REPORT

November 30, 2005
EWI Project No. 48565GTH
ATI Subcontract Agreement No. 2005-365
NSRP Report

High Speed Narrow Groove Submerged Arc Welding for Thin Steel Panels

Revised: December 5, 2005

Submitted to:

Advanced Technology Institute
Charleston, SC

EWI

MATERIALS JOINING TECHNOLOGY

Report

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on

High Speed Narrow Groove Submerged Arc Welding for Thin Steel Panels

to

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Final Revision

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Executive Summary

In response to increased performance requirements for U.S. Navy ships, the complexity of ship structure has increased. As a result, the use of thinner steels is a major trend in current ship structure design. Recent research efforts have identified many gaps in welding technology required to fabricate thin steel with the current shipbuilding infrastructure that was designed to fabricate structures with thick plate.

Northrop Grumman Ship Systems (NGSS) currently uses a modified two-electrode series arc submerged arc welding (S-SAW) process for single sided butt welding. The process was originally developed for thicker materials and, when applied to thin materials, can result in excessive weld face reinforcement and inconsistent root bead contour. High heat-input legacy welding procedures also result in excessive distortion when applied to thinner materials. NGSS needs precision butt-welding methods that are more suitable for welding thin plate materials.

The objective of this project was to reduce welding distortion and improve weld consistency through the use of precision SAW welding techniques for thin steel panels. High-speed tandem narrow groove (NG) submerged arc welding (SAW) procedures were developed with improved flux copper backing (FCB) using advanced power supplies and controlled weld joint root gap openings.

NGSS currently fits and welds plates without additional edge preparation following plasma cutting. While this approach is adequate for thicker materials, application of NG SAW for thin materials generally requires more precise control of joint gap than is currently achieved. For thin steel, milling (or laser cutting) weld joints offers significant accuracy improvement and better gap control, thus enabling the use of more highly productive NG welding technologies that feature lower heat inputs and decreased weld distortion. NGSS shipyards are currently investing in new panel lines that will have plate milling and laser cutting. This investment lays the ground-work for deployment of NG tandem SAW.

High-speed NG tandem SAW FCB butt joint welding procedures were developed and successfully demonstrated on 5-, 8-, and 10-mm DH36 plate. For each plate thickness, preferred parameters were selected that doubled welding productivity while improving weld quality and mechanical properties.

Key findings:

- An improved FCB design was developed. The improved design incorporates a parabolic groove that substantially improved weld bead shape and arc stability as compared to the

current shipyard practice of using a FCB with a square groove configuration. This is expected to decrease the need for post-weld repair as compared with current practice.

- Preferred welding consumables were identified. Type AWS EM12K (Lincoln L-61) electrodes of sizes 5/32-in. diameter (for the lead) and 3/32-in. diameter (for the trail) were used in combination with TYPE AWS F7A2 flux (Lincoln 761 flux).
- Advanced AC-AC and DC-AC waveform control offered distinct advantages for procedure development, as adjustment of waveform parameters allowed creation of more robust welding procedures.
- The degree of gap tolerance depended on the plate thickness. The 5-mm plate procedure had approximately 1-mm root opening tolerance while the 8- and 10-mm plate procedures had approximately 3-mm tolerance. Further procedure refinement could increase gap tolerance.
- Distortion was minimal for each plate welded with the preferred procedures. The most pronounced distortion measured was on the thinnest plate (5-mm), where out-of-plane distortion measured 10-mm. Transverse shrinkage of the plates was minimal; the largest measured was 1.4-mm at the middle of the weld for the 8- and 10-mm plates.
- Tandem NG SAW FCB offers production cost savings opportunities. The tandem NG SAW FCB procedures more than doubled the welding travel speed (i.e., the same weld can be deposited in half the time) as compared with the current S-SAW process. Tandem NG SAW FCB also requires half the weld filler metal; produces a better quality weld more consistently; takes less time to set-up; and should reduce post-weld repairs.
- Weld mechanical properties (evaluated for the 10-mm plate only) met all requirements of the applicable standards for procedure qualification.

Additional work is suggested to optimize the welding process parameters to allow for greater gap tolerances. This would permit broader implementation of tandem NG SAW FCB into existing operations, where plate milling may not be available. Optimization may involve refinement of the FCB groove design as well as other welding process parameters. Once optimized, procedure qualification testing should be performed for each material thickness of interest. A study evaluating the performance of the developed NG SAW FCB procedures in a production environment and on full-size panels is also recommended as a precursor to full implementation. This would include characterizing the fit-up requirements and the distortion and weld quality improvements when welding production panels.

Finally, tandem SAW should be developed for other base materials that are applicable to additional weapon systems. For example, NGNN would be interested in evaluating the process for HSLA-65 which is used on the CVN-21.

1.0 Introduction

Northrop Grumman Ship Systems (NGSS) has studied the problems of thin steel panel fabrication in a Navy ManTech Program project entitled *Fabrication and Engineering Technology for Lightweight Ship Structures*; commonly called the *Thin Steel Project*. This project identified many gaps in technology required for thin steel using shipbuilding facilities that were designed for thick plate. The *Thin Steel Project* is meeting many of these needs including numerical distortion analysis, material handling, thermal cutting, panel welding, and accuracy control technology. The *High Speed Narrow Groove SAW for Thin Steel Panels* project compliments the efforts of the Thin Steel Project, which has limited resources to address a variety of production technologies. The technology developed for this project can be implemented at any shipyard that needs to fabricate complex panels from thin steel using the submerged arc welding (SAW) process. NGSS - New Orleans (Avondale), NGSS - Pascagoula (Ingalls), Marinette Marine, and Todd have committed to implement, or could readily implement, this technology if successful.

MARTIECH ASE has sponsored work on SAW flux copper backing (FCB) technology for thick plate using large tandem electrodes. This study developed welding procedures and parameter relationships for 0.5-in. to 1.25-in. thick plate. Tandem electrode diameters of 0.125-in., 0.19-in., and 0.25-in. were used with currents as high as 1,500 amps. This technology does not support low heat input welding of thin steel; therefore, the *High Speed Narrow Groove SAW for Thin Steel Panels* project is not a duplication of prior effort.

2.0 Background

Current and future Navy ship programs, including the DDG, DD(X), LPD, LHD, and the Coast Guard Deepwater System, are and will deploy more thin plate (3- to 10-mm) to optimize weight. To yield first-time weld quality and minimize distortion on complex panel fabrications, shipyards must be able to fabricate panels from plate pieces of various thickness and geometry. All panel seam welds must be sound, full penetration welds. Thin steel research has shown that dissimilar thickness panel joints are very susceptible to buckling distortion. Submerged arc welding (SAW) using flux copper backing (FCB) is preferred for long seam welding of plates into panels using single-sided welding procedures. This process is well established for thick steel where high heat input welding procedures are used to provide tolerance to fit-up variations. To minimize distortion, narrow groove welding procedures are needed especially on thin steel panels that are made from a range of plate thickness. Many Navy shipyards have dedicated SAW welding systems that can be improved by using plate with weld joints prepared by milling instead of using oxyfuel or plasma arc cutting. For thin steel, the use of milling or laser cutting offers significant improvement in accuracy and provides support for narrow groove welding technology. This project developed novel narrow groove (NG) SAW welding procedures using precision machined weld preparations, and advanced SAW power supply technology.

Combined with modern FCB systems that employ rigid clamping, distortion mitigation on complex thin steel panels may be feasible and comparable to high energy density processes for a much lower capital investment cost. This project is timely, as NGSS shipyards are investing in new panel lines that will have plate milling and laser cutting that support NG SAW FCB, which will maximize the potential of these investments and help meet the stringent fairness requirements of new ship designs like the DD(X).

3.0 Objectives

The primary objective of this project was to reduce distortion on complex, thin steel (5- to 10-mm) panels due to long seam welds. High-speed tandem narrow groove (NG) submerged arc welding (SAW) procedures with flux copper backing (FCB) were used with precise root gap openings and advanced SAW power supplies to minimize single-sided, full penetration weld size and heat input on thin steel butt joints. A secondary objective was to maximize the utilization of existing welding equipment to reduce distortion with the least amount of investment.

4.0 Technical Approach

High-speed NG SAW FCB welding procedures were developed for 5-, 8-, and 10-mm thin steel plate. These plate thicknesses were identified as the most common for NGSS applications and appropriately demonstrate the potential of NG SAW FCB. Both conventional and advanced tandem SAW power with both Direct Current - Alternating Current (DC-AC) and Alternating Current - Alternating Current (AC-AC) polarity were evaluated for maximizing travel speed and fusion quality. The current and electrode phase were developed to control filler melting rate, base metal dilution and bead shape, and minimize heat input. Joint preparation with a controlled gap permitted rapid fusion of the faying edges, assured complete penetration, and minimized the weld size and heat input. The effect of gap size on process performance was also assessed for each plate size.

This report contains a description of the existing modified series arc submerged arc welding (S-SAW) process in place at NGSS; tooling/fixturing requirements for high-speed NG tandem SAW FCB; the welding procedures developed for advanced waveform tandem SAW; and a description of the process demonstration hosted by the Navy Joining Center (NJC) which is operated by Edison Welding Institute (EWI) in Columbus, Ohio.

4.1 Existing Process Evaluation

Evaluation of the welding process currently in use at NGSS - Pascagoula was performed at the initial stage of this project. A visit was made to the Pascagoula shipyard where the modified

S-SAW process was observed and fixture design data, welding joint fit-up and general procedure data were collected. In addition, three large modified S-SAW groove welds were made on 5-, 8-, and 10-mm plate and shipped to EWI for evaluation. Cross-sectional macrographs were taken from weld beads of each plate thickness. Welding parameter data and general distortion measurements were also collected from these welds and used for later comparison to developed high-speed tandem NG SAW FCB procedures.

4.2 Tooling and Fixturing Development

A special fixture was designed to accommodate the flux copper backing bar and the small (6-in x 24-in.) test plate sizes. This fixture incorporated a similar fixture design as that employed at NGSS – Pascagoula. Clamp spacing, backing bar size, and plate support locations were designed to be similar to the current fixture in order to facilitate procedure transfer from EWI to the shipyard.

4.3 Procedure Development

This task focused on developing stable, low heat input high-speed tandem NG SAW FCB welding parameters that produced high quality welds on each plate thickness tested. Weld joints were NG butt joints using plates of similar thickness. AC-AC and DC-AC polarities were investigated, with several waveform factors such as current balance, DC offset, and root mean square (RMS) current being varied. Various root openings and travel speeds were also studied.

Initial weld joint quality was evaluated by examining macrographs of the weld cross-section and through visual observation of the weld bead. Good joint quality was defined as those welds that had complete root bead penetration, did not have excessive reinforcement on either the top or root surfaces, did not have significant undercut, and were free of other visible defects such as cracks, burn-through, and porosity.

Distortion and shrinkage measurements were made on each plate using the preferred procedure developed. Transverse shrinkage measurements were made since the small size of the plates and inability to provide more down force through the fixture contributed to the plates pulling in slightly toward the weld center during welding. Distortion measurements were also made using a ROMER arm, which allowed for precise coordinate measurements of the before and after welded plates in the x, y, and z directions.

Welds produced with preferred procedures were then subjected to procedure qualification per NAVSEA technical publication 89074-AQ-GIB-0010/248. Visual and NDE inspection (radiography and magnetic particle) was performed on each plate thickness. Due to the thin size of the plates, the 10-mm plate procedure was selected for mechanical testing since it allowed the most material for the test specimens to be properly machined. The 10-mm plate also allowed the widest range of qualified material thicknesses. Mechanical testing consisted of face and root bends, charpy impact testing, and transverse tensile tests.

4.4 Process Demonstration

At the conclusion of the project, a demonstration was held at EWI for team members from NGSS - New Orleans (Avondale), NGSS- Pascagoula (Ingalls), Northrop Grumman Newport News (NGNN), and The Lincoln Electric Company. Project results were presented and benefits of results were discussed. Full plate mock-ups of each plate size were successfully welded using the high-speed NG tandem SAW FCB procedures developed for this project.

5.0 Results and Discussions

This section is a discussion of the significance of the results of this investigation.

5.1 Existing Modified S-SAW Process Assessment

A visit was made to NGSS - Pascagoula to evaluate their existing process and procedure for thin panel welding. Pascagoula employs the modified series arc submerged arc welding (S-SAW) process with FCB for single-sided welding of 5-, 8-, and 10-mm thick panels. The modified S-SAW process traditionally incorporates three electrodes, but NGSS uses the process with just the first two electrodes (lead and middle) and do not use the third (i.e., trailing) electrode.

The mechanics of the S-SAW process are different than conventional tandem SAW in that the two electrodes pass current between them, with one electrode connected to the positive terminal of the power source and the other connected to the negative terminal. The two closest electrodes are positioned so that they form a common arc above the weld joint location. Figure 1 illustrates the modified S-SAW configuration of the electrodes. A connection also exists between the negative terminal of the power source and the work base material. This configuration causes the current to take two paths during welding, one through the two electrodes (lead and middle) and one through the electrodes to the base material. In effect, the S-SAW process delivers a lower heat input to the weld than that calculated by traditional heat input formulas (see Equation 1).

$$\text{Heat Input} = \frac{\text{Current} \times \text{Voltage}}{\text{Travel Speed}}$$

Equation 1 - Traditional Heat Input Formula

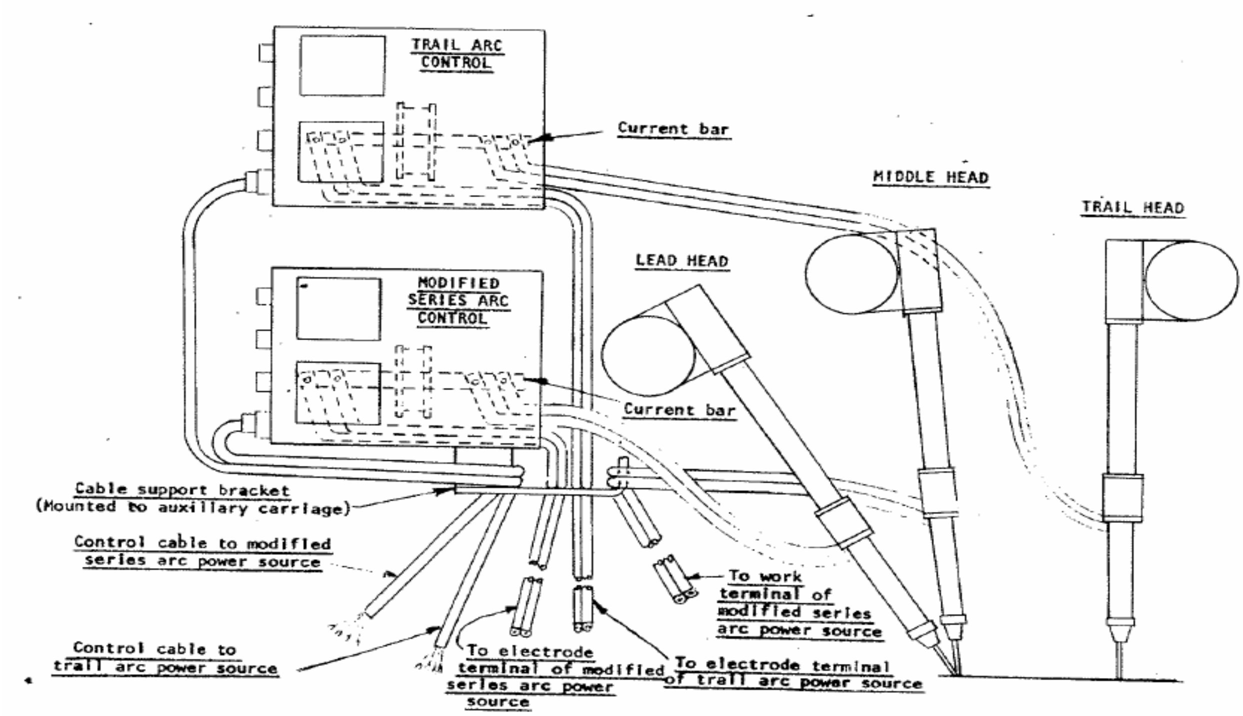

Figure 1 - Electrode Configuration of Modified S-SAW Process

The S-SAW process has a number of drawbacks. Approximately 2/3 of the heat generated by the S-SAW process goes into melting the electrodes, thus the heat required for welding is obtained from the current that diverts into the base material, as well as, the molten electrode deposited. In order to provide sufficient heat for the weld, more weld metal than necessary may be deposited into a joint, creating excessive reinforcement. This reduced heat input requires slower travel speeds and larger root openings to make single-sided full penetration welds. In addition, the process can suffer from instability problems such as misalignment of the electrodes due to filler metal cast variation or other factors. If a misalignment occurs, the arc between the two electrodes extinguishes and no heat is generated.

The panel line system at NGSS - Pascagoula is set up to weld long narrow groove (NG) butt joints of varying thicknesses. The current fixture system uses hydraulic clamps spaced 1.5-in. from the weld centerline and separated by 4.75-in. Figure 2 and Figure 3 show views of the panel line clamping system at Pascagoula. The clamps themselves are 6-in. by 14.5-in. (as shown in Figure 2). Rails and lift plates are used by the panel line to move plates into and out of the fixture.

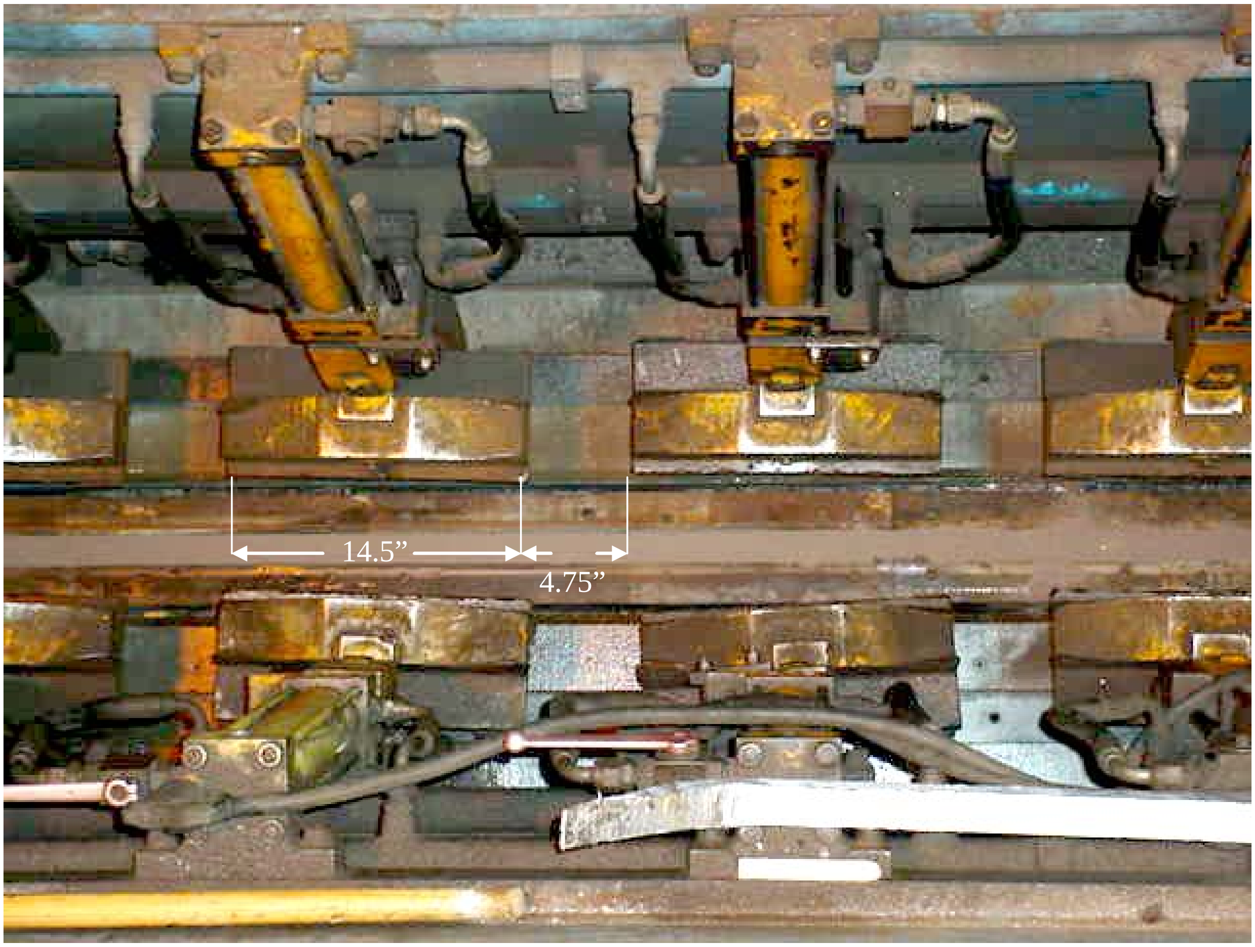

Figure 2 - Top View of NGSS - Pascagoula Panel Line Fixture

Figure 3 shows a side view of the panel line, with the FCB bar in the middle of the fixture. Two lift plates are situated on both sides of the copper bar, separated from the bar by a distance of 2.5-in.

