Figures 3.37 shows the weld microstructure in the fusion zone near the mid-section of the weld for the autogenous and four shim weld. The photograph to the right shows banding produced by perturbations in the fusion zone. The perturbations may have been produced by the stirring action caused by the oscillating beam pattern.

Figure 3.37  Microstructure in the fusion zone near the mid-section of the weld produced with a straight beam at a travel speed of 19 mm/s: (a) autogenous weld; (b) four shims

Figure 3.38 show part of the HAZ and partially melted zone. The average width of the HAZ measures about 0.50 mm based on hardness measurements regardless of the welding conditions.

Figure 3.38  Micrograph of typical HAZ in the EBWs.
3.3 MECHANICAL TESTING AND EVALUATION

The mechanical analysis included hydrostatic testing followed by dye penetrant testing, helium leak testing, mechanical tensile testing, and fractography of the failed tensile bars. The non-destructive hydrostatic testing of the welded assembly was performed to determine the structural integrity of the welded assembly under design loading. The dye penetrant testing was used to look for surface weld defect and cracking from the hydrostatic testing. The helium testing was used to check for any leakage resulting from the welding or structural testing. The test fixture is illustrated in Figure 3.39.

Figure 3.39 Schematic of the helium and hydrostatic pressure fixturing used for NDT testing of the welded assembly.
Each weldment was hydrostatically tested to 6.9 megapascals (1000 psi). The units were then dye penetrant tested per MIL-STD-6866, Type I, Method A, Sensitivity Level II by a qualified technician. No cracks were found in any of the weldments. The weldments were helium leak tested to $10^{-4}$ mbar cc/s using the same fixture. All weldments passed helium leak testing. Every welded assembly in this study was tested in this manner. All assemblies passed the design requirements set forth on the component drawing.

Tensile properties of the EB welded joint were determined by testing conventional flat longitudinal tensile specimens at room temperature. The tensile properties measured were yield strength, tensile strength, and ductility. All specimens were tested in the as-welded condition. Four specimens were tested for each of the twelve tests conducted for the DOE. No reduction in properties was observed for specimens extracted from the weld overlap zone. Table 3.20 summarizes the averaged metallurgical and mechanical properties of the EB welded joints for the DOE tests performed.

Table 3.20 Metallurgical and mechanical properties of EB welded joints for DOE tests performed

<table>
<thead>
<tr>
<th>Test#</th>
<th>Weld Parameters</th>
<th>Ultimate Strength</th>
<th>Yield Strength</th>
<th>Elongation %</th>
<th>Fusion Zone Hardness (HK, 100g)</th>
<th>Percent Porosity (%)</th>
<th>Percent change of Si in fusion zone</th>
<th>Percent change of Mg in fusion zone</th>
<th>Joint Efficiency</th>
<th>Ultimate Strength of Joint / Ultimate Strength of Base Metal %</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>19 / STR / 0.000</td>
<td>155.3</td>
<td>149.2</td>
<td>2.9</td>
<td>58</td>
<td>0.0</td>
<td>-75.6</td>
<td>-35.6</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>1</td>
<td>25 / STR / 0.000</td>
<td>169.6</td>
<td>152.3</td>
<td>1.7</td>
<td>68</td>
<td>0.2</td>
<td>-48.0</td>
<td>-12.4</td>
<td>51</td>
<td>49</td>
</tr>
<tr>
<td>12</td>
<td>19 / OSC / 0.000</td>
<td>150.9</td>
<td>143.2</td>
<td>2.0</td>
<td>57</td>
<td>1.2</td>
<td>-74.3</td>
<td>-34.9</td>
<td>50</td>
<td>49</td>
</tr>
<tr>
<td>2</td>
<td>25 / OSC/0.000</td>
<td>148.5</td>
<td>141.9</td>
<td>1.5</td>
<td>62</td>
<td>1.5</td>
<td>-30.1</td>
<td>-10.8</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>3</td>
<td>19 / STR / 0.015</td>
<td>209.2</td>
<td>194.5</td>
<td>5.8</td>
<td>75</td>
<td>1.9</td>
<td>+60.0</td>
<td>-51.4</td>
<td>67</td>
<td>67</td>
</tr>
<tr>
<td>4</td>
<td>25 / STR / 0.015</td>
<td>219.6</td>
<td>202.7</td>
<td>5.2</td>
<td>73</td>
<td>1.1</td>
<td>+164</td>
<td>-28.1</td>
<td>71</td>
<td>48</td>
</tr>
<tr>
<td>5</td>
<td>19 / OSC / 0.015</td>
<td>196.6</td>
<td>182.6</td>
<td>3.1</td>
<td>75</td>
<td>4.8</td>
<td>+75.0</td>
<td>-38.9</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>6</td>
<td>25 / OSC / 0.015</td>
<td>191.4</td>
<td>180.9</td>
<td>4.2</td>
<td>76</td>
<td>2.7</td>
<td>+194</td>
<td>-16.7</td>
<td>62</td>
<td>62</td>
</tr>
<tr>
<td>7</td>
<td>25 / STR / 0.030</td>
<td>177.9</td>
<td>172.9</td>
<td>2.9</td>
<td>81</td>
<td>3.9</td>
<td>+340</td>
<td>-99.4</td>
<td>57</td>
<td>57</td>
</tr>
<tr>
<td>8</td>
<td>25 / STR / 0.030</td>
<td>189.4</td>
<td>184.2</td>
<td>2.7</td>
<td>80</td>
<td>4.1</td>
<td>+514</td>
<td>-46.3</td>
<td>61</td>
<td>61</td>
</tr>
<tr>
<td>9</td>
<td>19 / OSC / 0.030</td>
<td>154.7</td>
<td>147.2</td>
<td>2.3</td>
<td>79</td>
<td>7.5</td>
<td>+438</td>
<td>-57.9</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>10</td>
<td>25 / OSC / 0.030</td>
<td>166.8</td>
<td>152.9</td>
<td>2.4</td>
<td>83</td>
<td>6.6</td>
<td>+960</td>
<td>-23.9</td>
<td>54</td>
<td>54</td>
</tr>
</tbody>
</table>