Figure 3 - Side view of Pascagoula Panel Line Fixture

A dimensioned cross section of the FCB bar design is shown in Figure 4. The actual FCB bar has bevels on both sides of the copper bar, which is not shown in the dimensioned figure (can be seen above in Figure 3). To fill the backing bar with flux, procedures were followed which called for the entire groove area to be filled with flux and an additional 3-mm of flux piled above the top surface of the copper bar. This was accomplished by filling the FCB bar with flux, then carefully raking it so that a 3-mm flux bed height was obtained.

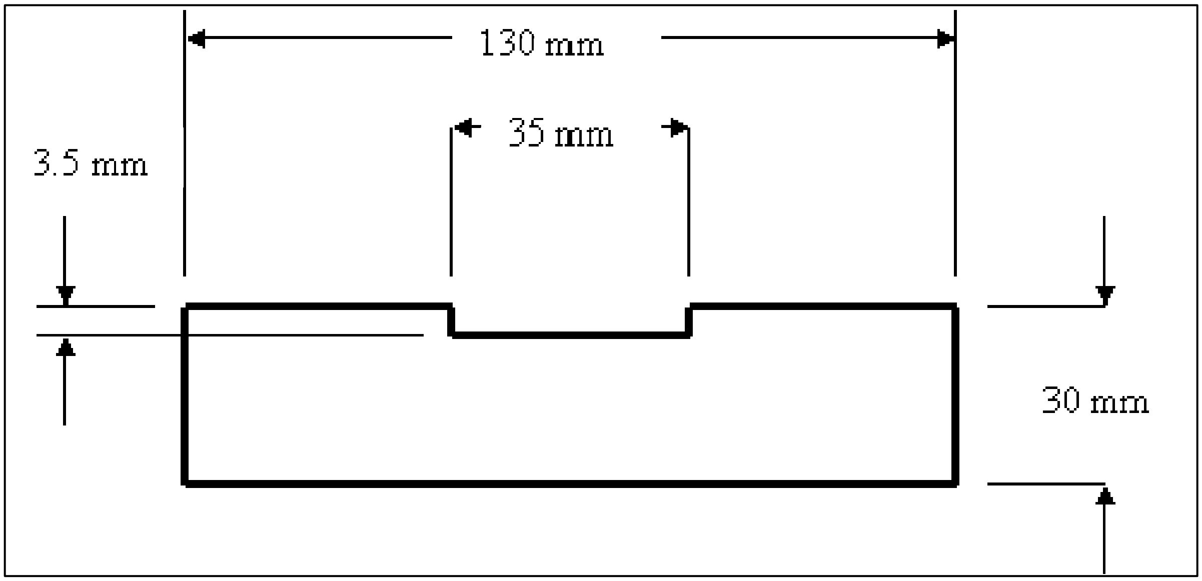

Figure 4 - Dimensions of Original FCB Bar Design Used by Pascagoula

Before the plates are positioned in the fixture, the primer is ground from the edges and end to clean the weld area. A large travel carriage containing the modified S-SAW electrodes, controller, and flux applicator traverse the joint while welding.

The following electrodes and flux types are used at NGSS - Pascagoula:

- Lincoln Electric L-61 electrode (AWS Electrode classification EM12K)
  - Lead Electrode Diameter: 3/16-in.
  - Trail Electrode Diameter: 1/8-in.
- Lincoln Electric 780 Flux (AWS Flux classification F7A2)

Benchmark welds were made on each plate thickness at Pascagoula; two 4-ft. by 4-ft. plates were tacked together with run-on and run-off tabs. Table 1 lists the root opening and welding parameters provided by NGSS for the 5-, 8-, and 10-mm S-SAW butt welds. Heat input calculated by the conventional method is also given in Table 1.

Table 1 - Benchmarked S-SAW Welding Parameters

Plate Thickness (mm)	Root Opening (mm)	Amperage	Voltage	Wire Feed Speed (ipm)	Travel Speed (ipm)	Heat Input (kJ/in)
5	4	600	33.5	48	20	60.3
8	4 to 5	725	36	54	16	97.9
10	5 to 6	800	36	60	14	123.4

Distortion measurements were made at NGSS - Pascagoula and are summarized in Table 2. Measurements were made by comparing before and after dimensions of the plates at the ends of the weld seam. From the results, the 8-mm plate registered the most bowing distortion (i.e., out-of-plane) and the 10-mm plate had the most transverse shrinkage.

Table 2 - Modified S-SAW Butt Weld Distortion Measurements

Plate Thickness (mm)	Transverse Shrinkage (in.)		Buckling Distortion (in.)	
	End 1	End 2	End 1	End 2
5	0.0313	0.0625	0.1875	0.1250
8	0.0625	0.0313	0.1875	0.6250
10	0.0938	0.1250	0.2500	0.3750

Photo macrographs of the weld cross-section were taken from each plate thickness and are shown in Figure 5 through Figure 7.

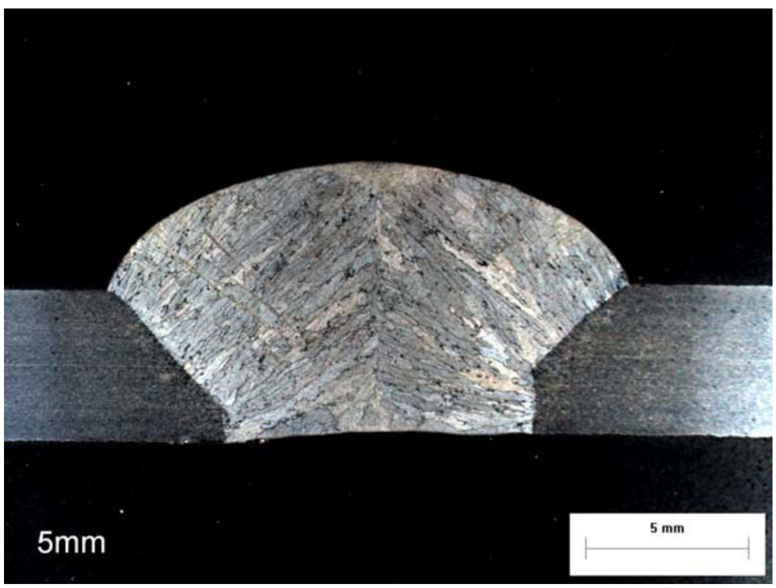

Figure 5 - Modified S-SAW Weld 5-mm Plate

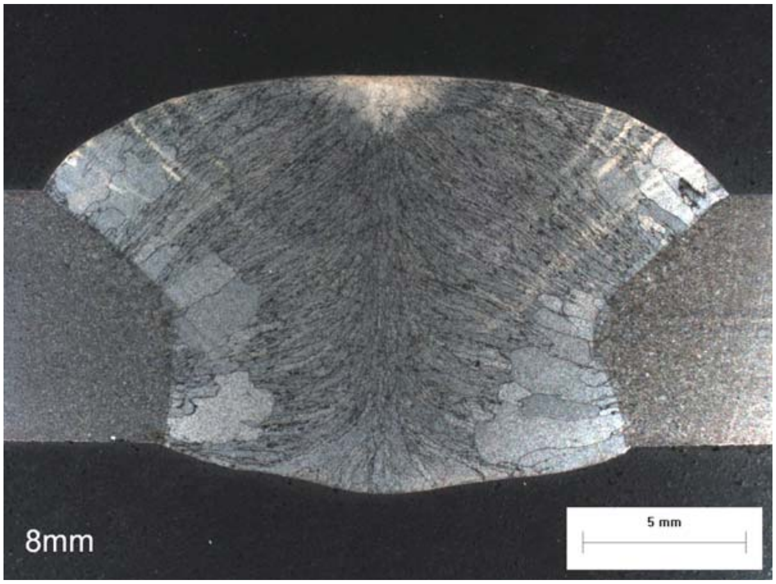

Figure 6 - Modified S-SAW Weld 8-mm Plate

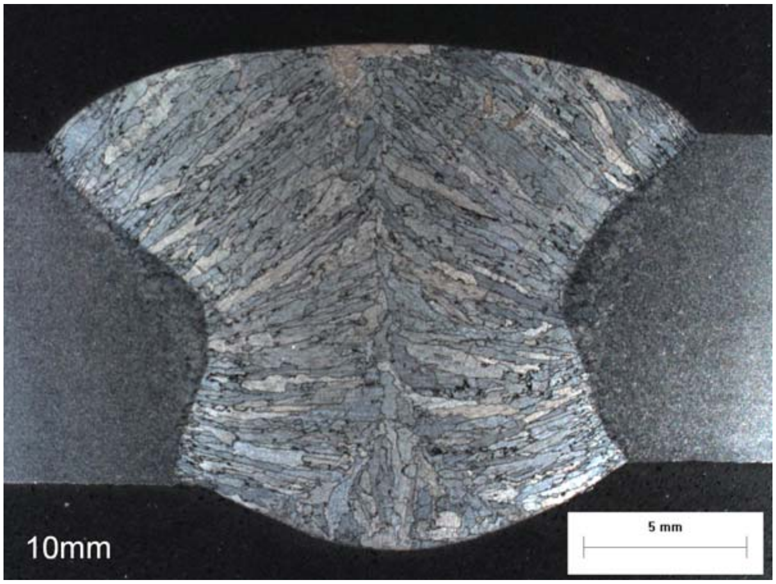

Figure 7 - Modified S-SAW Weld 10-mm Plate

Table 3 lists the dimensional measurements made from these cross-sections. Image-Pro software was used to measure weld area, top and bottom bead widths, and reinforcement heights. Reinforcement amount on the top surface was excessive, and for the 5-mm plate weld, negative reinforcement was measured on the root side.

Table 3 - S-SAW Bead Measurements

Plate Size (mm)	Top Reinforcement Height (mm)	Bottom Reinforcement Height (mm)	Total Weld Bead Area (mm^2)	Deposition Area (mm^2)	Top Bead Width (mm)	Root Bead Width (mm)	Base Metal Dilution %
5	3.83	-0.236	98.8	64.258	16.04	9.5	34.96
8	3.6	1.5	188.12	105.859	21.12	14.5	43.73
10	3.04	2.36	204.96	117.9	20.18	13.93	42.48

5.2 Tooling and Fixturing Development

A fixture was designed by EWI to be used for small scale NG butt joint welding of thin steel plate. Figure 8 shows a butt joint plate positioned in the EWI fixture (run-on and run-off tabs not shown) which is very similar to fixture design used at NGSS - Pascagoula. The fixture accommodated the 6-in. wide by 24-in. long plates provided by NGSS, as well as, the run-on and run-off tabs. Clamp spacing and plate contact area was copied from the NGSS panel line fixture, as well as support areas for the plate. Large toe clamps were used to hold down 0.5-in. x 6-in. x 14.5-in. steel blocks (similar to the hydraulic clamp sizes used by NGSS). These blocks were positioned approximately 1.25-in. from the weld centerline and spaced 4.5- to 5-in. apart. Two toe clamps were used to apply downward force on each plate; each clamp was tightened manually.

Figure 8 - Mock-up Plate Positioned in EWI Fixture

The NGSS FCB bar design was also used in the EWI fixture. Figure 9 shows the FCB bar and its location in the center of the fixture. Initial dimensions of the FCB bar are the same as those in Figure 4. (An improved FCB bar design was later used with a small parabolic groove measuring 0.75-in. wide and 0.09-in. deep. This topic is addressed in section 5.3.5).

Figure 9 - EWI Fixture with FCB Bar Centered

Figure 10 shows a close-up view of the ground cable attachments on the FCB bar. A layer of non-conducting ceramic was placed between the FCB and the fixture to force the current path to go from the plate through the FCB bar as opposed to traveling around the FCB bar through the fixture and clamps. The ground cables were placed on both sides of the FCB bar, separating the positive and negative leads.

Figure 10 - Electrical Grounding Arrangement on Improved FCB Bar

5.3 Tandem SAW Procedure Development

5.3.1 Overview

This task developed parameters using the high-speed narrow groove (NG) tandem submerged arc welding (SAW) process with flux copper backing (FCB). The tandem SAW process offers much higher deposition rates and travel speeds compared to single electrode SAW. A two electrode configuration was used in which the lead and trail electrodes are oriented in-line with respect to the welding direction and spaced a specified distance from each other. This is configuration is shown in Figure 11. The electrodes must be precisely arranged so they share a common weld pool.

The polarity used and current waveform shape is an important variable in the tandem SAW process. In order to minimize arc blow and interaction effects, AC-AC and DC-AC polarities were tested on the lead and trail arcs respectively. The effects of certain waveform variables such as balance, DC offset, and RMS current levels were also evaluated.

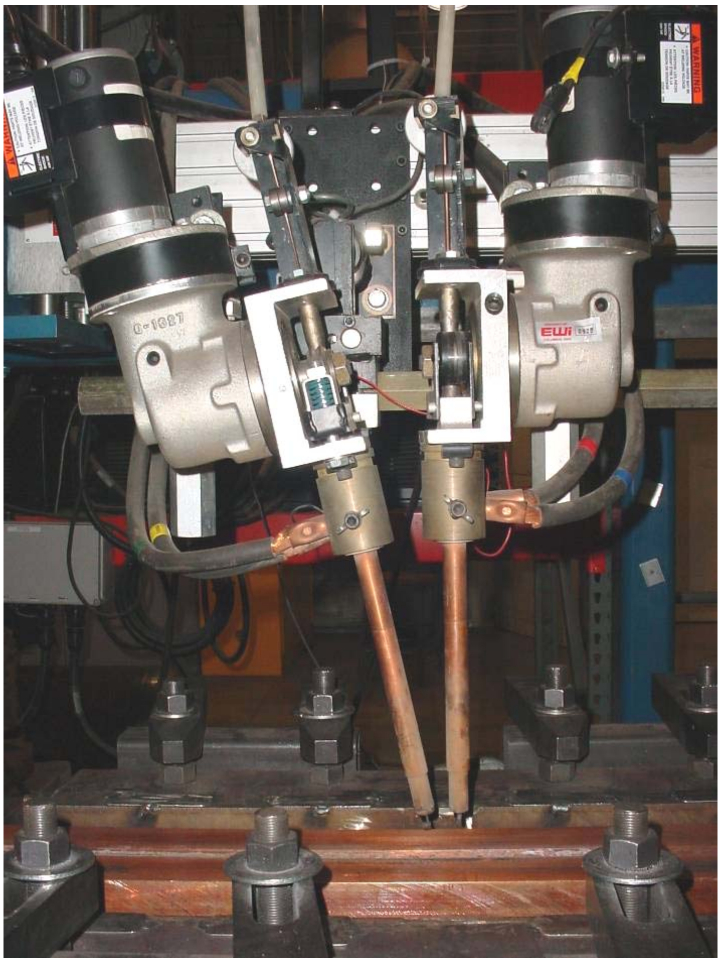

Figure 11 - Tandem SAW Torch Positioning

Other than the waveform variables, the design of the FCB groove was determined to be a critical variable affecting weld bead shape. In the middle of this project, the design of the FCB bar groove was changed to yield more desirable bead shape and weld quality. This was an important turning point in the project and is noted in the results.

5.3.2 Equipment and Set-up

Project work was conducted in a work area that contained the EWI fixture, FCB bar, travel carriage, weld controller, and power sources as shown in Figure 12.

The following welding equipment was used:

- Two Lincoln Electric PowerWave 500s connected to each electrode (four total)
- Pandjiris side beam and travel carriage
- Two Power Feed 10S wire feeders
- Lincoln Electric tandem arc framework assembly
- Two Lincoln Electric copper torch conduits
- Lincoln Electric microprocessor computer (for waveform and welding parameter control)

Figure 12 - Tandem SAW Work Area at EWI

For each electrode, two power sources were connected in a parallel configuration to provide the necessary current required by the process. (Note: The two power supply configuration has been replaced by one dedicated power source by Lincoln Electric on current and future models.) Since two electrodes were used, a total of four PowerWave 500s were employed. A microprocessor computer (controller) was used to control welding parameters such as voltage and current, as well as many additional waveform variables. Wire feed speed was determined by the controller. Since electrode melting rate was set by the waveform variables entered, the control adjusted wire feed speed during the process to maintain the set voltage. Most welds were performed using a square waveform shape rather than a sine wave.

Principle waveform variables are.

- **Balance:** This represents the time spent by the current in positive and negative polarities. For example, a 60/40 balance would mean that the electrode current experienced positive polarity 60% of the time and negative polarity 40% of the time.
- **RMS Current:** This is the root mean square value of the current delivered to the electrode. The RMS current is used in calculating the heat input for the tandem SAW process.
- **Phase Angle:** The phase angle refers to the temporal spacing of the current waveforms of the two electrodes. It is important that the phase angle not allow the two waveforms to be in-phase with each other. Careful setting of the phase angle helps minimize arc interaction effects that could be detrimental to the weld.
- **Frequency:** The number of complete cycles of the AC waveform in one second of time. Frequency is measured in Hertz (Hz). The frequency is usually adjusted to achieve arc stability. Changing the balance to certain settings will often require a change in frequency.
- **DC Offset:** This is the amount that the waveform current levels are shifted +/-. With a DC-AC configuration on the lead and trail arcs respectively, DC Offset will affect the bead width.

Figure 13 illustrates some of these concepts on a *Current vs. Time* plot.

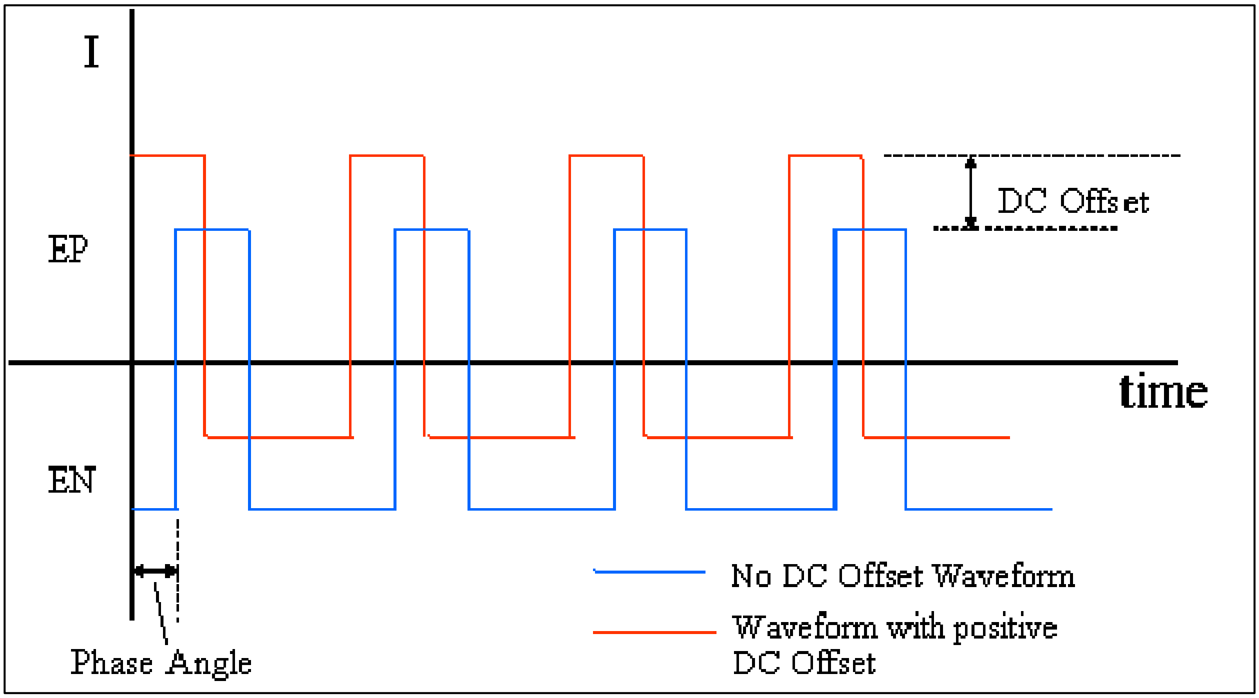

Figure 13 - Waveform Variables Used in Tandem SAW Development

The tandem SAW framework assembly was used to position the copper torch conduits in-line and accurately spaced with the correct angles. The lead copper conduit was positioned vertically straight (0° work and travel angle) and the trail copper conduit was positioned with a specified push travel angle and 0° work angle. Electrode spacing was measured by inching the wires out to the plate surface and measuring the center-to-center distance between them.

5.3.3 Materials

The materials used in this project consisted of the base plates, electrode, and flux. Each weld plate consisted of two 6-in. wide by 24-in. long steel plates tacked together using run-on and run-off tabs. All welds were made on square butt joints with varying root openings. The sides of the plates were milled flat and primer was ground off the top and bottom surfaces around the joint.

The following plate thicknesses and material types were used:

- 5-mm plate, DH-36 steel
- 8-mm plate, DH-36 steel
- 10-mm plate, EH-36 steel

The following welding consumables were used:

- Lincoln Electric L-61 electrode (AWS designation EM12K)
- 761 flux (AWS designation F7A2)

Depending on the FCB groove design used, different electrode diameters were used. Welds made with the original FCB groove design used a 3/16-in. diameter lead electrode and a 1/8-in. diameter trail electrode. Welds made with the improved FCB groove design used a 5/32-in. diameter lead and a 3/32-in. diameter trail electrode.

5.3.4 Original FCB Groove Design Procedure Development and Results

All welds in this section were made using the original FCB groove design with the dimensions shown in Figure 4. The square groove in the copper bar was filled with flux up to a nominal 3-mm height above the bar surface. Plates were then laid into the fixture with the root opening compressed on the flux bed. Electrode sizes were 3/16-in. diameter and 1/8-in. diameter for the lead and trail, respectively. Run-on and run-off tabs were used for most welds. The on/off tabs were welded to the ends of the plate and used to help maintain the gap during welding. If no run-on or run-off tabs were used, then tack welds were made at the ends and middle of the joint to help maintain root openings.

Initial welding trials for each plate thickness used a 50-50 balance AC waveform on both lead and trail electrodes (AC-AC) as a starting point. Initial contact tip-to-work distance, electrode spacing, trail electrode travel angle, and root opening values were based closely on recommendations in the 13th edition of The Procedure Handbook of Arc Welding published by Lincoln Electric. These values were changed during welding in order to improve arc stability and weld bead quality.

Appendix A lists the parameters used for all butt welds made with the original FCB groove design. Unless otherwise noted, the waveform frequency was 80 Hz and the phase angle between the two electrode waveforms was 90° out-of-phase. In some trials for the 5-mm plate, the lead electrode was switched to 1/8-in. diameter (the same as the trail).

For each material thickness, Table 4 contains the range of root openings, travel speeds, and RMS currents tested at the 50-50 balance for each electrode using the tandem SAW process.

Table 4 - Root Openings, Travel Speeds, and RMS Current Ranges Evaluated

Plate Thickness (mm)	Root Opening Range (mm)	Travel Speed Range (ipm)	RMS Current Range	
			Lead (amps)	Trail (amps)
5	0.0 - 4.0	30 - 65	350 - 750	300 - 500
8	3.0 - 6.2	35 - 50	650 - 900	500 - 700
10	4.0 - 5.0	30 - 40	700 - 950	500 - 650

Almost all welds suffered from some type of defect or inconsistency with the root bead. The most common defect was root bead suck-back. A macrograph with typical suck-back is shown in Figure 14. Several steps were attempted to overcome the suck-back defect. Increasing or decreasing RMS current and travel speed, varying the balance, using wider root openings, and even adjusting the electrode spacing and contact tip-to-work distance (CTWD) did not effectively eliminate all occurrences of suck-back.

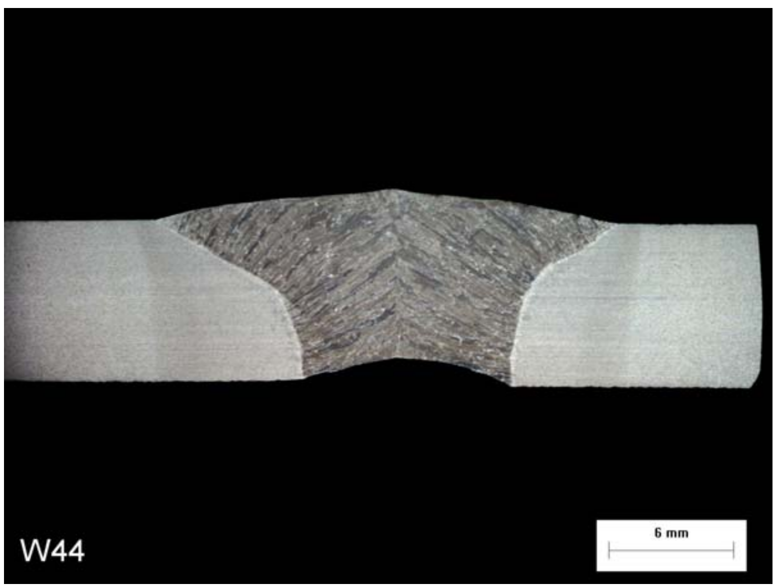

Figure 14 - Weld with Typical Root Bead Suck-Back

Repeatability of the welds was also a problem. When a good weld was obtained, it was very hard to repeat in terms of bead shape and overall quality. Figure 15 shows the root side of two welds each made with the same joint fit-up and welding parameters. W39 had good root bead penetration, but W41 had extreme suck-back along the entire weld length. Inconsistency along the length of the weld was also a factor. Many welds had good start and end bead shapes but exhibited suck-back in the middle portion of the joint.

Figure 15 - Inconsistent Suck-Back Defects on Welds Made with Identical Parameters

Figure 16 shows three welds that illustrate this problem. The middle portion of each weld has more pronounced suck-back than the ends.

Figure 16 - Welds with Pronounced Suck-Back in the Middle Span

Suck-back and repeatability problems may result from the compression of the plates onto the flux backing. The pressure exerted by the flux may force the weld bead to suck-back from the root side. Faster travel speeds and cooling rates may also contribute to this condition. Tests were performed with varying levels of flux height on the FCB. Leaving the flux level flush with the FCB bar surface had the greatest effect on eliminating suck-back. Inconsistency and repeatability problems still occurred, and the root bead was found to over-penetrate with excessive reinforcement in some areas. Based on these observations, the FCB groove design and flux fill procedures were found to play a major role in weld quality.

Since suck-back and inconsistency problems with tandem SAW could not be fixed, single electrode SAW was performed to further investigate the phenomena. Welds were performed on 5-mm plate butt joints using parameters listed in Appendix A. Single wire SAW welds did not exhibit the same suck-back or inconsistency problems as those made with the tandem SAW process on the original FCB groove design, perhaps due to the slower travel speeds inherent to the process.

The best single wire process parameters were determined as follows:

- Wire Diameter: 3/16-in.
- CTWD: 1.25-in.
- RMS Current: 650 A (square waveform)
- Balance: 50-50 AC
- Voltage: 35 V
- Travel Speed: 32 ipm
- Root Opening: 0-mm (no gap)

5.3.4.1 Analysis of High-Speed Tandem SAW Process with Original FCB Groove

With the original FCB groove design and backside flux compression, welds made with the high-speed tandem SAW process exhibited several detrimental problems. Root bead suck-back, poor weld repeatability, and inconsistency along the weld length were issues that frequently occurred. Efforts made to resolve these issues were unsuccessful. The exact cause of these problems is unknown, but is most likely to involve factors such as the FCB groove design, backside flux compression, and the higher travel speeds. Single wire SAW was more successful in achieving better weld quality and bead shape using the original FCB groove design.

5.3.4.2 Consultation with The Lincoln Electric Company

After considerable experimentation, a consultation with The Lincoln Electric Company representatives was undertaken to discuss ways to resolve the suck-back and inconsistency problems and to improve the FCB bar groove design. The original FCB bar groove design was made for modified S-SAW welding in which wide root openings and slow travel speeds are commonly used. For the high-speed tandem SAW process, a FCB groove that accommodates the smaller root openings and faster speeds should be used. Lincoln Electric has experienced success with alternate FCB groove designs and proposed two options: one for 5-mm plate and another for 8- and 10-mm plate thicknesses. Figure 17 is an illustration of the 5-mm FCB groove design; Figure 18 is the 8- and 10-mm groove design.

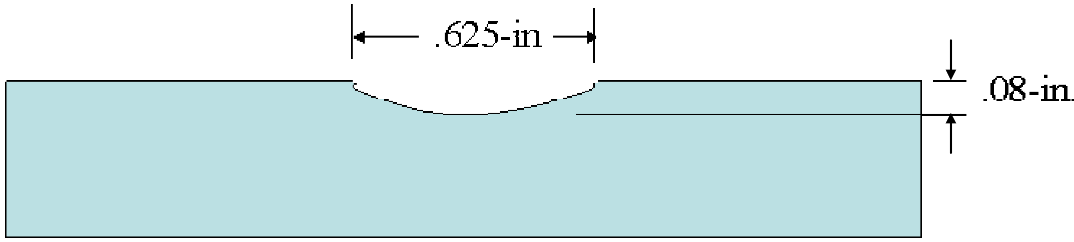

Figure 17 - Lincoln Recommended FCB Groove for 5-mm Square Butt Joints

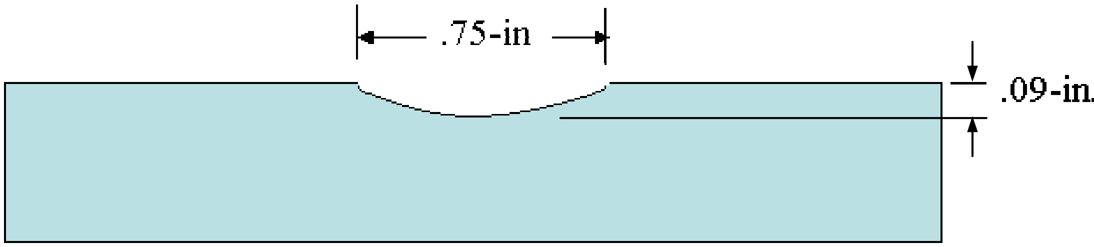

Figure 18 - Lincoln Recommended FCB Groove for 8- and 10-mm Square Butt Joints

The design for the 8- and 10-mm plates was selected for use with all plate thicknesses. Lincoln Electric recommended that the flux be filled only to the top of the FCB bar surface (avoiding any compression of flux against the weld root) and recommended changing electrode diameters to a 5/32-in. lead and a 3/32-in. trail.

The polarity and balance for the electrodes was also discussed. Lincoln was not sure if an AC-AC waveform would provide enough heat to penetrate through the plates. They suggested that the plate thicknesses, root opening, and joint design may necessitate the use of DC+ polarity on the lead electrode to achieve full penetration.

5.3.5 Improved FCB Groove Design Procedure Development and Results

The copper bar used in the previous experiments was turned over and a new groove with the dimensions in Figure 18 was machined. Before welding, the groove was filled with flux and the top surface of the FCB bar was scraped flush. 5/32-in. diameter and 3/32-in. diameter electrodes were used on the lead and trail arcs, respectively.

Appendix B contains the welding parameters and joint fit-ups for each weld made with the improved FCB groove design. Square butt joints with variable root openings were used for all welds. Primer was ground off the top and bottom of each plate. Run-on and run-off tabs were used for all welds made with the improved FCB groove design. The sections below provide details on the procedure, welding, distortion, and qualification results for each plate thickness.

5.3.5.1 5-mm Procedure

Initially single wire DC+ parameters were run in order to obtain an estimate of the amount of current needed to achieve penetration, as well as, to determine a starting point for travel speed. Initial tandem SAW welds with DC+ polarity on the lead electrode and 50-50 AC balance on the trail provided too much penetration on the 5-mm plate. The lead electrode polarity was switched to AC with a 50-50 balance (trail electrode also at 50-50 AC balance) and tests were performed to maximize travel speed with these polarities.

Table 5 lists the parameters for the developed AC-AC procedure using 50% electrode positive (EP) on both electrodes (W96). Figure 19 shows the macrograph of weld W96. Penetration was complete, root bead shape was very consistent along the entire weld length, and no suck-back was observed. The root bead also appeared to be a bright silver color compared to the dull gray color of the welds made with the original FCB bar. Subsequent tests were run to repeat the weld, all of which produced similar weld beads, demonstrating a high degree of repeatability for high-speed tandem SAW with the improved FCB bar design.

Table 5 - W96 Parameters (5-mm Plate)

WELD ID	Plate Thickness (mm)	Root Opening (mm)	Wire Separation (in.)	TRAVEL SPEED (ipm)	Combined Heat Input (kJ/inch)	Lead WFS (ipm)	Trail WFS (ipm)	DATA ACQ FILENAME
W96	5	1.9 to 2.0	0.78	55	41.9	60	180	_10-21-05_10.06.59.txt
	------------------------------LEADING WIRE PARAMETERS------------------------------							
	Wire Dia (in.)	Trav. Angle (degr.)	Tip-to-Work (in.)	Waveform, %EP, DCOffst	RMS Current SETPOINT	VOLT SETPOINT		
	0.15625	0	1.25	CC sq, bal=50%, DCOffs=0	650	33		
	----------------------------TRAILING WIRE PARAMETERS----------------------------							
	Wire Dia (in.)	Trav. Angle (degr.)	Tip-to-Work (in.)	Waveform, %EP, DCOffst	RMS Current SETPOINT	VOLT SETPOINT		
	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34		

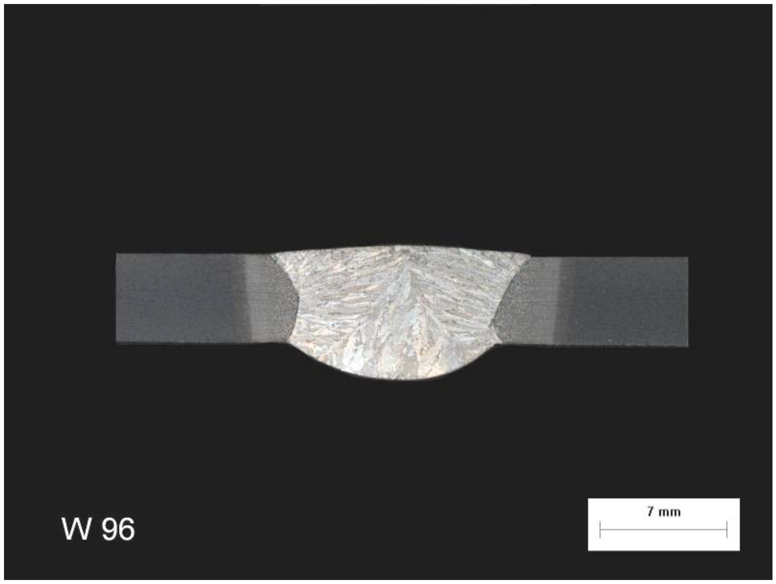

Figure 19 - Macrograph of Weld on 5-mm Plate (W96)

Additional welds were run using a 50-50 AC balance on the lead electrode and a 40-60 (40% EP) AC balance on the trail for added electrode deposition and slightly less root bead reinforcement. While keeping all the aforementioned benefits of the W96 procedure, this procedure allowed better bridging of wider root openings and was selected as the *preferred* 5-mm procedure; parameters are listed in Table 6 (W108). The macrograph of weld W108 is shown in Figure 20. Table 7 lists the bead measurements.

Table 6 - Preferred 5-mm Plate Procedures (W108)

WELD ID	Plate Thickness (mm)	Root Opening (mm)	Wire Separation (in.)	TRAVEL SPEED (ipm)	Combined Heat Input (kJ/inch)	Lead WFS (ipm)	Trail WFS (ipm)	DATA ACQ FILENAME
W108	5	1.9 to 2.0	0.78	55	41.4	60	190	_10-27-05_08.35.19.txt
	------------------------------LEADING WIRE PARAMETERS------------------------------							
	Wire Dia (in.)	Trav. Angle (degr.)	Tip-to-Work (in.)	Waveform, %EP, DCOffst	RMS Current SETPOINT	VOLT SETPOINT		
	0.15625	0	1.25	CC sq, bal=50%, DCOffs=-8200	650	33		
	----------------------------TRAILING WIRE PARAMETERS---------------------------							
	Wire Dia (in.)	Trav. Angle (degr.)	Tip-to-Work (in.)	Waveform, %EP, DCOffst	RMS Current SETPOINT	VOLT SETPOINT		
	0.09375	12	1.250	CC sq, bal(+)=40%, DCOffs=-8200, Phase=105 deg	500	33		

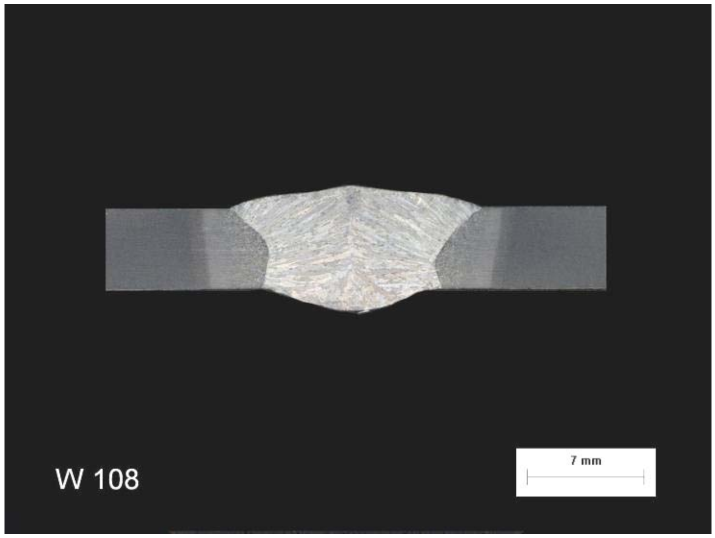

Figure 20 - Weld Made with Preferred 5-mm Plate Procedures (W108)

Table 7 - Bead Measurements with Preferred 5-mm Plate Procedures (W108)

W108 Plate Size (mm)	Top Reinforcement Height (mm)	Bottom Reinforcement Height (mm)	Total Weld Bead Area (mm^2)	Deposition Area (mm^2)	Top Bead Width (mm)	Root Bead Width (mm)	Base Metal Dilution %
5	1.31	1.34	77.66	30.853	15.3	11	62.5

Gap Weldability

Gap weldability tests were performed by varying the root opening of the butt joint. The nominal gap used for the 5-mm welds was 2.0-mm. Tests were run on 0.0- to 3.0-mm wide root openings with the same welding parameters as in Table 6. The developed 5-mm procedure successfully bridged gaps from 2.0- to 3.0-mm (macro shown in Figure 21). The procedure was able to penetrate down to a gap of 1.4-mm, but the arc became slightly unstable (due to inconsistent wire feed) and the root bead width was small compared to the other welds (macro shown in Figure 22).