Table 3.21 presents typical mechanical properties for Al6061-T6 and GTAW groove joint welded Al6061-T6 with alloy Al4047 filler wire in the as-welded condition.

Figure 3.40 shows the representative engineering stress-strain curves for welds performed autogenously, with two Al4047 shims, and with four Al4047 shims. The 16 tests performed for each shim count were averaged together for each curve. The loss of ductility for the 2 and 4
Table 3.21 Typical mechanical properties of Al6061-T6 base material and GTAW groove joint welded with alloy Al4047 filler

<table>
<thead>
<tr>
<th>Material</th>
<th>Ult. Strength MPa</th>
<th>Yld. Strength MPa</th>
<th>Elongation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al6061-T6</td>
<td>310</td>
<td>276</td>
<td>12</td>
</tr>
<tr>
<td>GTAW Al6061 with alloy Al4047 filler as-welded</td>
<td>186</td>
<td>124</td>
<td>8</td>
</tr>
</tbody>
</table>

Shim curves is probably due to the presence of defects. For the zero shim welds there was probably little eutectic liquid due to low Si to back fill the cracks during solidification. In the four shim welds a larger amount of eutectic was expected yet the ductility was low. It is plausible that the low ductility is due to the large number of voids in the fusion zone. The two shim welds had better ductility then either autogenous or the 4 shim welds. They had fewer hot cracks than the autogenous weld and less porosity then the four shim welds. Better ductility could be developed if less porosity was present in the case of the two shim weld. Since bending and impact loading are important design considerations, further study into these types of loads should be considered. Bending loads could be simulated using 3-point bending and the weld toughness by Charpy testing.

In all cases, the specimens fractured in the fusion zone. Tensile results showed significant losses in ductility, owing to strain concentration in the lower strength weld region as expected from the hardness profile of the joint shown earlier in Figures 3.25 – 3.27. Other significant features in a weld that affects ductility is the number of defects, porosity, second phase, or cracks, etc. Gross defects can strongly affect the performance of a weld in tensile testing. Bend and impact testing can better characterize these behaviors.

Weld strength matching can also affect weld mechanical properties. The joint efficiency of the welds in this investigation in terms of elongation never exceeded 5.8% which is not too unusual due to the significant strength undermatching encountered in EB welding of age-hardenable aluminum alloys. In undermatching cases, the stress concentration and consequent failure (confined plasticity) generally occur in the lower strength weld region of the joint, leading to an increase of constraint within the weld region, resulting in lower elongation values.
Strength undermatching could not explain the differences in elongation between the different tests. Dilution testing showed that the autogenous weld had a significant loss of Si and Mg and higher amount of solidification cracking in the fusion zone and liquation cracking in the HAZ. The strength and ductility of the joint were poor. One potential scenario was the remaining Si and Mg combined to form precipitation strengthening Mg2Si. The weld became brittle due to the absence of Si required to heal the liquation and solidification cracks. This hypothesis may help to explain the poor mechanical properties when no filler metal was used.