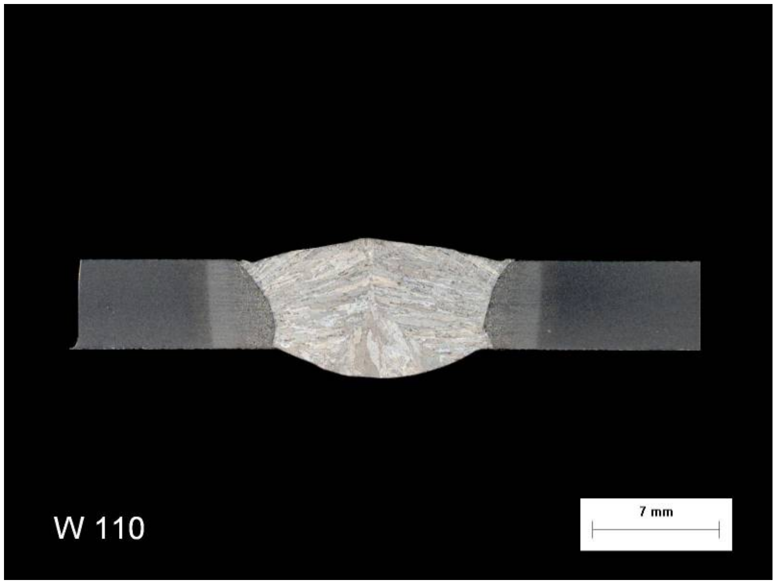

Figure 21 - Weld with 3.0-mm Root Opening on 5-mm Plate

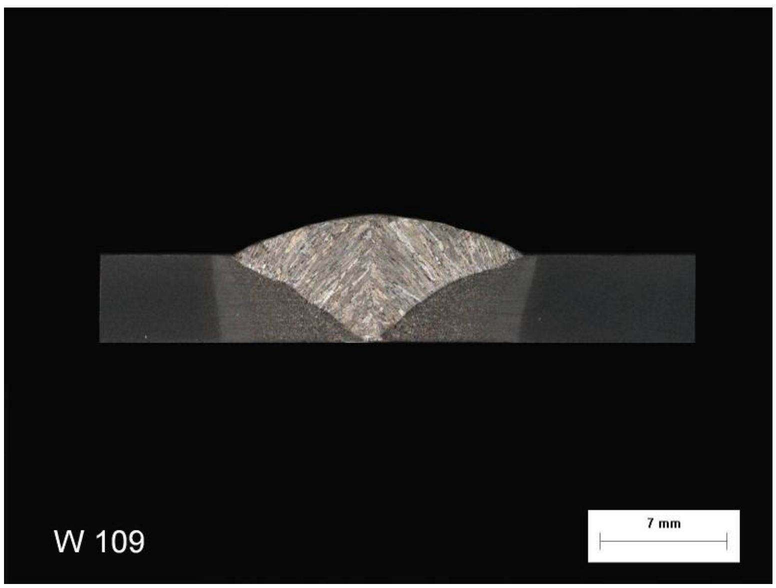

Figure 22 - Weld with 1.4-mm Root Opening on 5-mm Plate

At the request of NGSS, a procedure for a zero gap butt joint was developed for the 5-mm plate. Several current levels and waveform variables were adjusted to attempt a successful tandem SAW weld with no gap. The process was not able to penetrate the plate unless travel speed was slowed considerably or RMS current was increased (both of which increase heat input and distortion potential). When penetration was full and complete, the level of bead quality was not the same as with the AC-AC procedures developed previously with root openings.

5.3.5.2 8-mm Procedure

DC+ polarity was used on the lead electrode with a 50-50 AC balance on the trail. Initial welds performed with this configuration yielded good results, so work was focused on maximizing travel speed with a DC-AC configuration. With this configuration, the trail electrode polarity balance was always kept at 50% EP and 50% electrode negative (EN). This was done to minimize arc blow effects resulting from different balance amounts. RMS current values and DC offset were varied during the tests.

DC offset was typically kept at 0 for most tests. The effect of DC offset on wire feed speed is shown in Figure 23 (wire feed speed (WFS) was measured from the 3/32-in. diameter trail electrode operating at 500 amps RMS current and 50% EP balance (values listed in Appendix C). While lower (less than 0) offset values did not significantly affect the wire feed, higher offset values did. Less deposition was experienced with higher DC offset values, which would necessitate a reduction in travel speed if all other variables are kept the same.

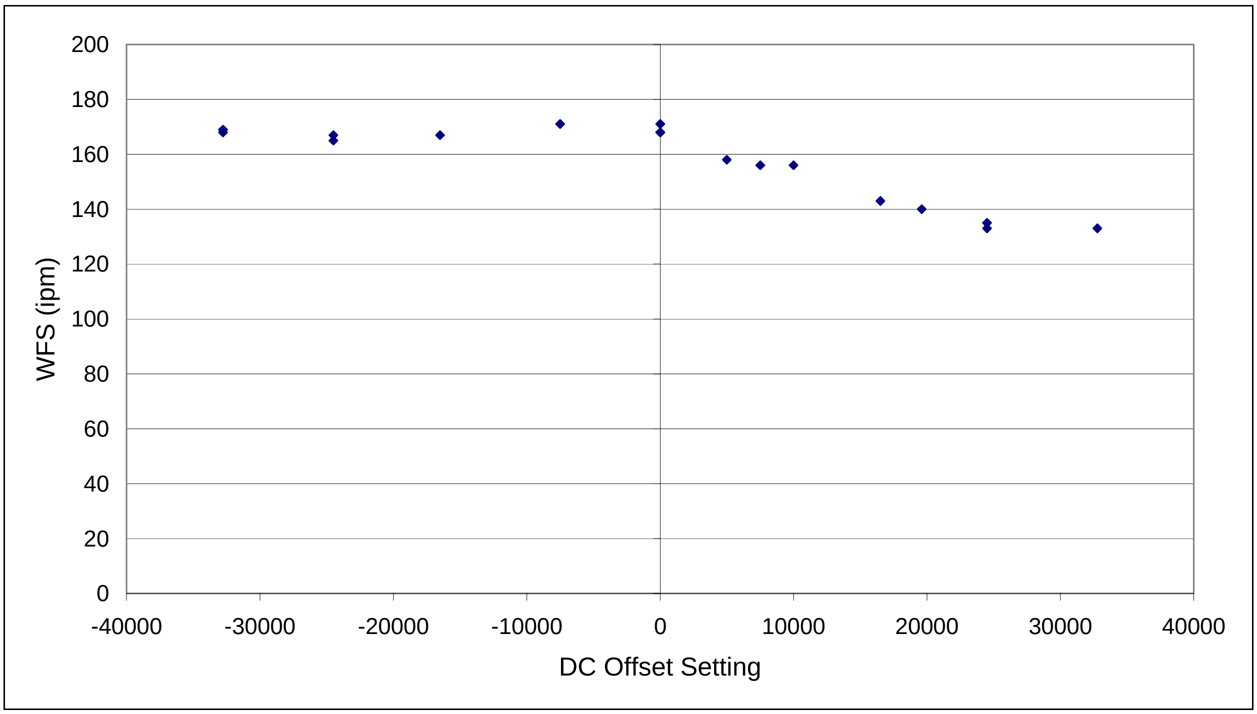

Figure 23 - Effect of DC Offset on Wire Feed Speed of Trail Electrode

Table 8 lists the parameters for the preferred 8-mm procedure (W97). Bead shape was very consistent along the weld length and exhibited good root bead penetration with no visible defects or discontinuities. Figure 24 shows a macrograph of the W97 weld. Table 9 lists the bead measurements. This weld was repeated successfully several times.

Table 8 - Preferred 8-mm Plate Procedure (W97)

WELD ID	Plate Thickness (mm)	Root Opening (mm)	Wire Separation (in.)	TRAVEL SPEED (ipm)	Combined Heat Input (kJ/inch)	Lead WFS (ipm)	Trail WFS (ipm)	DATA ACQ FILENAME
W97	8	3.4 to 3.3	0.78	35.0	72.9	62	175	_10-21-05_11.01.49.txt
	-------------------------------LEADING WIRE PARAMETERS-------------------------------							
	Wire Dia (in.)	Trav. Angle (degr.)	Tip-to-Work (in.)	Waveform, %EP, DCOffst	RMS Current SETPOINT	VOLT SETPOINT		
	0.15625	0	1.25	CC DC+	750	34		
	-----------------------------TRAILING WIRE PARAMETERS----------------------------							
	Wire Dia (in.)	Trav. Angle (degr.)	Tip-to-Work (in.)	Waveform, %EP, DCOffst	RMS Current SETPOINT	VOLT SETPOINT		
	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34		

Figure 24 - Weld Made with 8-mm Preferred Procedures (W97)

Table 9 - Bead Measurements with Preferred 8-mm Procedures (W97)

W97 Plate Size (mm)	Top Reinforcement Height (mm)	Bottom Reinforcement Height (mm)	Total Weld Bead Area (mm^2)	Deposition Area (mm^2)	Top Bead Width (mm)	Root Bead Width (mm)	Base Metal Dilution %
8	1.34	1.25	137.03	50.53	21.05	11.4	63.1

Gap Weldability

The preferred 8-mm procedure (W97) incorporated a nominal 3.0-mm root opening. Gap weldability tests were performed by varying the root opening from 1.2-mm to 5.5-mm. Root bead penetration was found to be complete over the entire range of root openings, with the lower end of the range (less than 1.5-mm gap) not demonstrating the same bead shape quality as the rest of the root openings tested. The range of root openings that the 8-mm procedure successfully bridged and produced high quality bead shape in this experiment was between 2.0-mm and 5.0-mm (macros shown in Figure 25 and Figure 26 respectively).

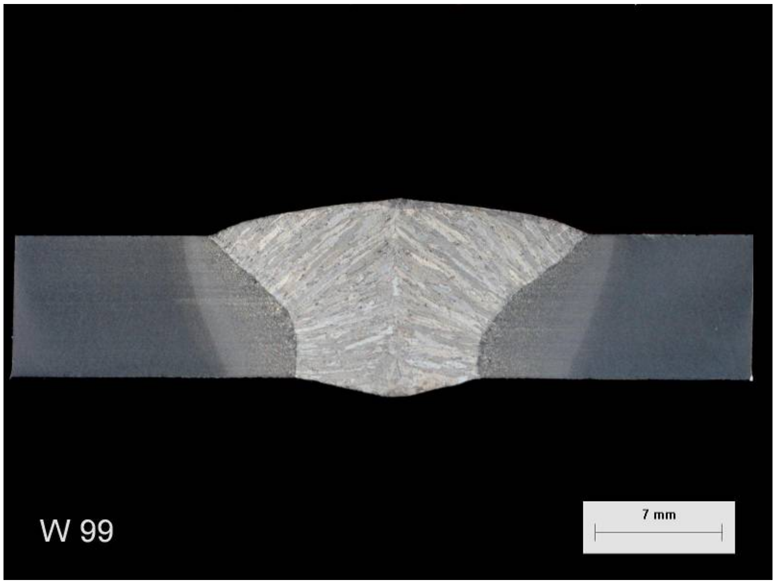

Figure 25 - Weld with 8-mm Procedures and 2.0-mm Root Opening

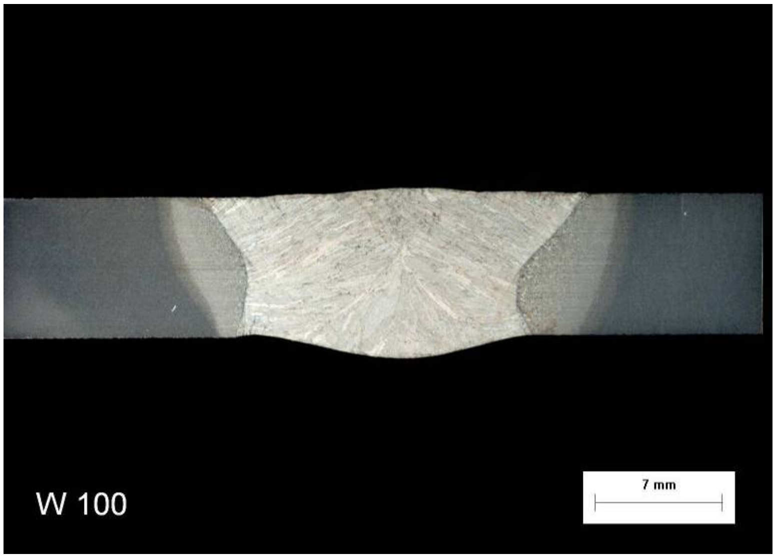

Figure 26 - Weld with 8-mm Procedure and 5.0-mm Root Opening

5.3.5.3 10-mm Procedure

Procedure development for the 10-mm plate was similar to that of the 8-mm plate. DC+ polarity was run on the lead electrode using a 50-50 AC balance on the trail. RMS current values, root openings, and DC offset were varied during the experiment to obtain a high travel speed tandem SAW procedure.

Table 10 lists the parameters for the preferred 10-mm procedure (W98). Bead shape was very consistent along the entire weld length and exhibited good root bead penetration with no visible defects or discontinuities. Figure 27 shows a macrograph of the W98 weld. Table 11 lists the bead measurements. This weld was repeated successfully several times.

Table 10 - Preferred 10-mm Plate Procedure (W98)

WELD ID	Plate Thickness (mm)	Root Opening (mm)	Wire Separation (in.)	TRAVEL SPEED (ipm)	Combined Heat Input (kJ/inch)	Lead WFS (ipm)	Trail WFS (ipm)	DATA ACQ FILENAME
W98	10	3.8 to 4.0	0.78	30.0	88.4	70	175	_10-21-05_13.03.36.txt
	------------------------------LEADING WIRE PARAMETERS------------------------------							
	Wire Dia (in.)	Trav. Angle (degr.)	Tip-to-Work (in.)	Waveform, %EP, DCOffst	RMS Current SETPOINT	VOLT SETPOINT		
	0.15625	0	1.25	CC DC+	800	34		
	----------------------------TRAILING WIRE PARAMETERS----------------------------							
	Wire Dia (in.)	Trav. Angle (degr.)	Tip-to-Work (in.)	Waveform, %EP, DCOffst	RMS Current SETPOINT	VOLT SETPOINT		
	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34		

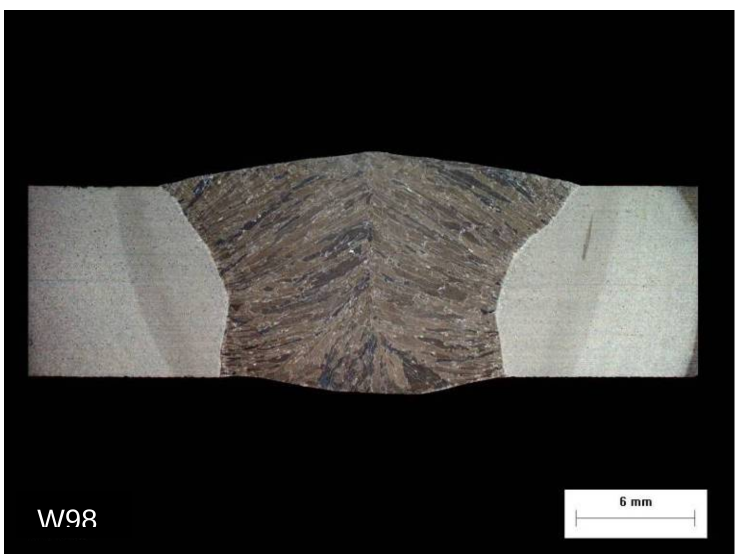

Figure 27 - Weld Made with 10-mm Preferred Procedure (W98)

Table 11 - Bead Measurements with Preferred 10-mm Procedures (W98)

W98 Plate Size (mm)	Top Reinforcement Height (mm)	Bottom Reinforcement Height (mm)	Total Weld Bead Area (mm^2)	Deposition Area (mm^2)	Top Bead Width (mm)	Root Bead Width (mm)	Base Metal Dilution %
10	1.76	0.834	181	67.77	21.45	14.45	62.5

In addition, several tests were performed to develop a set of AC-AC parameters for the 10-mm plate (see tests W94, W95, and W103 in Appendix B). Parameters were obtained that produced acceptable welds in terms of bead shape and quality, but not as good as the quality level of the DC-AC welds. In addition, the AC-AC parameters did not provide a significant reduction in heat input compared to the DC-AC parameters. For that reason, the DC-AC parameters were selected for the preferred 10-mm procedure.

Gap Weldability

The preferred 10-mm procedure (W98) incorporated a nominal 4.0-mm root opening. Gap weldability tests were performed by varying the root opening from 1.5-mm to 6.0-mm. Root bead penetration was found to be complete over the entire range of root openings, with the lower end of the range (less than 2.2-mm gap) not having the same bead shape quality as the rest of the root openings tested. The range of root openings that the 10-mm procedure successfully bridged and produced high quality bead shape in this experiment was between 3.0-mm and 5.5-mm. Macros of a 3.0-mm root opening and a 6.0-mm root opening are shown in Figure 28 and Figure 29 respectively. A root opening of 6.0-mm resulted in some undercut on the root bead side, likely resulting from lack of fill. Root openings less than 3.0-mm still produced high quality welds, but the level of repeatability was not as high as with larger root openings.

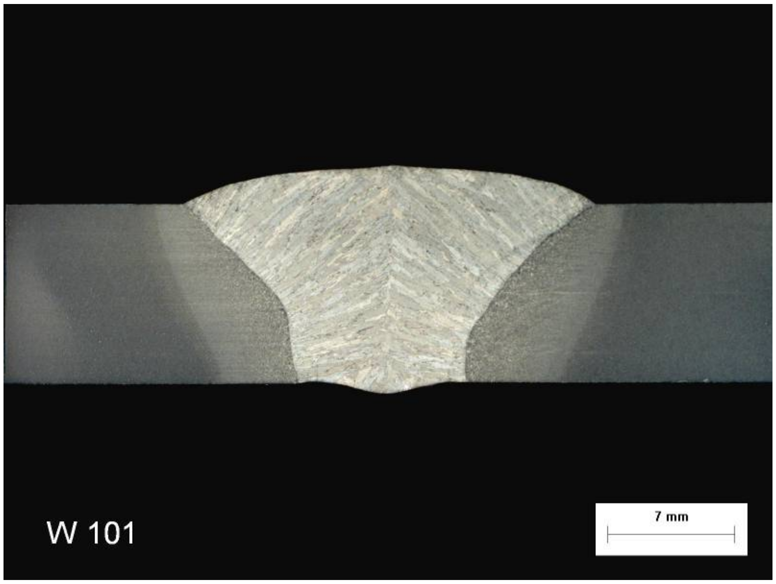

Figure 28 - Weld with 10-mm Procedure and 3.0-mm Root Opening

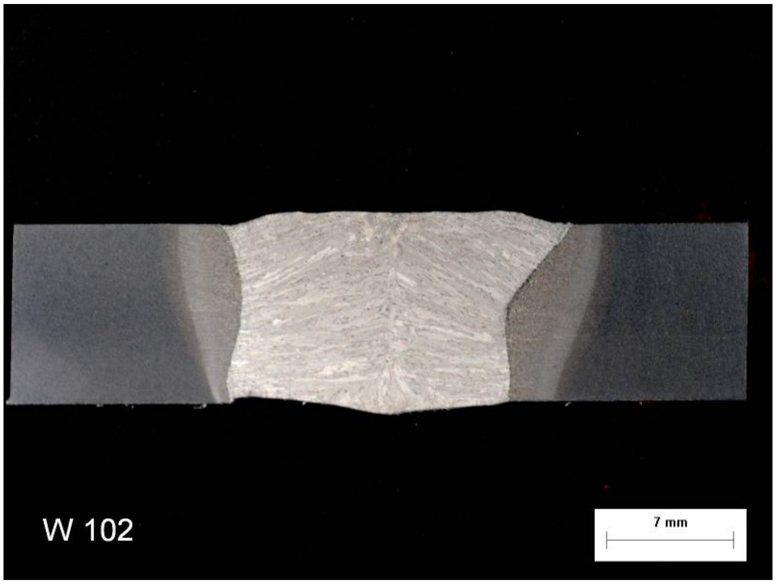

Figure 29 - Weld with 10-mm Procedure and 6.0-mm Root Opening

5.3.5.4 Distortion Measurements

Before and after distortion measurements were taken on plates W96, W97, and W98. A ROMER arm (Figure 30) was used to measure the out-of-plane distortion (z coordinate) from a selected reference point on the plate.

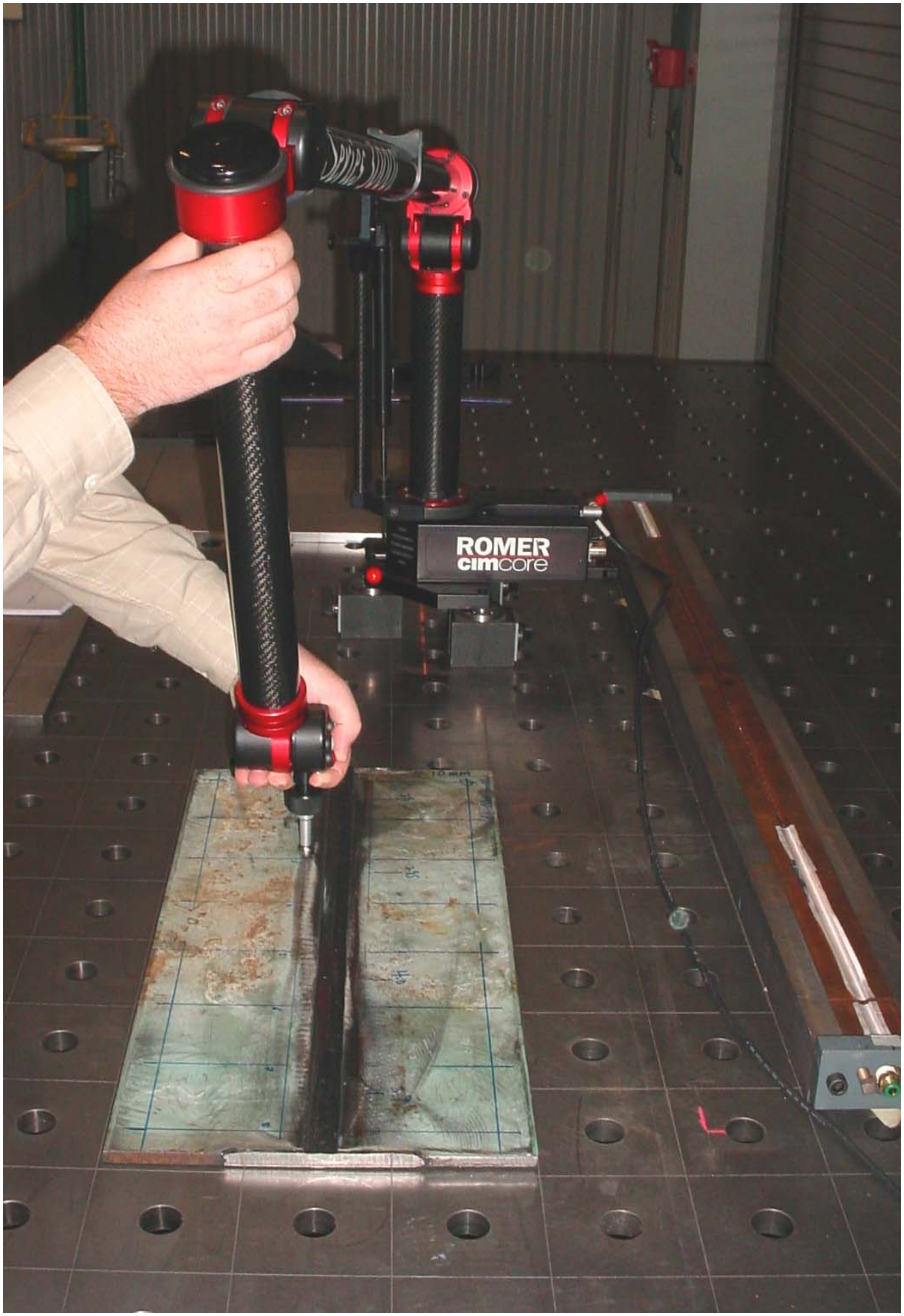

Figure 30 - ROMER Arm Coordinate Measuring System

Figure 31 shows a layout of the weld plate and the location of the distortion points measured (32 total points). Point 1 is the reference point.

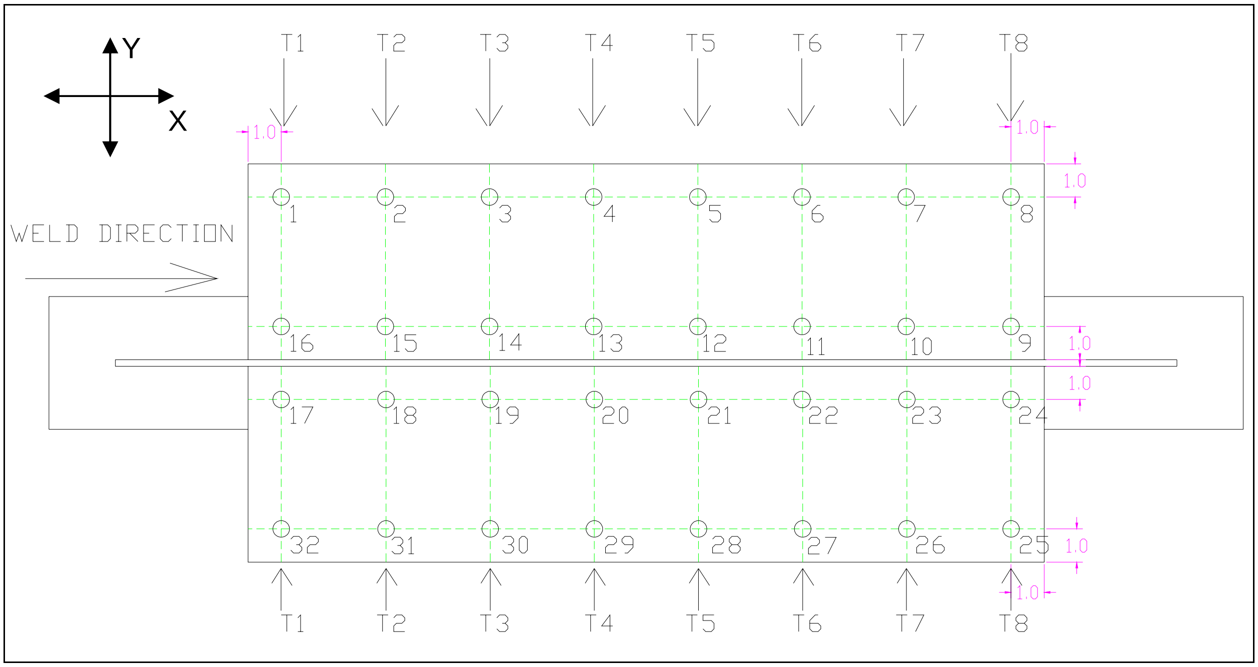

Figure 31 - Distortion Measurement Locations

The W96 test weld represents the worst case distortion of all 5-mm plates welded using both the W96 procedures and the preferred W108 procedures. Figure 32 shows a three-dimensional graph of the distortion for the 5-mm weld W96. Before weld distortion measurements are listed in Appendix D; after weld values are in Appendix E. Reference point 1 corresponds to the 0, 0, 0 location on the graph. The maximum out-of-plane distortion measured was in the middle of the plate where it bowed approximately 0.4-in. (10-mm) above the original location. However, even when welded using the same procedures, the 5-mm plates did not always exhibit the same degree of distortion. Most plates had flexible buckling, in which the plate could be flexed in two positions, rather than being locked into one stiff position.

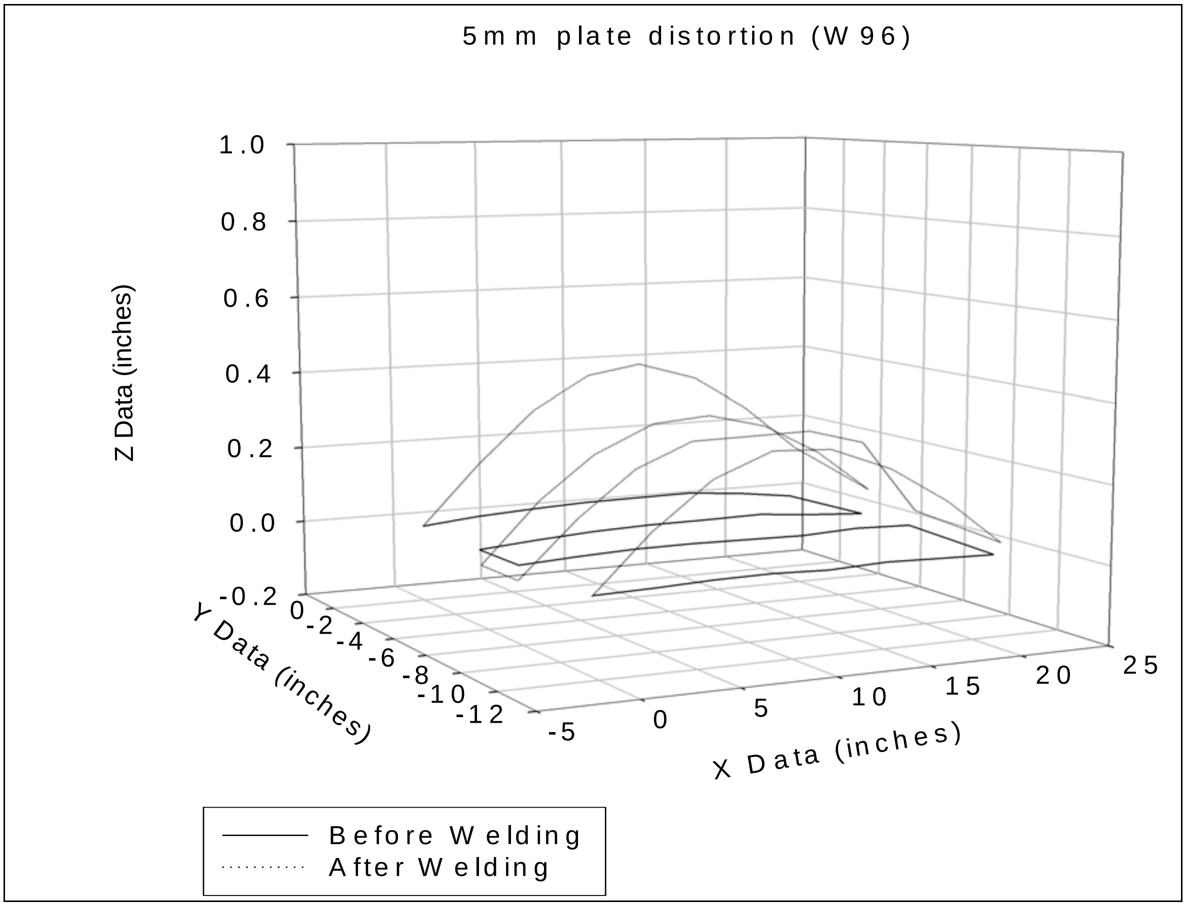

Figure 32 - 3-D Graph of Distortion Before and After Weld (5-mm Plate W96)

The W97 and W98 welds were made using the preferred 8- and 10-mm procedures and root openings. These plates did not exhibit much out-of-plane distortion. Figure 33 shows the three-dimensional graphs of the distortion for the 8-mm plate (W97). Before weld distortion measurements are listed in Appendix F; after weld values are in Appendix G. Figure 34 show three-dimensional graphs of the distortion for the 10-mm plate (W98). Before weld values are listed in Appendix H; after weld values are in Appendix I.

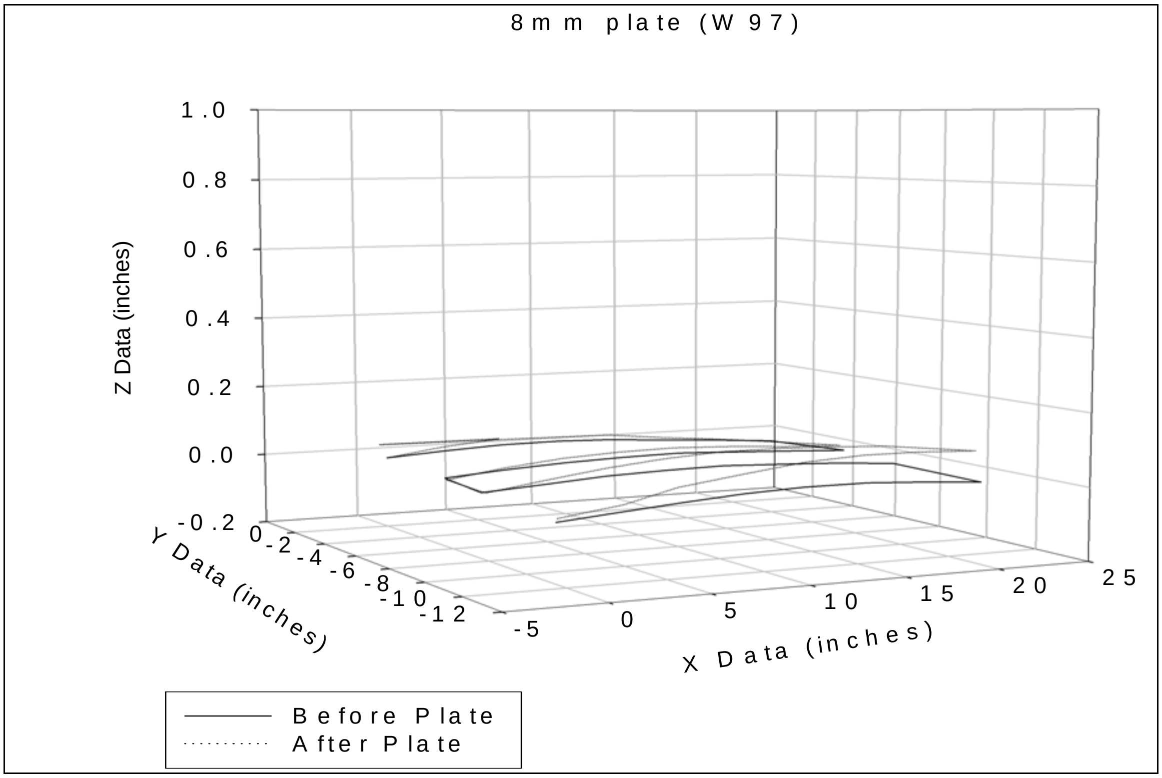

Figure 33 - 3-D Graph of Distortion Before and After Weld (8-mm Plate W97)

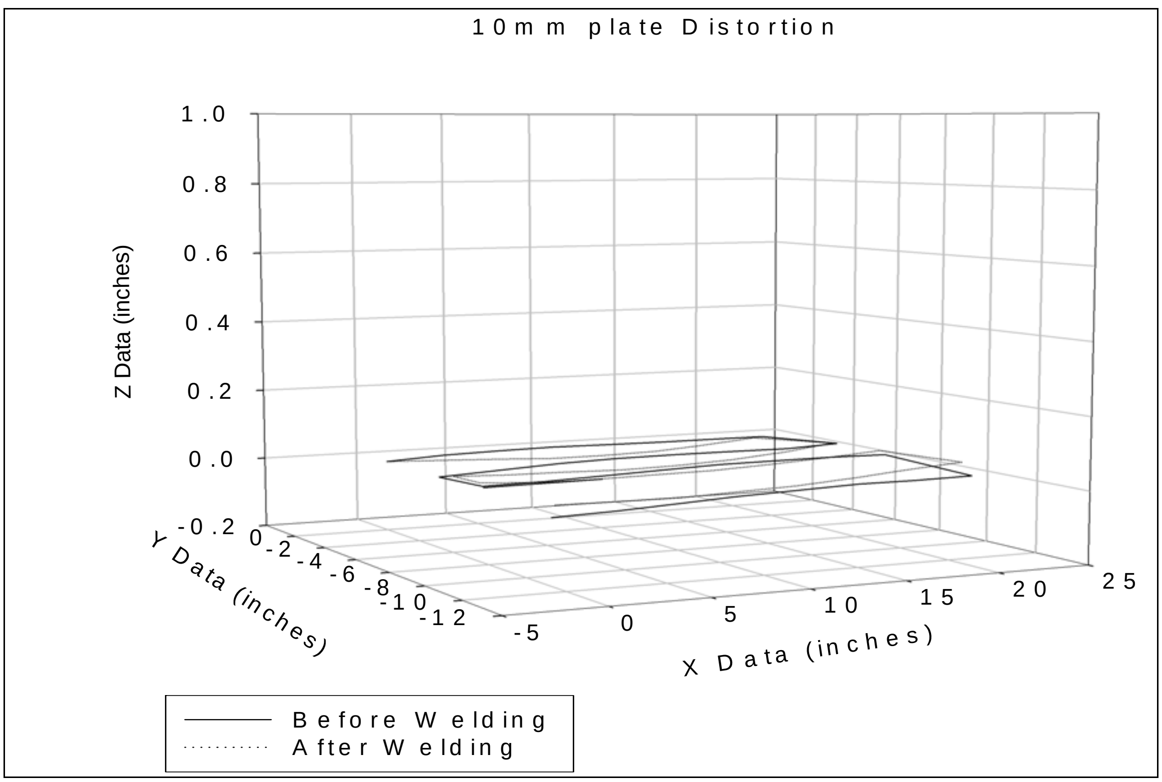

Figure 34 - 3-D Graph of Distortion Before and After Weld (10-mm Plate W98)

Transverse shrinkage measurements were made by measuring eight end locations along the length of the plate (shown in Figure 31 as points T1 through T8). Since the plate sizes were small and the clamps were not hydraulic (supplied less hold down force), the plates had a tendency to pull towards the center of the weld. This may have affected the root opening of the joint, meaning that the root opening measured before welding may not have been exactly the same once the arc passed over that location.

Figure 35 shows a graph of the transverse shrinkage experienced for each plate thickness. The effect of root opening on transverse shrinkage was also assessed in Figure 36 (8-mm plate thickness used). These graphs show that the worst shrinkage is experienced that in the middle of the joint. In the middle of the weld, the 5-mm plate pulled in toward the weld approximately 1-mm and the 8- and 10-mm plates pulled in approximately 1.4-mm. Varying root openings did not significantly affect the amount of transverse shrinkage.