Two shims provided higher strength and better ductility in the joint. The calculation were summarized previously in Table 3.20. The large infusion of Si in the FZ was evident from the percentages measured, although the amount required to reduce weld cracking was not clear. It is likely that one shim may have been sufficient to reduce the liquation and solidification cracking without further diluting the amount of Mg. Two shims introduced the possibility of more surface

Figure 3.40 Typical Engineering Stress-Strain curves for EBW performed autogenously, with two shims, and with four shims. Each of the curves are an average of the four tests run with each shim thickness.
contamination and more potential for voids that are evident in higher porosity levels. The percentage of porosity may have been a significant factor in the joint efficiency.

Four shims accelerated the detrimental effects experienced with two shims. At this point, cross-sectional area of the shim represents about 2% of the joint volume. The percentage of porosity at this point was as high as 7.5% which is unacceptably high for even low grade sand castings which exhibit a ductility in the range of 2%. This may have been the most significant contributor to the loss of ductility and strength. In addition, since the Al4047 metal filler contains no magnesium its dilution effects became more apparent, and its effects on the strength and ductility of the weld joint become more detrimental.

Increased welding speed reduced element losses slightly, but Mg boil off was still an inherent problem. The straight beam pattern provided a FZ with less porosity than the oscillating beam pattern. The effect of the porosity can be visualized for tests nine and ten shown in Figure 3.41.

In order to better understand the failure modes, SEM examination was conducted on the fracture surfaces of several specimens. Figure 3.42 shows the surface morphology of Test #11, an autogenous weld, run at 19 mm/s, with a straight beam pattern. The mode of failure consists of dimples with micro-void coalescence, which was an indication that the tensile specimens failed in a ductile manner, yet the ductility was one of the lowest tested. This may be due to the increased amounts of solidification cracking resulting from the loss of Si in the FZ.

Figure 3.42  SEM fractography of Test #11: (a) 30X magnification; (b) 150X magnification

Figure 3.22 shows the surface morphology of the weld specimens with two 0.0075 mm Al4047 filler shims, run at 19 mm/s, with a straight beam. The mode of failure consists of a combination of dimples with micro-void coalescence. The failure was probably due to pre-existing voids or cracks.
Figure 3.41 Tensile sample fracture surfaces and their respective mechanical properties for each of the twelve DOE tests run.
Table 3.22 Summary of test parameters and mechanical properties for Test #11

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel speed (mm/s)</td>
<td>19</td>
</tr>
<tr>
<td>Beam Pattern</td>
<td>Straight</td>
</tr>
<tr>
<td>Shim Thickness (mm)</td>
<td>Autogenous</td>
</tr>
<tr>
<td>Ultimate tensile Strength (MPa)</td>
<td>155</td>
</tr>
<tr>
<td>Yield Strength (MPa)</td>
<td>149</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>2.9</td>
</tr>
<tr>
<td>Hardness</td>
<td>58</td>
</tr>
<tr>
<td>% Porosity</td>
<td>0.0</td>
</tr>
<tr>
<td>% Loss or gain of Si</td>
<td>-75.6</td>
</tr>
<tr>
<td>% Loss or gain of Mg</td>
<td>-35.6</td>
</tr>
<tr>
<td>% Joint Efficiency (Weld Ult/Bas Ult)</td>
<td>50</td>
</tr>
</tbody>
</table>

Figure 3.42  SEM fractography of Test #11: (a) 30X magnification; (b) 150X magnification

Table 3.23 Summary of test parameters and mechanical properties for Test #3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Travel speed (mm/s)</td>
<td>19</td>
</tr>
<tr>
<td>Beam Pattern</td>
<td>Straight</td>
</tr>
<tr>
<td>Shim Thickness (mm)</td>
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</tr>
<tr>
<td>Ultimate tensile Strength (MPa)</td>
<td>209.2</td>
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<tr>
<td>Yield Strength (MPa)</td>
<td>194.5</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>5.8</td>
</tr>
<tr>
<td>Hardness</td>
<td>51</td>
</tr>
<tr>
<td>% Porosity</td>
<td>1.9</td>
</tr>
<tr>
<td>% Loss or gain of Si</td>
<td>+60.0</td>
</tr>
<tr>
<td>% Loss or gain of Mg</td>
<td>-51.4</td>
</tr>
<tr>
<td>% Joint Efficiency (Weld Ult/Bas Ult)</td>
<td>67</td>
</tr>
</tbody>
</table>
Figure 3.43  SEM fractography of Test #3: (a) 30X magnification; (b) 150X magnification

Figure 3.43 shows the surface morphology of the weld specimens with four 0.0075 mm Al4047 filler shims, run at 25 mm/s, with an oscillating beam. The mode of failure consists of a combination of dimples with micro-void coalescence. The failure is probably due to pre-existing voids and cracks. The lower strength and ductility is mainly due to voids and cracks and a loss of Mg required for adequate amounts of Mg$_2$Si.