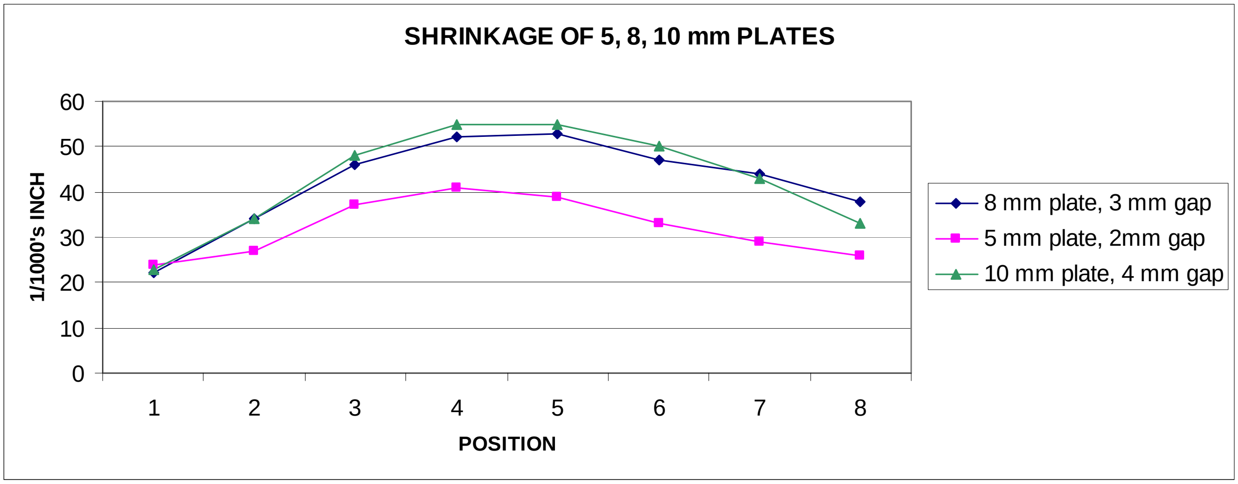

Figure 35 - Transverse Shrinkage of Preferred Procedure Welds

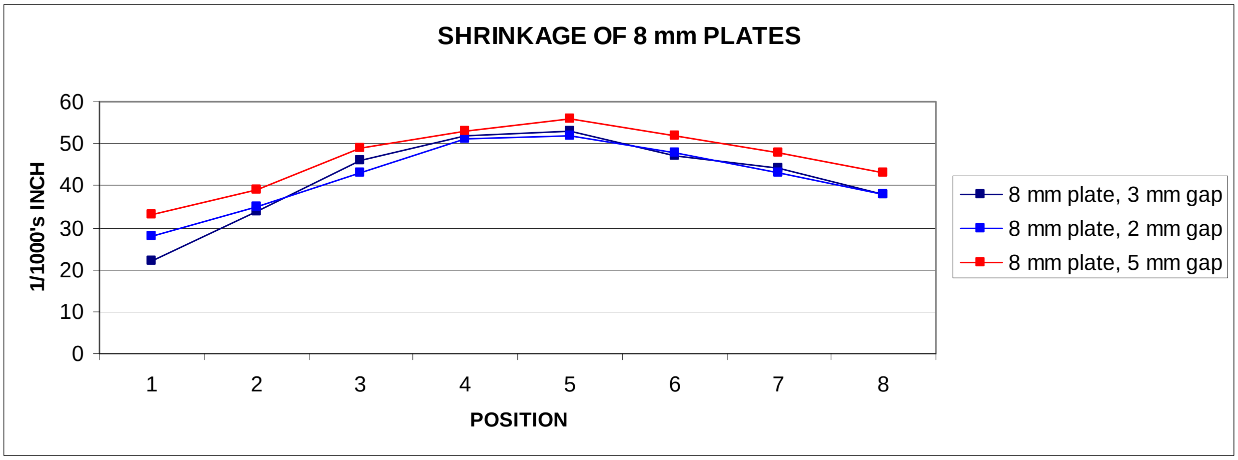

Figure 36 - Effect of Root Opening on Transverse Shrinkage

5.3.5.5 Procedure Qualification

5-mm Procedure

The weld made using the preferred 5-mm procedures (W108) was subjected to visual and nondestructive evaluation (NDE) standards. The weld was found to pass Class 1 visual observation criteria as given in MIL-STD-2035A. NDE using radiography and magnetic particle testing was performed in accordance with NAVSEA technical publication 89074-AQ-GIB-010/248. No defects or discontinuities were found and the weld was acceptable under Class 1 MIL-STD-2035A radiograph and magnetic particle standards. Appendix J contains the welding parameter data and the lead/trail electrode Current waveforms captured with high speed data acquisition equipment during the execution of this weld.

8-mm Procedure

The weld made using the preferred 8mm procedures (W97) was subjected to visual and NDE standards. The weld was also found to pass Class 1 visual observation criteria as given in MIL-STD-2035A. NDE using radiographs and magnetic particle testing was performed in accordance with NAVSEA technical publication S9074-AQ-GIB-010/248. No defects or discontinuities were found and the weld was acceptable under Class 1 MIL-STD-2035A radiograph and magnetic particle standards. Appendix K contains the welding parameter data and the lead/trail electrode Current waveforms captured with high speed data acquisition equipment during the execution of this weld.

10-mm Procedure

The weld made using the preferred 10-mm procedures (W97) was subjected to visual and NDE standards. The weld was found to pass Class 1 visual observation criteria as given in MIL-STD-2035A. NDE using radiographs and magnetic particle testing was performed in accordance with NAVSEA technical publication 89074-AQ-GIB-010/248. No defects or discontinuities were found and the weld was acceptable under Class 1 MIL-STD-2035A radiograph and magnetic particle standards. Appendix L contains the welding parameter data and the lead/trail electrode current waveforms captured with high speed data acquisition equipment during the execution of this weld.

The 10-mm plate was selected for mechanical testing to NAVSEA technical publication S9074-AQ-GIB-010/248. Mechanical tests results are presented in Table 12. Transverse tensile tests and root and face bends were performed in accordance to AWS B4.0 standards. Although not required on this thickness, charpy impact tests were performed in the base material, heat-affected zone (HAZ), and weld metal (also in accordance to AWS B4.0). These charpy specimens were sub-sized. A conversion to full sized specimen impact energy is given in Table 13. All tests results passed acceptance criteria as given by the filler metal standard MIL-E-23765/4, which required a minimum tensile elongation of 22%, a minimum 20 ft-lbs impact strength at -20°F, and no visible defects on the bend specimens.

Table 12 - Mechanical Test Results for Preferred 10-mm Plate Weld – Actual Values

1250 Arthur E. Adams Drive Columbus, OH 43221 **Lab Services**

WELD QUALIFICATION TEST RECORD-AMENDED

Amended: To correct charpy notch location
Project No.: 48565 GDE-03 **Weld No.:** **W-98**
Job No.: 2006-98873 **Customer:** Brian Baughman

CROSS WELD TENSION TEST RESULTS - ASTM E8

Technician: Kristen Merlo **Test Date:** November 3, 2005
Test Frame: H1938 UK18 **Loading Rate:** 0.05 (in/min) 1.27 (mm/min)
Orientation: Cross Weld **Test Temperature:** Room Temperature

Spec. ID	Width (in.)	Thickness (in.)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	0.2% Yield Strength (ksi)	0.2% Yield Strength (MPa)	Elongation (%)	%RA (%)	Failure Location
T-1	1.503	0.389	77.5	534.5	65.4	451.0	29.4	66.6	Base Metal
T-2	1.499	0.384	79.3	546.9	62.7	432.4	27.6	63.0	Base Metal

CHARPY IMPACT ENERGY TEST RECORD - ASTM E23

Technician: Kristen Merlo **Test Date:** November 3, 2005
Test Frame: 151297 **Notch Orientation:** T-L per AWS B4.0

Spec. ID	Notch Location	Test Temperature (^oC)	Test Temperature (^oF)	Absorbed Energy (J)	Absorbed Energy (ft-lbs)	Lateral Expansion (mm)	Lateral Expansion (mils)	Shear (%)
1	WCL	-29	-20	40.7	30	1.02	40.2	60
2	WCL	-29	-20	40.7	30	0.91	35.8	60
3	WCL	-29	-20	48.8	36	0.96	37.8	61
4	WCL	-29	-20	37.3	27.5	0.84	33.1	56
5	WCL	-29	-20	37.3	27.5	0.81	31.9	51
6	HAZ	-29	-20	230.5	170	2.37	93.3	100
7	HAZ	-29	-20	238.6	176	1.86	73.2	100
8	HAZ	-29	-20	303.7	224	2.06	81.1	100
9	Base Metal	-29	-20	279.3	206	2.26	89.0	100
10	Base Metal	-29	-20	279.3	206	2.26	89.0	100
11	Base Metal	-29	-20	273.9	202	2.30	90.6	100

BEND TEST RECORD - ASTM E190

Technician: Kristen Merlo **Test Date:** November 3, 2005

Spec. ID	Thickness (in.)	Orientation	Mandrel Diameter (in.)	Results	Validity
FB-1	0.378	Face	1.5	No Visual Defects	Pass
FB-2	0.378	Face	1.5	No Visual Defects	Pass
RB-1	0.375	Root	1.5	No Visual Defects	Pass
RB-2	0.378	Root	1.5	No Visual Defects	Pass

Test Conducted By: ____________________ Reviewed by: ____________________

Title: Senior Technician Title: Senior Engineer

Date Amended: December 5, 2005

This report is the confidential property of our client and may not be used for advertising purposes.

Table 13 below gives the converted values of the charpy impact energies. Equation F.20 from API Recommended Practice 579, Appendix F was used to correlate the sub-size absorbed energy to a calculated full size absorbed energy.

The sub-size absorbed energy was multiplied by the ratio of the full size thickness over the sub-size thickness [i.e., 32 ft-lbs x (10-mm/7.47-mm)].

Table 13 – Converted Charpy Impact Absorbed Energies – Full Size Conversion

CHARPY IMPACT ENERGY TEST RECORD - ASTM E23

Full size correlation from subsize samples
API recommended practice, Eqn. F.20

Spec. ID	Notch Location	Test Temperature (^{o}C)	Test Temperature (^{o}F)	Absorbed Energy (J)	Absorbed Energy (ft-lbs)
1	WCL	-29	-20	54.5	40.2
2	WCL	-29	-20	54.5	40.2
3	WCL	-29	-20	64.4	47.5
4	WCL	-29	-20	49.4	36.5
5	WCL	-29	-20	49.8	36.7
6	HAZ	-29	-20	308.6	227.6
7	HAZ	-29	-20	318.2	234.7
8	HAZ	-29	-20	405.5	299.1
9	Base Metal	-29	-20	372.9	275.0
10	Base Metal	-29	-20	373.4	275.4
11	Base Metal	-29	-20	365.2	269.3

5.3.5.6 Thick Section Welding with 8-mm Procedures

Although not part of the project plan, at the request of Paul Hebert of NGNN (the NSRP Program Technical Representative (PTR)), EWI attempted to weld 1-in. thick steel plates using the developed tandem SAW procedures. A butt joint configuration with each plate having a 45° bevel and a 5.5-mm root face was used. The root opening between the two plates was 3.0-mm.

The preferred procedure developed for the 8-mm plate thickness was used. The bead profile was very nice, with complete penetration, good wetting into the joint, and consistent root bead reinforcement height. Future 1-in. thick butt joints may benefit from a reduced bevel angle. Welding parameters and a photo macrograph are presented in Appendix M.

5.3.5.7 Analysis of High-Speed Tandem SAW with Improved FCB Groove

The improved FCB groove design allowed for successful high-speed NG tandem SAW FCB. Welds exhibited high quality bead shape, repeatability, and consistency along the weld length. Welds made using the preferred procedures for each plate thickness were found to meet visual, NDE, and mechanical property criteria of all relevant codes and standards.

Distortion of the plates was minimal. The maximum distortion measured on the 5-mm plate was 0.4-in. of bowing distortion and 1-mm of transverse shrinkage. Most 5-mm plates exhibited flexible buckling. The maximum bowing distortion measured for the 8- and 10-mm plates was 0.05-in. and 0.03-in. respectively. The maximum transverse shrinkage for both plate thicknesses was 1.4-mm.

Comparison to the modified S-SAW process reveals the benefits of the high-speed tandem SAW process. The following tables (Table 14 and Table 15) compare known process parameters and bead shape measurements. (Note: Distortion measurements are not compared since different plate sizes and fixtures were used for both processes. Mechanical test results for the modified S-SAW welds were not available.)

Travel speeds for the tandem SAW process were more than twice as fast as the S-SAW process. Calculated heat input of tandem SAW was 2/3 less than that of the modified S-SAW process (note: heat input measured with thermal couples may differ significantly from the calculated). Tandem SAW improved bead shape and eliminated excessive reinforcement on both faces of the joint. Deposition area was reduced approximately 50% for each plate thickness with the tandem SAW process. Base metal dilution percentage increased approximately 20% with the tandem SAW process. Bead widths on the top and root sides did not vary significantly between processes.

Table 14 - Modified S-SAW vs. Tandem SAW Welding Parameter Comparison

SERIES ARC											
Plate Thickness (mm)	Electrode Dia. (in)		**Root Opening** (mm)	**Current** (A)		**Voltage** (V)		**WFS** (ipm)		**Travel Speed** (ipm)	**Heat Input** (kJ/in)
	Lead	Trail									
5	3/16	1/8	4.0	600		33.5		48		20	60.30
8	3/16	1/8	4 to 5	725		36		54		16	97.88
10	3/16	1/8	5 to 6	800		36		60		14	123.43
TANDEM SAW											
Plate Thickness (mm)	Electrode Dia. (in.)		**Root Opening** (mm)	**RMS Current** (A)		**Voltage** (V)		**WFS** (ipm)		**Travel Speed** (ipm)	**Heat Input** (kJ/in)
	Lead	Trail		Lead	Trail	Lead	Trail	Lead	Trail		
5	5/32	3/32	2.0	650 - 50% EP	500 - 40% EP	33	33	60	190	55	41.40
8	5/32	3/32	3.0	750 - DC+	500- 50% EP	34	34	62	175	35	72.90
10	5/32	3/32	4.0	800 - DC+	500- 50% EP	34	34	70	175	30	88.40

Table 15 - Modified S-SAW vs. Tandem SAW Bead Shape Dimension Comparison

SERIES ARC							
Plate Size (mm)	Top Reinforcement Height (mm)	Bottom Reinforcement Height (mm)	Total Weld Bead Area (mm2)	Deposition Area (mm2)	Top Bead Width (mm)	Root Bead Width (mm)	Base Metal Dilution %
5	3.83	-0.236	98.8	64.258	16.04	9.5	34.96
8	3.6	1.5	188.12	105.859	21.12	14.5	43.73
10	3.04	2.36	204.96	117.9	20.18	13.93	42.48
TANDEM SAW							
Plate Size (mm)	Top Reinforcement Height (mm)	Bottom Reinforcement Height (mm)	Total Weld Bead Area (mm2)	Deposition Area (mm2)	Top Bead Width (mm)	Root Bead Width (mm)	Base Metal Dilution %
5	1.31	1.34	77.66	30.853	15.3	11	62.56
8	1.34	1.25	137.03	50.53	21.05	11.4	63.12
10	1.76	0.834	181	67.77	21.45	14.45	62.56

5.4 Process Demonstration

On November 22, 2005, a process demonstration was held at EWI for team members and the NSRP PTR. Participants included Lee Kvidahl (NGSS - Pascagoula), Nick Evans (NGSS - New Orleans), Harry Sadler (Lincoln Electric Company), and Jon Sweeny (NGNN) representing Paul Hebert (the NSRP PTR).

The agenda consisted of a presentation of project results (Appendix N) followed by a successful demonstration of high-speed NG tandem SAW of each plate thickness using the preferred procedures developed by this project. Figure 37 through Figure 39 are pictures taken during the welding demonstrations.

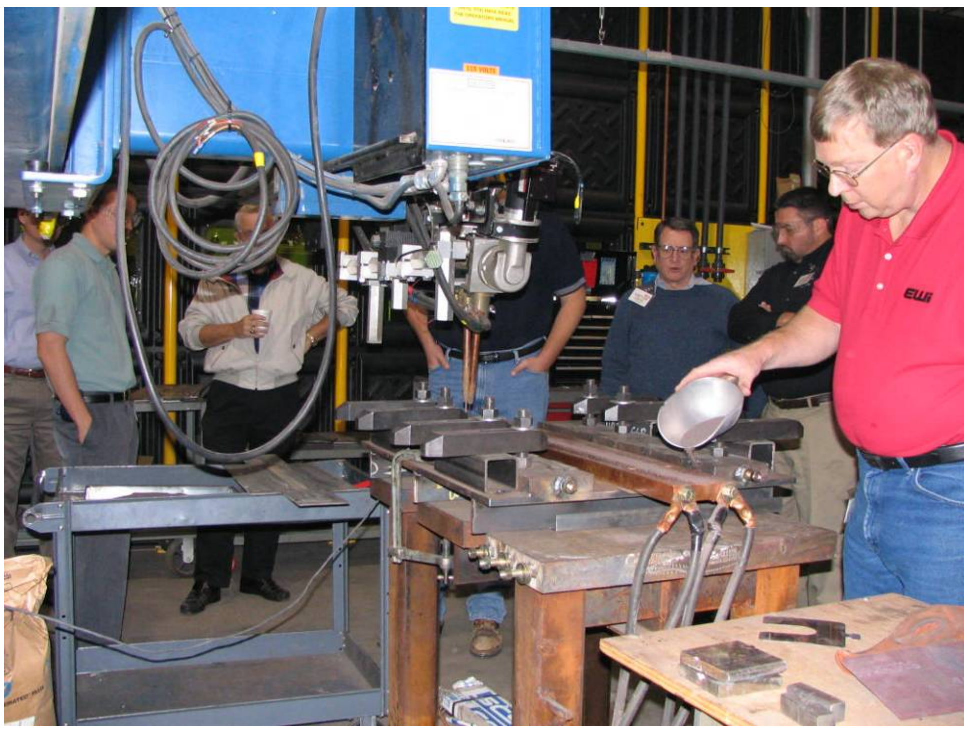

Figure 37 - Loading Flux into the Improved FCB Before Welding

Figure 38 - High Speed Data Acquisition During Weld

Figure 39 - Representatives from NGSS and NGNN Examine Plates After Welding

5.5 Financial Considerations

Narrow groove (NG) butt joint welding technology is required to make complex panels with multiple thickness transitions, cut-outs, and inserts without distortion. This welding technology is feasible for NGSS since the new panel line is being purchased with a plate mill that can assure joint gap and profile accuracy. Even without the precision of a plate mill, the wide ranging gap tolerance of the developed tandem SAW procedures may allow high quality welds with the current oxyfuel and plasma arc plate cutting systems.

The results can also be deployed at shipyards that use tandem SAW welding with FCB that need to build thin steel panels. NGSS believes that the combination of machined weld preparations, rigid clamping (provided by the FRO machine), and NG high-speed SAW FCB offer the ability to minimize heat input and distortion with the least amount of capital investment.

A brief cost analysis was performed comparing the modified S-SAW process to the tandem SAW process; Table 16 is a summary of these results. Variables evaluated were the savings in weld metal, process times, and FCB flux layering times (the time it took to build up the flux in the FCB groove). Set-up times and post-weld repair costs were not used since they were not known for the modified S-SAW process.

Table 16 - Modified S-SAW vs. Tandem SAW Cost Comparison

Plate Size and Process	Flux Fill Cost		Electrode Cost		Process Cost		Total Cost ($/ft)
	Time (min./ft)	Labor Rate ($/hr)	Metal (lbs/ft.)	Cost ($/lb)	Speed (min/ft.)	Labor ($/hr)	
5mm - Series	0.5	55	0.3345	1.75	0.57	55	1.57
5mm - Tandem	0.25	55	0.1606	1.75	0.22	55	0.71
8mm - Series	0.5	55	0.5511	1.75	0.75	55	2.11
8mm - Tandem	0.25	55	0.2631	1.75	0.34	55	1.00
10mm - Series	0.5	55	0.6138	1.75	0.86	55	2.32
10mm - Tandem	0.25	55	0.3528	1.75	0.40	55	1.21

The flux fill time was measured by recording how much time is required to fill the FCB groove with flux. Since the tandem welds incorporated the new FCB groove, the time was much less since no layering of the flux above the bar surface was necessary. The electrode amount used was calculated by measuring the deposition area and multiplying by a foot length and by the density of steel. Based on the fact that the tandem SAW process is twice as fast as the modified S-SAW process, the tandem SAW process will produce welds in 50% less time. Given the fact that tandem SAW requires very little set-up time and no post-weld repair, the cost savings will be greater if modified S-SAW set-up time and post-weld repair costs are factored in.

6.0 Conclusions

High-speed narrow-groove (NG) butt joints on 5-, 8-, and 10-mm plate thicknesses were successfully welded using the tandem SAW process. Preferred parameters were selected for each plate based on travel speeds, arc stability, weld bead shape, and weld quality. Each weld made using the preferred parameters passed MIL-STD-2035A criteria for visual, radiography, and magnetic particle examination. The 10-mm butt joint was subjected to mechanical testing per NAVSEA technical publication S9074-AQ-GIB-010/248 and passed all required tests for procedure qualification.

The design of the FCB groove was found to have a significant effect on the quality of the tandem SAW process and weld bead shape. A change from the original FCB groove (square shape, 3.5-mm deep by 35-mm wide) used with the current modified S-SAW production process to an improved FCB groove (parabolic shape, 0.09-in. deep by 0.75-in. wide) substantially improved bead shape and arc stability. In addition, the flux fill procedure for the FCB was also found to be significant. Instead of a 3-mm flux height buildup above the FCB bar surface, the flux in the FCB groove need only be filled to the top of the bar surface.

The ability to use precision AC-AC and DC-AC waveforms for procedure development was a definite advantage in developing the preferred procedures. Adjustment of the waveform parameters allowed creation of robust procedures with a degree of gap tolerance. The 5-mm plate procedure had approximately 1-mm root opening tolerance while the 8- and 10-mm plate procedures had approximately 3-mm tolerance. It is anticipated that gap tolerance could be increased for the 5-mm plate by refining the procedure to increase the weld metal fill volume.

Distortion was found to be minimal for each plate welded with the preferred procedures. The most pronounced distortion measured was on the thinnest plate (5-mm), where out-of-plane distortion was measured at 10-mm. Transverse shrinkage of the plates was minimal, with the most measured being 1.4-mm at the middle of the weld length for the 8- and 10-mm plates.

The high-speed NG tandem SAW process was found to offer several benefits over the modified S-SAW process: higher travel speeds (more than twice the speed), less deposited filler metal, improved bead shape, reduced set-up times, and improved quality with reduced post-weld repair. A cursory cost analysis (including FCB flux fill time, process labor time, and filler metal costs) revealed that the tandem SAW process can reduce welding cost per foot by approximately 50% as compared with the current modified S-SAW process. Additional savings could be realized by factoring in reduced weld repair and distortion re-work costs.

7.0 Recommendations

The high-speed NG tandem SAW FCB process should be considered for implementation at NGSS for thin panel butt welding. Additional procedure refinement is recommended to further increase the tolerance of the procedures to joint fit-up variation. Refined procedures may allow the process to be deployed without milling the plate edges, which would increase the range of deployment opportunities. Once procedures are refined, additional mechanical testing should be performed to qualify the range of material thicknesses.

A study evaluating the performance of the developed NG-SAW procedures in a production environment and on full-size panels is also recommended as a precursor to full implementation. This would include characterizing the fit-up requirements and the resultant distortion and weld quality improvements when welding production panels.

Finally, welding procedures should be developed for other base materials (e.g., HSLA-65) which are more applicable to other weapon systems like the CVN-21.

8.0 References

The Lincoln Electric Company, *The Procedure Handbook of Arc Welding 13th Edition* (Cleveland: The Lincoln Electric Company. 1994).

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Naval Sea System Command (NAVSEA) Ship Systems, *Nondestructive Testing Acceptance Criteria MIL-STD-2035A* (Washington: NAVSEA Ship Systems. 1995).

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American Welding Society, *Standard Methods for Mechanical Testing of Welds (U.S. Customary Units) ANSI/AWS B4.0* (LeJeune: American Welding Society. 1997).

American Welding Society, *Standard Welding Terms and Definitions AWS A3.0* (LeJeune: American Welding Society. 2001).

American Petroleum Institute, *API Recommended Practice 679, Appendix F, Equation F.20* (Washington: American Petroleum Institute, 2000).

9.0 Acronyms

Acronym	Definition
AC	Alternating Current
CTWD	Contact Tip-to-Work Distance
DC	Direct Current
EN	Electrode Negative
EP	Electrode Positive
EWI	Edison Welding Institute
FCB	Flux Copper Backing
ipm	Inches per Minute
NG	Narrow Groove
NGNN	Northrop Grumman Newport News
NGSS	Northrop Grumman Ship Systems
NJC	Navy Joining Center
RMS	Root Mean Square
SAW	Submerged Arc Welding
S-SAW	Series Arc Submerged Arc Welding
WFS	Wire Feed Speed

Appendix A – Original FCB Groove Design Welding Parameters

WELD ID	Date	Nominal Plate Thickness (mm)	Gap (mm)	Wire Separation (in.)	----LEADING WIRE PARAMETERS----						----TRAILING WIRE PARAMETERS----						TRAVEL SPEED (ipm)	DATA ACQ FILENAME	COMMENTS	Combined Heat Input (kJ/inch)	WFS (lead)	WFS (trail)	%over	Combined Deposit Area (in^2)
					Wire Diameter (in.)	Travel Angle (deg.)	Tip -to- Work (in.)	Waveform, %EP, DCOffst	AMP or WFS SETPOINT	VOLT SETPOINT	Wire Dia (in.)	Travel Angle (deg.)	Tip -to- Work (in.)	Waveform, %EP, DCOffst	AMP or WFS SETPOINT	VOLT SETPOINT								
W1	4/26/05	5	1.5	0.56	0.125	0	1.25	CC sq, bal=50%, DCOffs=0	350	30	0.125	9.5	1.250	CC sq, bal=50%, DCOffs=0	320	29.5	45.5	_04-26-05_13.46.13.txt		26.3				
W2	4/26/05	5	1.2	0.56	0.125	0	1.25	CC sq, bal=50%, DCOffs=0	350	30	0.125	9.5	1.250	CC sq, bal=50%, DCOffs=0	320	29.5	55	_04-26-05_13.55.22.txt		21.8				
W3	4/26/05	5	1.5	0.56	0.125	0	1.25	CC sq, bal=50%, DCOffs=0	450	30.5	0.125	9.5	1.250	CC sq, bal=50%, DCOffs=0	320	29.5	45.5	_04-26-05_14.21.43.txt		30.5				
W4	4/26/05	5	1.0 to 1.2	0.56	0.125	0	1.25	CC sq, bal=50%, DCOffs=0	500	31	0.125	9.5	1.250	CC sq, bal=50%, DCOffs=0	350	30	45.5	_04-26-05_14.30.27.txt		34.3	75	50		0.0337
W5	4/26/05	5	3.2	0.56	0.125	0	1.25	CC sq, bal=50%, DCOffs=0	500	31	0.125	9.5	1.250	CC sq, bal=50%, DCOffs=0	350	30	45.5	_04-26-05_14.53.33.txt		34.3				
W6	4/26/05	5	2.5 to 3	0.56	0.125	0	1.25	CC sq, bal=50%, DCOffs=0	450	30.5	0.125	9.5	1.250	CC sq, bal=50%, DCOffs=0	350	30	45.5	_04-26-05_14.59.51.txt		31.9				
W7	4/26/05	5	2.5	0.56	0.125	0	1.25	CC sq, bal=50%, DCOffs=25K	450	31	0.125	9.5	1.250	CC sq, bal=50%, DCOffs=-25K	350	31	30	_04-26-05_16.47.04.txt		49.6				
W8	4/26/05	5	2.0 to 2.5	0.56	0.125	0	1.25	CC sq, bal=50%, DCOffs=25K	400	31	0.125	9.5	1.250	CC sq, bal=50%, DCOffs=-25K	300	30	30	_04-26-05_17.08.43.txt		42.8				
W09	5/19/05	10	4.1	0.45	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	800	33	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	500	31	30	_05-19-05_16.19.58.txt		83.8				
W10	5/19/05	10	4.1 to 5.0	0.45	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	900	34	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	600	32	40	_05-19-05_17.29.07.txt		74.7				
																			Does compressing the flux underneath make any difference? (W09 & W10 were compressed) Try W11 not compressing. Just flux flush with top of copper.					
W11	5/20/05	10	4.1	0.45	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	900	34	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	600	32	40	_05-20-05_13.35.52.txt	Flux flush with top of copper and welded at same param's as W09. Compressing the flux made a big difference. This bead melted through, casting against the copper. There appears to be one small spot where it arced on the copper, leaving steel stuck to the copper. Not good, front face is concave, unfilled.	74.7				
W12	5/20/05	10	4.1	0.45	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	950	34	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	650	32	40	_05-20-05_14.17.29.txt	Fairly good bead. Amount of reinforcement on back and front are balanced. Root side of bead has some undercut.	79.7				
																			Next, a wider gap. It is expected that current can be lower for penetration, but deposit area will have to be larger.					
W13	5/19/05	10	4.6	0.45	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	800	33	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	500	31	30	_05-20-05_15.02.47.txt	Good.	83.8				
W14	5/19/05	10	4.6	0.45	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	700	32.5	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	500	31	30	_05-20-05_15.11.25.txt	Not quite enough reinforcement on the root side.	76.5				

WELD ID	Date	Nominal Plate Thickness (mm)	Gap (mm)	Wire Separation (in.)	---LEADING WIRE PARAMETERS---						---TRAILING WIRE PARAMETERS---						TRAVEL SPEED (ipm)	DATA ACQ FILENAME	COMMENTS	Combined Heat Input (kJ/inch)	WFS (lead)	WFS (trail)	%over	Combined Deposit Area (in^2)
					Wire Diameter (in.)	Travel Angle (deg.)	Tip -to- Work (in.)	Waveform, %EP, DCOffst	AMP or WFS SETPOINT	VOLT SETPOINT	Wire Dia (in.)	Travel Angle (deg.)	Tip -to- Work (in.)	Waveform, %EP, DCOffst	AMP or WFS SETPOINT	VOLT SETPOINT								
W15	5/19/05	10	4.6	0.45	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	800	33	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	500	31	30	_05-20-05_15.52.56.txt	Repeat W13 on a full length plate with run/off tabs.. Good penetration, right amount all the way	83.8	63	92		0.0956
W16	5/24/05	5	3.2	0.45	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	500	31	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	400	31	55	_05-24-05_14.40.05.txt		30.4				
W17	5/24/05	5	3.2	0.45	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	550	31	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	500	32	55	_05-24-05_14.45.49.txt		36.1				
W18	5/24/05	5	3.2	0.875	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	550	31	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	500	32	55	_05-24-05_15.38.46.txt		36.1				
W19	5/24/05	5	3.2	0.875	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	600	31	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	450	32	65	_05-24-05_16.07.02.txt		30.5				
W20	5/27/05	5	4.1	0.875	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	550	31	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	500	32	55	_05-27-05_08.47.40.txt	Repeat W18, but with a 4mm gap.	36.1				
W21	5/27/05	5	4.1	0.875	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	500	31	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	400	31	55	_05-27-05_09.04.25.txt	Repeat W16, but with a 4mm gap.	30.4				
																			Next, try to develop a base line procedure for 8 mm plate. Use W15 as a guideline					
W22	6/13/05	8	4.6	0.85	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	700	32	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	500	31	35	_06-13-05_13.23.16.txt		65.0				
W23	6/13/05	8	4.6	0.85	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	700	30	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	500	30	35	_06-13-05_14.23.54.txt	Try lower voltages. Ran ok at lower voltages. Probably better. Fair amount of penetration, but could use some more penetration, especially at start of weld.	61.7				
W24	6/13/05	8	4.6	0.85	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	750	30	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	550	31	35	_06-13-05_15.29.49.txt	Inconsistent on penetration, some of it suck-back, some penetrated ok.	67.8				
W25	6/13/05	8	4.6	0.85	0.1875	0	1.75	CC sq, bal=70%, DCOffs=+20k	750	30	0.125	9.5	1.875	CC sq, bal=30%, DCOffs=-20k	550	31	35	_06-13-05_15.29.49.txt	Try heavy dc+ on lead and heavy dc- on trail. Inconsistent on penetration, some of it suck-back, some penetrated ok. Why, with more current was W24 & W25 penetrated less than W22 & W23	67.8				
																			Is suck-back occurring with the lead wire? Is penetration sufficient with the lead wire?					
W26	6/14/05	8	4.6	N/A	0.1875	0	1.75	CC sq, bal=70%, DCOffs=+20k	700	30							35	_06-14-05_08.47.02.txt	Ran lead wire only. Root is well penetrated and consistent, but suck-back.					
W27	6/14/05	8	4.6	N/A	0.1875	0	1.75	CC sq, bal=70%, DCOffs=+20k	750	30							35	_06-14-05_08.54.37.txt	Ran lead wire only. Root is well penetrated and consistent, but suck-back.					
W28	6/14/05	8	4.6	N/A	0.1875	0	1.75	CC sq, bal=70%, DCOffs=+20k	900	31							42	_06-14-05_09.41.59.txt	Ran lead wire only.					
W29	6/14/05	8	4.6	N/A	0.1875	0	1.75	CC DC+	900	32							35	_06-14-05_09.56.12.txt	Ran lead wire only.					
W30	6/14/05	8	4.6	N/A	0.1875	0	1.75	CC DC+	900	32	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	650	33	45	_06-14-05_11.00.22.txt	Trail arc unstable					

WELD ID	Date	Nominal Plate Thickness (mm)	Gap (mm)	Wire Separation (in.)	LEADING WIRE PARAMETERS						TRAILING WIRE PARAMETERS						TRAVEL SPEED (ipm)	DATA ACQ FILENAME	COMMENTS	Combined Heat Input (kJ/inch)	WFS (lead)	WFS (trail)	%over	Combined Deposit Area (in^2)
					Wire Diameter (in.)	Travel Angle (deg.)	Tip -to- Work (in.)	Waveform, %EP, DCOffst	AMP or WFS SETPOINT	VOLT SETPOINT	Wire Dia (in.)	Travel Angle (deg.)	Tip -to- Work (in.)	Waveform, %EP, DCOffst	AMP or WFS SETPOINT	VOLT SETPOINT								
W31	6/14/05	8	4.0 to 4.6	N/A	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	900	32	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	650	33	50	_06-14-05_12.56.52.txt	Suck-back					
																			Test full-length plate with slotted run-on/off tabs, no tacks in joint. Try parameters similar to W23, but higher voltage on trail torch.					
W32	6/16/05	8	4.8 to 4.6	0.85	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	700	30	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	500	35	35	_06-16-05_15.27.19.txt	Plate setup: Full-length plate with slotted run-on/off tabs, no tacks in joint. Root flux =761. Const depth=2.7 mm. Result: Suck-back all the way. Total root fusion all the way, but penetration is not coming through. Fairly consistent contour, the penetration lacking most at the halfway point of the plate.	66.0	55	85		
W33	6/21/05	8	4.7	0.85	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	700	30	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	500	35	35	_06-21-05_12.24.41.txt	Same plate setup as W32. Root flux =761. Variable root flux depth (2.7 mm +- 1 mm)					
W34	6/21/05	8	4.7	0.85	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	700	30	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	500	35	35	_06-21-05_13.38.04.txt	Same plate setup as W32. Root flux =780. Const depth=2.7 mm					
W35	6/21/05	8	4.8	0.85	0.1875	0	1.75	CC sq, bal=30%, DCOffs=-20k	700	30	0.125	9.5	1.875	CC sq, bal=30%, DCOffs=-20k	500	35	35	_06-21-05_12.24.41.txt	Same plate setup as W32. Root flux =761. Const depth=2.7 mm. Feed more wire at same I,V,TS by increasing EN on both wires. Result: Arc instability, interaction of the arcs. Penetration was less.					
W36	6/21/05	8	6.2 to 6.0	0.85	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	700	30	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	500	35	35	_06-21-05_15.57.04.txt	Same plate setup as W32. Root flux =761. Const depth=2.7 mm. Results: Good penetration and underbead. A little undercut on the root side. Not much cap reinforcement. Lead torch ran less stable than it did with narrower gap. Some arcing on the copper.	66.0	68	85	8.5%	
																			Try for less wire on lead torch and more wire on the trail.					
W37	6/22/05	8	6.2	0.85	0.1875	0	1.75	CC sq, bal=70%, DCOffs=0	700	30	0.125	9.5	1.875	CC sq, bal=30%, DCOffs=-20k	550	35	35	_06-22-05_12.40.59.txt	Same plate setup as W32. Root flux =761. Const depth=2.7 mm. Results: Lead torch even less stable than W36. Lots of penetration, no cap reinforcement. Arcing on the copper.					
																			Try less current, longer arc on lead., keeping WFS around 55, keep trail same as W37.					
W38	6/22/05	8	6.2	0.85	0.1875	0	1.75	CC sq, bal=40%, DCOffs=0	650	32	0.125	9.5	1.875	CC sq, bal=30%, DCOffs=-20k	550	35	35	_06-22-05_13.46.03.txt	Same plate setup as W32. Root flux =761. Const depth=2.7 mm. Results: This time the lead torch was fairly stable and the trail torch a little unstable. Did not arc on the copper.	68.7	60	115	14.0%	
																			A possible approach for this gap is less current on the lead and more on the trail. Next repeat W36 with a gap in-between (nom 5.5 mm)					
W39	6/23/05	8	5.5	0.85	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	700	30	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	500	35	35	_06-23-05_09.28.23.txt	Repeat of W36 with 5.5 mm gap. Root flux =761. Const depth=2.7 mm. Results: Good penetration and underbead. A little undercut on the root side (favors one side). Cap reinforcement better than W36. Lead and trail torches ran stable. Did not arc on the copper.	66.0	67	86	21.7%	
W40	6/23/05	8	5.4 to 5.5	0.85	0.1875	0	1.75	CC sq, bal=40%, DCOffs=0	650	32	0.125	9.5	1.875	CC sq, bal=30%, DCOffs=-20k	550	35	35	_06-23-05_14.02.36.txt	Repeat of W38 with 5.5 mm gap. Root flux =761. Const depth=2.7 mm. Result: Suck-back all the way except a little on the run-on tab which has minimal root reinforcement.	68.7	47	120	16.0%	
W41	6/23/05	8	5.5 to 5.4	0.83	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	700	30	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	500	35	35	_06-23-05_16.02.43.txt	Repeat of W39. Root flux =761. Const depth=2.7 mm. Results: Suck-back all the way except a little at the start that is minimal. Lead and trail torches ran stable. Did not arc on the copper.	66.0	54	86	6.7%	
																			Changed placement of ground leads. Connected them to starting end of the fixture. Added a pair of bolts in the middle of the fixture to directly bolt down the plates.					
W42	6/24/05	8	5.3	0.83	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	700	30	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	500	35	35	_06-24-05_11.48.49.txt	Repeat of W39,41 with grounding placement changed and the additional direct bolting of the plates. Root flux =761. Const depth=2.7 mm. Results:	66.0				
																			Try a plate with no gap. Plat is just tacked together, no run-on/off tabs					
W43	6/27/05	8	0	0.83	0.1875	0	1.75	CC DC+	700	30	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	700	36	40	_06-27-05_09.30.40.txt	I forgot to tighten clamps, only finger tightened. Results: Intermittent penetration. Where it penetrated, no suck-back. Plate very little distortion	69.3				