Figures 3.45 – 3.47 illustrate the effects of shim thickness on the mechanical properties of the EB welded joint. The two shim joint has the best overall mechanical properties followed by four shims, and finally the autogenous weld. The poor results for the autogenous weld are based on the lack of excess Si leading to significant solidification and liquation cracking. Four shims produced a large number of voids and diluted the Mg content to the point that there was an inadequate amount of Mg$_2$Si, the main strengthening agent in Al, Mg-Si alloys. The two shim joint produced an adequate amount of Mg$_2$Si and excess silicon to heal cracking in the fusion zone. Excess porosity in the joint reduced the mechanical properties to some extent.
Table 3.24 Summary of test parameters and mechanical properties for Test #10

<table>
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<tr>
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<td>Beam Pattern</td>
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<tr>
<td>Shim Thickness (mm)</td>
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<tr>
<td>Ultimate tensile Strength (MPa)</td>
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<tr>
<td>Yield Strength (MPa)</td>
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<tr>
<td>Elongation (%)</td>
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<tr>
<td>Hardness</td>
<td>51</td>
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<tr>
<td>% Porosity</td>
<td>6.6</td>
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<tr>
<td>% Loss or gain of Si</td>
<td>+660</td>
</tr>
<tr>
<td>% Loss or gain of Mg</td>
<td>-23.9</td>
</tr>
<tr>
<td>% Joint Efficiency (Weld Ult/Bas Ult)</td>
<td>54</td>
</tr>
</tbody>
</table>

Figure 3.44 SEM fractography of Test #10: (a) 30X magnification; (b) 150X magnification
Figure 3.45 Ultimate tensile strength as a function of shim thickness for various combinations of travel speed and beam pattern

Figure 3.46 Yield strength as a function of shim thickness for various combinations of travel speed and beam pattern

Figure 3.47 Elongation as a function of shim thickness for various combinations of travel speed and beam pattern
CHAPTER 4: CONCLUSIONS

The narrow FZ of the EB weld proved to be extremely sensitive to alloy additions. The autogenous EBW was weak and brittle due to the lack of excess silicon needed for healing solidification cracking in the FZ and liquation cracks in the HAZ. Addition of two filler shims provided increased strength and ductility by reducing solidification cracking, but the improvements were tempered by increased porosity. Four shims proved to be unfavorable for strength and ductility due lack of Mg$_2$Si, and further increases in the porosity in the FZ.

The shims provided a consistent infusion of Si to the joint as intended, but the porosity increased dramatically with each addition. Every additional shim provided two more surfaces with gas producing oxides that were trapped in the fusion zone. Further study is needed in understanding the best way to remove oxides and determine the amount of time between oxide removal and welding. Only one shim of the required thickness is recommended in the joint to minimize defects.

The range of travel speeds used in this study did not affect the defects, dilution in the FZ, or mechanical properties of the weld. The speed did affect the weld penetration. Further research is required to understand at what point turbulence in the keyhole column increases the defects in the FZ. Further increases in speed would require an increase in the accelerating voltage to compensate for the decrease in penetration.

The oscillating beam pattern did not provide a reduction in porosity experienced by deep penetration welds in high melt temperature alloys. The oscillating beam pattern produced more porosity, lower strength and less ductility. These observations likely suggests that the benefits seen in deep welds of high-temperature materials may not translate to shallow EBW with low melting temperatures.

Based on the DOE results the best weld parameters for the intended application would be 25 mm/s travel speed, a straight beam and one shim of the correct thickness or chemical composition to provide adequate Mg$_2$Si and excess Si. Further research into adequate cleaning procedures are required to remove oxides if shims are to be used.
REFERENCES


LIST OF APPENDICES

Appendix A  Material certifications, weld sample sketches, fixturing, and other Equipment.................................................................70

Appendix B  Macrophotographs of weld bead profiles.........................................................80

Appendix C  Knoop microhardness graphs.................................................................88

Appendix D  Bar charts of dilution as a function of location...........................................94
Appendix A

Appendix A has material certifications, sketches, and several photos of the electron beam welding equipment.

---

CERTIFICATE OF TEST

CUSTOMER ORDER NUMBER
14956

EARLE M. JORGENSEN COMPANY
6050 DOWNING STREET
P.O. BOX 16065
DENVER CO 80216

Invoice Number
T46578

CUSTOMER PART NUMBER

C-6197

Page 02 of 02

Certification Date
21-SEP-2006

SOLD TO: BARBER-NICHOLS ENGR CO
6125 WEST 55TH AVE
ARVADA CO 80002

SHIP TO: BARBER-NICHOLS ENGR CO
6325 WEST 55TH AVENUE
ARVADA CO 80002

Description: 6061-T6511 EXT. SMLS TUBING QQ A 200/8 AMS QQ
7.500 OD X 1.000 W (5.500 ID) X 24'
HEAT: 4631055
ITEM: 106126

Line Total: 48 FT

MATERIAL IS FREE FROM MERCURY CONTAMINATION

COMMENTS
MEETS TS TEMPER REQUIREMENTS
SI .1
FE .33
CU .33
MN .08
NG .9
CR .08
ZN .04
TI .02

The above data were transcribed from the manufacturer's Certificate of Test after verification for completeness and specification requirements of the information on the certificate. All test results remain in our possession.

We hereby certify that the material covered by this report will meet the applicable requirements described herein, including any specification forming a part of the description.

The willful volunteering of false, fictitious, or fraudulent statements in connection with test results may be punishable as a felony under federal statutes.

Material did not come in contact with mercury while in our possession.

MICHAEL BOSCH
MANAGER, QUALITY ASSURANCE

70
# CERTIFICATE OF TEST

**CUSTOMER ORDER NUMBER**: 23741  
**EARLE M. JORGENSEN COMPANY**: 6050 DOWNING STREET  
**P.O. BOX 16065**: DENVER CO 80216  
**CUSTOMER PART NUMBER**: 106126  
**Invoice Number**: TS45108  
**Page 01 of 02**  
**Certification Date**: 13-JUL-2010  
**SHIPPING TO**: BARBER-NICHOLS ENGR CO  
**6325 WEST 55TH AVENUE**: ARVADA CO 80002  
**SHIP TO**: BARBER-NICHOLS ENGR CO  
**6325 WEST 55TH AVENUE**: ARVADA CO 80002  
**SOLD TO**: BARBER-NICHOLS ENGR CO  
**6325 WEST 55TH AVE**: ARVADA CO 80002

**Description**: 6061-T6511 EXT SMLS TUBING QQ A 200/8 AMS QQ 7.500 OD X 1.000 W S/C 12'0" (144.0")  
**Line Total**: 12 FT  
**HEAT**: 20435223  
**ITEM**: 106126

**Specifications**:

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<td>ASTM B345 02</td>
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<td>0.04</td>
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<td>0.04</td>
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<tr>
<td>MAX</td>
<td>0.8</td>
<td>0.7</td>
<td>0.4</td>
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**OTHERS**:

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<tr>
<th>EACH</th>
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<tr>
<td>0.05</td>
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**RCPT**: R107186  
**MILL**: SAPA INDUSTRIAL EXTRUSIONS  
**COUNTRY OF ORIGIN**: USA

**MECHANICAL PROPERTIES**

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<td>KSI</td>
<td>IN 02 IN</td>
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</tr>
<tr>
<td>44.1</td>
<td>49.3</td>
<td>14.5</td>
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<td>49.3</td>
<td>14.5</td>
<td></td>
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</tr>
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The above data were transcribed from the manufacturer's Certificate of Test after verification for completeness and specification requirements of the information on the certificate. All test results remain at the subject to examination.

We hereby certify that the material covered by this report will meet the applicable requirements described herein, including any specification forming a part of the description.

The willful recording of false, fictitious, or fraudulent statements in connection with test results may be punishable as a felony under federal statutes.

Material did not come in contact with mercury while in our possession.

MICHAEL BOSCH  
MANAGER, QUALITY ASSURANCE

71
CERTIFICATE OF TEST

CUSTOMER ORDER NUMBER
23741
CUSTOMER PART NUMBER
106126

SOLD TO: BARBER-NICHOLS ENGR CO
6325 WEST 55TH AVE
ARVADA CO 80002

SHIP TO: BARBER-NICHOLS ENGR CO
6325 WEST 55TH AVENUE
ARVADA CO 80002

Description: 6061-T6511 EXT SMLS TUBING QQ A 200/8 AMS QQ
7.500 OD X 1.000 W S/C 12’0" (144.0"") Line Total: 12 FT
HEAT: 20435223 ITEM: 106126

COMMENTS
PRODUCTS MFG WITH A T6511 TEMPER ALSO
MEET T6 TEMPER REQUIREMENTS
YIELD @ .2% OFFSET

The above data were transcribed from the manufacturer's Certificate of Test after verification for completeness and specification requirements of the information on the certificate. All test results remain on file subject to examination.

We hereby certify that the material covered by this report will meet the applicable requirements described herein, including any specification forming a part of the description.

The willful recording of false, fictitious, or fraudulent statements in connection with test results may be punishable as a felony under federal statute.

Material did not come in contact with mercury while in our possession.

MICHAEL BOSCH
MANAGER, QUALITY ASSURANCE

Page 02 of 02
Certification Date 13-JUL-2010
Invoice Number T545108
# Certified Inspection Report

<table>
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<td>10210741</td>
<td>3.498</td>
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**Applicable Specifications, Standards and Exceptions**

**Composition Notes:** The values for "Min. Mass" and "Max. Mass" have not been listed as shown on this certified inspection report. Resende S. America.

**Agreed to and Signed**

Daniele A. Larosa

33-MAR-18

**Quality Inspector**

Quality Manager

---

**Certification**

The material covered in this report has been manufactured, inspected, and tested in accordance with the requirements of the applicable specifications and standards listed. The material met the requirements and has been found to be in compliance with the specifications and standards listed.

**Applicable Specifications, Standards and Exceptions**

- **Material Description:**
  - 1.905 OD x 0.125 ID

**Composition Notes:**

- The values for "Min. Mass" and "Max. Mass" have not been listed as shown on this certified inspection report.

**Certification**

Daniele A. Larosa

33-MAR-18

**Quality Inspector**

Quality Manager

---

**Certification**

The material covered in this report has been manufactured, inspected, and tested in accordance with the requirements of the applicable specifications and standards listed. The material met the requirements and has been found to be in compliance with the specifications and standards listed.

**Applicable Specifications, Standards and Exceptions**

- **Material Description:**
  - 1.905 OD x 0.125 ID

**Composition Notes:**

- The values for "Min. Mass" and "Max. Mass" have not been listed as shown on this certified inspection report.

**Certification**

Daniele A. Larosa

33-MAR-18

**Quality Inspector**

Quality Manager
## Certified Inspection Report

**Material:** 6081

| Alloy  | Ti & Vl | Re | Fe | Mg | Cr | Si | Ni | Al | Cu | Zn | Mn | Ti | H2O | Other Total |
|--------|---------|----|----|----|----|----|----|----|----|----|----|----|----|----|-----------|
|        | Min.    | Max.| Min. | Max.| Min. | Max. | Min. | Max. | Min. | Max. | Min. | Max. | Min. | Max. | 0.25 | 0.05 | 0.10 |
| 6081   | --      | 0.25 | --   | --  | --   | --   | 0.05 | --  | 0.10 |

**Concentration Results**

- **Test Results:**
  - Test Type: UTS, TYR, EC-40-Long
  - Max. Value: 540 MPa, 180 MPa, 150 MPa
  - Min. Value: 420 MPa, 150 MPa, 120 MPa

**Mechanical Property - Test Limits**

- **UTS (MPa):**
  - Min. Value: 540 MPa
  - Max. Value: 540 MPa

- **TYR (MPa):**
  - Min. Value: 180 MPa
  - Max. Value: 180 MPa

- **EC-40-Long (MPa):**
  - Min. Value: 150 MPa
  - Max. Value: 150 MPa

- **Additional Notes:**
  - Product manufactured with a T611 temper also meets T6 temper requirements.
  - Test results have been declared by the E.U. and tested under the E.U. standard.

---

**Conclusion:**

Qualified pursuant to Sapa's Industrial Customer standard with the exception of Ti brazing addition. Made in USA.
1 - Weld seam
2 - Weld sampe A
3 - Weld sampe B

Section A-A
Figure 1 EBE, Inc. EB Welding Station & EB Welding Supervisor Tom Hurt

Figure 2 EB Welding Machine Tower
Appendix B

Appendix B contains weld profile microphotographs of all testing not reported in the body of the thesis.

Figure 4  a) Test #1 weld bead geometry (25/STR/0.000)  b) Macrophotograph of root porosity

Figure 5  a) Test #2 weld bead geometry (25/OSC/0.000)  b) Macrophotograph of root porosity

Figure 6  Test #3 weld bead geometry (19/STR/0.015)
Figure 7  Test #4 weld bead geometry (25/STR/0.015)

Figure 8  Test #5 weld beam geometry (19/STR/0.030)

Figure 9  Test #6 weld bead geometry  (25/STR/0.030)
Figure 10  Test #7 weld bead geometry  (19/OSC/.015)

Figure 11  Test #8 weld bead geometry  (25/OSC/0.015)

Figure 12  Test #9 weld bead geometry (19/OSC/0.030)
Figure 13  Test #10 weld bead geometry (25/OSC/0.030)

Figure 14  Test #11 weld bead geometry (19/STR/0.000)

Figure 15  Test #12 weld bead geometry (19/OSC/0.000)
Figure 16 Optical micrographs of weld section and fusion boundary of Al6061-T6 weld joint using no Al4047 metal filler shims (Test #1, #2, #11, and #12)
Figure 17 Optical micrographs of weld section and fusion boundary of Al6061-T6 weld joint using two .0075mm, Al4047 metal filler shims (Test #3, #4, #7, and #8)
Figure 18 Optical micrographs of weld section and fusion boundary of Al6061-T6 weld joint using four .0075mm, Al4047 metal filler shims (Test #5, #6, #9, and #10)
Figure 19 Optical micrographs of weld section and fusion boundary of Al6061-T6 weld joint using four .0075mm, Al4047 metal filler shims (Test 11,12)
Appendix C

Appendix C contains Knoop hardness results for all the testing not reported in the body of the thesis.

![Microhardness profile](image1)

**Figure 20** Microhardness profile of the weld joint in as-welded condition for a travel speed of 25 mm/s, a straight beam, and no Al4047 metal filler shim (Test #1)

![Microhardness profile](image2)

**Figure 21** Microhardness profile of the weld joint in as-welded condition for a travel speed of 25 mm/s, an oscillating beam, and no Al4047 metal filler shim (Test #2)
Figure 22 Microhardness profile of the weld joint in as-welded condition for a travel speed of 19 mm/s, a straight beam, and two .0075 mm Al4047 metal filler shims (Test #3)

Figure 23 Microhardness profile of the weld joint in as-welded condition for a travel speed of 25 mm/s, a straight beam, and two .0075 mm Al4047 metal filler shims (Test #4)
**Figure 24** Microhardness profile of the weld joint in as-welded condition for a travel speed of 19 mm/s, a straight beam, and four, .0075 mm Al4047 metal filler shims (Test #5)

**Figure 25** Microhardness profile of the weld joint in as-welded condition for a travel speed of 25 mm/s, a straight beam, and four, .0075 mm Al4047 metal filler shims (Test #6)
Figure 26 Microhardness profile of the weld joint in as-welded condition for a travel speed of 19 mm/s, an oscillating beam, and two .0075 mm Al4047 metal filler shims (Test #7)

Figure 27 Microhardness profile of the weld joint in as-welded condition for a travel speed of 25 mm/s, an oscillating beam, and two .0075 mm Al4047 metal filler shims (Test #8)
Figure 28 Microhardness profile of the weld joint in as-welded condition for a travel speed of 19 mm/s, an oscillating beam, and four, .0075 mm Al4047 metal filler shims (Test #9)

Figure 29 Microhardness profile of the weld joint in as-welded condition for a travel speed of 25 mm/s, an oscillating beam, and four, .0075 mm Al4047 metal filler shims (Test #10)
Figure 30 Microhardness profile of the weld joint in as-welded condition for a travel speed of 19 mm/s, a straight beam, and no Al4047 metal filler shims (Test #11)

Figure 31 Microhardness profile of the weld joint in as-welded condition for a travel speed of 19 mm/s, an oscillating beam, and no Al4047 metal filler shims (Test #12)
Appendix D

Appendix D contains EDX dilution results for all the testing not reported in the body of the thesis.

Figure 32 SEI mode dilution x-ray map of Si and Mg for a travel speed of 25 mm/s, a straight beam, and no Al4047 metal filler shim taken at the upper section of the weld (Test #1)

Figure 33 SEI mode dilution x-ray map of Si and Mg for a travel speed of 25 mm/s, a straight beam, and no Al4047 metal filler shim taken at the mid-section of the weld (Test #1)

Figure 34 SEI mode dilution x-ray map of Si and Mg for a travel speed of 25 mm/s, an oscillating beam, and no Al4047 metal filler shim taken at the upper section of the weld (Test #2)
Figure 35 SEI mode dilution x-ray map of Si and Mg for a travel speed of 25 mm/s, an oscillating beam, and no Al4047 metal filler shim taken at the mid-section of the weld (Test #2)

Figure 36 SEI mode dilution x-ray map of Si and Mg for a travel speed of 19 mm/s, a straight beam, and two, .0075mm thick Al4047 metal filler shims taken at the upper section of the weld (Test #3)

Figure 37 SEI mode dilution x-ray map of Si and Mg for a travel speed of 19 mm/s, a straight beam, and two, .0075 mm thick Al4047 metal filler shim taken at the mid-section of the weld (Test #3)
Figure 38 SEI mode dilution x-ray map of Si and Mg for a travel speed of 25 mm/s, a straight beam, and two, .0075 mm thick Al4047 metal filler shims taken at the upper section of the weld (Test #4)

Figure 39 SEI mode dilution x-ray map of Si and Mg for a travel speed of 25 mm/s, a straight beam, and two, .0075 mm thick Al4047 metal filler shim taken at the mid-section of the weld (Test #4)

Figure 40 SEI mode dilution x-ray map of Si and Mg for a travel speed of 19 mm/s, a straight beam, and four, .0075 mm thick Al4047 metal filler shim taken at the upper section of the weld (Test #5)
Figure 41 SEI mode dilution x-ray map of Si and Mg for a travel speed of 19 mm/s, a straight beam, and four, .0075 mm thick Al4047 metal filler shim taken at the mid-section of the weld (Test #5)

Figure 42 SEI mode dilution x-ray map of Si and Mg for a travel speed of 25 mm/s, a straight beam, and four, .0075 mm thick Al4047 metal filler shims taken at the upper section of the weld (Test #6)

Figure 43 SEI mode dilution x-ray map of Si and Mg for a travel speed of 25 mm/s, a straight beam, and four, .0075 mm thick Al4047 metal filler shims taken at the mid-section of the weld (Test #6)
Figure 44 SEI mode dilution x-ray map of Si and Mg for a travel speed of 19 mm/s, a oscillating beam, and two, .0075mm thick Al4047 metal filler shims taken at the upper section of the weld (Test #7)

Figure 45 SEI mode dilution x-ray map of Si and Mg for a travel speed of 19 mm/s, a oscillating beam, and two, .0075 mm thick Al4047 metal filler shim taken at the mid-section of the weld (Test #7)

Figure 46 SEI mode dilution x-ray map of Si and Mg for a travel speed of 25 mm/s, a oscillating beam, and two, .0075mm thick Al4047 metal filler shims taken at the upper section of the weld (Test #8)
Figure 47 SEI mode dilution x-ray map of Si and Mg for a travel speed of 25 mm/s, a oscillating beam, and two, .0075 mm thick Al4047 metal filler shim taken at the mid-section of the weld (Test #8)

Figure 48 SEI mode dilution x-ray map of Si and Mg for a travel speed of 19 mm/s, a oscillating beam, and four, .0075mm thick Al4047 metal filler shims taken at the upper section of the weld (Test #9)

Figure 49 SEI mode dilution x-ray map of Si and Mg for a travel speed of 19 mm/s, a oscillating beam, and four, .0075 mm thick Al4047 metal filler shim taken at the mid-section of the weld (Test #9)
Figure 50 SEI mode dilution x-ray map of Si and Mg for a travel speed of 25 mm/s, a oscillating beam, and four, .0075mm thick Al4047 metal filler shims taken at the upper section of the weld (Test #10)

Figure 51 SEI mode dilution x-ray map of Si and Mg for a travel speed of 25 mm/s, a oscillating beam, and four, .0075 mm thick Al4047 metal filler shim taken at the mid-section of the weld (Test #10)

Figure 52 SEI mode dilution x-ray map of Si and Mg for a travel speed of 19 mm/s, a oscillating beam, and no Al4047 metal filler shims taken at the upper section of the weld (Test #11)
Figure 53 SEI mode dilution x-ray map of Si and Mg for a travel speed of 19 mm/s, a oscillating beam, and no Al4047 metal filler shim taken at the mid-section of the weld (Test #11)

Figure 54 SEI mode dilution x-ray map of Si and Mg for a travel speed of 25 mm/s, a oscillating beam, and no Al4047 metal filler shims taken at the upper section of the weld (Test #12)

Figure 55 SEI mode dilution x-ray map of Si and Mg for a travel speed of 25 mm/s, a oscillating beam, and no Al4047 metal filler shim taken at the mid-section of the weld (Test #12)