WELD ID	Date	Nominal Plate Thickness (mm)	Gap (mm)	Wire Separation (in.)	-----LEADING WIRE PARAMETERS-----						-----TRAILING WIRE PARAMETERS-----						TRAVEL SPEED (ipm)	DATA ACQ FILENAME	COMMENTS	Combined Heat Input (kJ/inch)	WFS (lead)	WFS (trail)	%over	Combined Deposit Area (in^2)
					Wire Diameter (in.)	Travel Angle (deg.)	Tip -to-Work (in.)	Waveform, %EP, DCOffst	AMP or WFS SETPOINT	VOLT SETPOINT	Wire Dia (in.)	Travel Angle (deg.)	Tip -to-Work (in.)	Waveform, %EP, DCOffst	AMP or WFS SETPOINT	VOLT SETPOINT								
																			Try thinner root flux layer.					
W44	6/27/05	8	5.4	0.85	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	700	30	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	500	35	35	_06-27-05_13.17.36.txt	Repeat of W39, 41 with root flux =761 and const depth=1.0 mm. Results: Less suck-back, almost flat root side. Lead torch very stable, trail torch stable also.	66.0	53	88	6.5%	
W45	6/27/05	8		0.85	0.1875	0	1.75	CC sq, bal=50%, DCOffs=0	750	30	0.125	9.5	1.875	CC sq, bal=50%, DCOffs=0	600	36	35	_06-27-05_15.52.41.txt		75.6	66	110	6.5%	
																			Try single electrode parameters provided by Nick Evans.					
W46	6/30/05	5	0	N/A	0.125	0	0.75	CC Sine, bal=50%, DCOffs=0	650	35							32	_06-30-05_16.57.19.txt	Used 3 mm rake method to place 761 flux layer. No steel blocks (clamps directly on 5 mm plate.). Result: Good amount of penetration, Should repeat	42.7	99			
W47	7/5/05	5	0	N/A	0.125	0	0.75	CC Sine, bal=50%, DCOffs=0	650	35							32	_07-05-05_09.22.31.txt	Repeat of W46. Result: Good amount of penetration.	42.7	99			
W48	7/5/05	5	0	N/A	0.125	0	0.75	CC Sine, bal=50%, DCOffs=0	650	35							32	_07-05-05_10.27.11.txt	Another repeat of W46 except that plate is shimmed up 2.7 mm so that it is approximately even with the built-up flux. Results: Penetration is inconsistent, excessive in the middle of weld. Plate bowed up in the opposite direction.	42.7	99			
W49	7/5/05	5	0	N/A	0.125	0	0.75	CC Sine, bal=50%, DCOffs=0	650	35							32	_07-05-05_13.46.01.txt	Another repeat of W46 except that steel blocks were used. Results: About the same as W47.	42.7	99			0.0380
W50	7/5/05	5	0	N/A	0.125	0	0.75	CC sq, bal=50%, DCOffs=0	650	35							32	_07-05-05_15.16.18.txt	Same flux layer & clamping as W49, but using CC Square wave. I forgot to tighten clamps, only finger tightened. Results: Generally a little more penetration than W47 which is expected since the flux wasn't compressed much. Consistent throughout length of weld.	42.7	98			
W51	7/6/05	5	0	N/A	0.125	0	0.75	CC sq, bal=50%, DCOffs=0	650	35							32	_07-06-05_07.47.22.txt	Same flux layer & clamping as W49, but using CC Square wave. Remembered to tighten clamps. Results: Good amount of penetration, consistent.	42.7	97			0.0372
W52	7/6/05	5	0	0.7	0.1875	0	1.25	CC sq, bal=50%, DCOffs=0	600	32	0.125	10	1.250	CC sq, bal=50%, DCOffs=0	400	34	45	_07-06-05_09.58.12.txt	3 mm rake method to place 761 flux layer. Clamping blocks used. Result: Not penetrated. Several pinholes.	43.7	37	60		0.0391
W53	7/6/05	5	0	0.7	0.1875	0	1.25	CC sq, bal=50%, DCOffs=0	700	32	0.125	10	1.250	CC sq, bal=50%, DCOffs=0	400	34	50	_07-06-05_11.05.03.txt	3 mm rake method to place 761 flux layer. Clamping blocks used. Result: Very minimal penetration with suck-back. Several pinholes.	43.2	47	58		0.0402
W54	7/6/05	5	0	0.7	0.1875	0	1.25	CC DC+	750	32	0.125	10	1.250	CC sq, bal=50%, DCOffs=0	450	34	50	_07-06-05_13.17.07.txt		47.2	43	75		0.0422
W55	7/6/05	5	0	0.7	0.1875	0	1.00	CC DC+	750	32	0.125	10	1.000	CC sq, bal=50%, DCOffs=0	450	34	50	_07-06-05_14.21.46.txt		47.2	42	70		0.0404
W56	7/12/05	5	0	N/A	0.1875	0	1.25	CC Sine, bal=50%, DCOffs=0	650	35							32	_07-12-05_11.09.00.txt	Repeat similar to W49 but with 3/16" dia. wire. Results: Very nice penetration.	42.7	40			0.0345
W57	7/12/05	5	0	N/A	0.1875	0	1.25	CC sq, bal=50%, DCOffs=0	650	35							32	_07-12-05_13.34.07.txt	Repeat but with square wave and 3/16" dia. wire. Results: Very nice penetration.	42.7	40			0.0345
																			Try a series of welds at different currents with single 3/16" dia. wire and traveling 50 ipm					
W58	7/12/05	5	0	N/A	0.1875	0	1.25	CC DC+	750	35							50	_07-12-05_16.03.44.txt		31.5	43			0.0234
W59	7/12/05	5	0	N/A	0.1875	0	1.25	CC DC+	800	35							50	_07-12-05_16.24.48.txt		33.6	45			0.0248
W60	7/14/05	5	0	N/A	0.1875	0	1.25	CC DC+	850	36							50	_07-14-05_08.34.09.txt		36.7	48			0.0265

WELD ID	Date	Nominal Plate Thickness (mm)	Gap (mm)	Wire Separation (in.)	LEADING WIRE PARAMETERS: Wire Diameter (in.)	Travel Angle (deg.)	Tip -to- Work (in.)	Waveform, %EP, DCOffst	AMP or WFS SETPOINT	VOLT SETPOINT	TRAILING WIRE PARAMETERS: Wire Dia (in.)	Travel Angle (deg.)	Tip -to- Work (in.)	Waveform, %EP, DCOffst	AMP or WFS SETPOINT	VOLT SETPOINT	TRAVEL SPEED (ipm)	DATA ACQ FILENAME	COMMENTS	Combined Heat Input (kJ/inch)	WFS (lead)	WFS (trail)	%over	Combined Deposit Area (in^2)
W61	7/14/05	5	0	N/A	0.1875	0	1.25	CC DC+	700	35							50	_07-14-05_09.15.14.txt		29.4	38			0.0210
W62	7/14/05	5	0	N/A	0.125	0	1.00	CC DC+	700	35							50	_07-14-05_13.52.57.txt		29.4	87			0.0214
W63	7/14/05	5	0	N/A	0.125	0	1.00	CC DC+	750	35							50	_07-14-05_14.42.42.txt		31.5	97			0.0238
W64	7/14/05	8	0	N/A	0.1875	0	1.25	CC DC+	850	36							40	_07-14-05_15.27.07.txt	Not penetrated	45.9	46			
W65	7/14/05	8	0	N/A	0.1875	0	1.25	CC DC+	950	38							40	_07-14-05_15.33.22.txt	Some inconsistent penetration with bad suck-back.	54.2	51			

Appendix B – Improved FCB Groove Design Weld Parameters

WELD ID	Date	Nominal Plate Thickness (mm)	Gap (mm)	Wire Separation (in.)	LEADING WIRE PARAMETERS						TRAILING WIRE PARAMETERS						TRAVEL SPEED (ipm)	DATA ACQ FILENAME	COMMENTS	Combined Heat Input (kJ/inch)	WFS (lead)	WFS (trail)	%over	Combined Deposit Area (in2)
					Wire Diameter (in.)	Travel Angle (deg.)	Tip -to- Work (in.)	Waveform, %EP, DCOffst	AMP or WFS SETPOINT	VOLT SETPOINT	Wire Dia. (in.)	Travel Angle (deg.)	Tip -to- Work (in.)	Waveform, %EP, DCOffst	AMP or WFS SETPOINT	VOLT SETPOINT								
W66	8/9/05	8	2.9 to 3.1	N/A	0.15625	0	1.25	CC DC+	750	34							17	_08-09-05_14.15.43.txt		90.0	58			0.0371
W67	8/9/05	8	2.9 to 3.1	0.78	0.15625	0	1.25	CC DC+	750	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	30	_08-09-05_14.45.15.txt		85.0	62	172		0.0766
W68	8/9/05	8	3.0 to 3.2	0.78	0.15625	0	1.25	CC DC+	750	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	35	_08-09-05_15.26.11.txt		72.9	62	172		0.0680
W69	8/9/05	8	3.2 to 3.3	0.78	0.15625	0	1.25	CC DC+	750	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	40	_08-09-05_16.02.20.txt		63.8	62	177		0.0603
W70	8/16/05	5	1.8 to 1.4	N/A	0.15625	0	1.25	CC DC+	650	33							30	_08-16-05_13.09.43.txt	Single wire weld. Root side bead looks very good, strong penetration. Face side has no reinforcement (flush) . Slag removed easily.	42.9	48			
W71	8/16/05	5	1.8 to 2	0.78	0.15625	0	1.25	CC DC+	650	33	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	40	_08-16-05_13.22.26.txt	Burned into the copper backing. Probably the combined heat from 2 wires caused this. Another possibility that not enough flux is getting t the underside.	57.7	52	180		
W72	8/17/05	5	1.7 to 1.6	0.78	0.15625	0	1.25	CC DC+	550	32	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	400	33	40	_08-17-05_08.44.52.txt	Still plenty of penetration. Some small melting to the copper. Face side scalloped and uneven. Trail wire ran unstable with swings in the WFS. Since penetration is not a problem and stability is, try ac on lead torch.	46.2	41	140		
W73	8/17/05	5	1.8 to 1.4	0.78	0.15625	0	1.25	CC sq, bal=50%, DCOffs=0	650	33	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	55	_08-17-05_14.18.12.txt	Good bead. Stuck to the copper some at the run-on and run-off tabs which were nominally wider gap (~2.5 mm).	41.9	60	180		
W74	8/18/05	10	3.8 to 3.9	0.78	N/A	0	1.25	CC DC+	800	34							17	_08-18-05_13.40.59.txt	Good penetration. Penetration goes away as joint gap closed up (probably closing a lot at slow travel speed.	96.0	70			
W75	8/18/05	10	2.8 to 3.8	0.78	0.15625	0	1.25	CC DC+	800	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	30	_08-18-05_13.48.04.txt	Good bead. Not a lot of excess penetration. A little suck-back @ start where gap was narrow, but quickly there's enough penetration. Didn't burn on the copper anywhere.	88.4	68	175		
W76	8/18/05	10	3.8 to 3.9	0.78	0.15625	0	1.25	CC DC+	800	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	30	_08-18-05_14.28.04.txt	Repeat same parameters on a full 24"weld.	88.4	70	177		
W77	8/18/05	10	3.9	0.78	0.15625	0	1.25	CC DC+	850	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	35	_08-18-05_15.34.20.txt		78.7	76	180		
																			Test baseline 8mm & 10mm parameters on varying gaps					
W78	8/30/05	8	Var. 1.2 to 5.0	0.75	0.15625	0	1.25	CC DC+	750	34	0.09375	12	1.25	CC sq, bal=50%, DCOffs=0	500	34	35	_08-30-05_14.26.43.txt	Increasing gap test. RESULT: Weld did poorly. Speculation of why it went bad. 1) Hard start on previous attempt caused bent wire(s). 2) Primer and/or flux between the plate and copper bar my prevent proper ground path.	72.9				0.0680
W79	8/30/05	8	3.6 to 3.4	0.75	0.15625	0	1.25	CC DC+	750	34	0.09375	12	1.25	CC sq, bal=50%, DCOffs=0	500	34	35	_08-30-05_16.15.09.txt	Try to repeat successful W68 (chosen baseline). Grind primer off back side. During weld, trail wire became jammed in the spool and quit feeding. Lead wire continued ok. I stopped the weld midway through the plate.	72.9				0.0680
W80	8/31/05	8	2.9 to 3.3	0.75	0.15625	0	1.25	CC DC+	750	34	0.09375	12	1.25	CC sq, bal=50%, DCOffs=0	500	34	35	_08-31-05_08.33.24.txt	Fixed jammed wire and continue repeat of W68 parameters on remainder of plate (primer ground off back side). RESULT: Good. Penetration is light at the start (where the gap is narrower). Top side looks good.	72.9	62	172		0.0680
W81	8/31/05	8	Var. 1.6 to 5.5	0.75	0.15625	0	1.25	CC DC+	750	34	0.09375	12	1.25	CC sq, bal=50%, DCOffs=0	500	34	35	_08-31-05_10.39.52.txt	Increasing gap test. Ground primer off back side. RESULT: Good. Penetrated all the way and did not burn the copper anywhere. Less penetration at mid plate, indicating it is still pulling in.	72.9				0.0680
W82	8/31/05	8	Var. 5.5 to 1.5	0.75	0.15625	0	1.25	CC DC+	750	34	0.09375	12	1.25	CC sq, bal=50%, DCOffs=0	500	34	35	_08-31-05_14.34.32.txt	Decreasing gap test. Ground primer off back side. RESULT: Good. Penetrated all the way and did not burn the copper anywhere. Less penetration at mid plate, indicating it is still pulling in.	72.9				0.0680
W83	8/31/05	10	Var. 2.0 to 5.7	0.78	0.15625	0	1.25	CC DC+	800	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	30	_08-31-05_15.13.36.txt	Increasing gap test. Ground primer off back side. RESULT: Good. Penetrated all the way and did not burn the copper anywhere.	88.4				
W84	9/1/05	10	Var. 6.0 to 1.5	0.78	0.15625	0	1.25	CC DC+	800	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	30	_09-01-05_10.27.52.txt	Decreasing gap test. Ground primer off back side. RESULT: Good. Penetrated most of the way and did not burn the copper anywhere. Missing penetration 2/3 of the way, (before the narrowest part), indicating it is still pulling in.	88.4				

Try to develop tandem on 5mm with zero gap using the .75 x .09 round copper back.

WELD ID	Date	Nominal Plate Thickness (mm)	Gap (mm)	Wire Separation (in.)	------------------------------LEADING WIRE PARAMETERS------------------------------						----------------------------TRAILING WIRE PARAMETERS----------------------------						TRAVEL SPEED (ipm)	DATA ACQ FILENAME	COMMENTS	Combined Heat Input (kJ/inch)	WFS (lead)	WFS (trail)	%over	Combined Deposit Area (in2)
					Wire Diameter (in.)	Travel Angle (deg.)	Tip -to- Work (in.)	Waveform, %EP, DCOffst	AMP or WFS SETPOINT	VOLT SETPOINT	Wire Dia. (in.)	Travel Angle (deg.)	Tip -to- Work (in.)	Waveform, %EP, DCOffst	AMP or WFS SETPOINT	VOLT SETPOINT								
W85	9/1/05	5	0	0.78	0.15625	0	1.50	CC DC+	650	33	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	55	_09-01-05_12.37.26.txt	APPROACH: Same parameters that over-penetrated on W96 run on tight joint fit up. Tacks each end and one in the middle. Ground primer off back side. Flush layer of flux in the backing recess. Mistakenly had the CTWD=1.50". RESULT: Some flare-ups and instability on the lead wire. Penetration was light. Lost penetration midway through. This could be due to the tack and the fact that the penetration is minimal. Looks like lead wire is not doing the penetration.	41.9	52	180		
W86	9/1/05	5	0	0.78	0.15625	0	1.25	CC DC+	725	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	400	32	55	_09-01-05_14.07.02.txt	APPROACH: In reviewing W62 & W63, single wire penetrated, so choose current between these. Keep current low on trail torch to keep deposit area down. Tacks each end and one in the middle. Ground primer off back side. Flush layer of flux in the backing recess. Result: Data trace shows it didn't run real stable. Lost penetration midway through again. This is odd because we thought the reason why gap pulling in, but this had no gap. Maybe a grounding issue because it happened exactly between the first and second set of hold-down blocks.	40.9	52	180		
Setup insulator on back of copper backing bar to isolate the fixture from the welding circuit																								
W87	9/6/05	5	0	0.78	0.15625	0	1.25	CC DC+	725	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	400	32	55	_09-06-05_15.59.30.txt	PURPOSE: Test the new grounding setup and compare with previous weld. APPROACH: Repeat W86, but no grinding of the primer on the root side, and trying the insulated copper bar. Tacks each end and one in the middle. Flush layer of flux in the backing recess. RESULT: Ran very poorly, unstable. Penetration intermittent and weak. Lead arc was unstable.	40.9	52	180		
																			Is the instability due to isolating the current path to the copper bar, or is it lack of good ground due to the primer coating? Since the best results so far have been on 8 or 10 mm plate, I'll try baseline procedure, but make sure primer is still on the back side.					
W88	9/7/05	10	3.9 to 4.0	0.78	0.15625	0	1.25	CC DC+	800	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	30	_09-07-05_08.54.18.txt	PURPOSE: See if primer between the plate and isolated copper block causes the instability. APPROACH: Repeat W76, but no grinding of the primer on the root side. Run-on/off tabs little grinding and do not clamp to the run-on/off tabs as this is a direct path from the copper bar through the clamps. RESULT: Good, stable weld. Bead looks good, root looks good.	88.4	70	180		0.0738
W89	9/7/05	8	3.4 to 3.2	0.78	0.15625	0	1.25	CC DC+	750	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	35	_09-07-05_10.48.46.txt	PURPOSE: See if primer between the plate and isolated copper block causes the instability. APPROACH: Repeat W68, but no grinding of the primer on the root side. Run-on/off tabs little grinding and do not clamp to the run-on/off tabs as this is a direct path from the copper bar through the clamps. Copper bar isolated. RESULT: Good, stable weld. Bead looks good, root looks good.	72.9	62	178		0.0691
W90	9/7/05	5	1.9 to 2.0	0.78	0.15625	0	1.25	CC sq, bal=50%, DCOffs=0	650	33	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	55	_09-07-05_13.13.41.txt	PURPOSE: See if primer between the plate and isolated copper block causes the instability. APPROACH: Repeat W73, but no grinding of the primer on the root side. Run-on/off tabs little grinding and do not clamp to the run-on/off tabs as this is a direct path from the copper bar through the clamps. Copper bar isolated. RESULT: Good, stable weld. Bead looks good, root looks good.	41.9	60	175		0.0249
																			Zero gap attempts on 5 mm plate					
W91	9/7/05	5	0	0.78	0.15625	0	1.25	CC DC+	725	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	400	32	55	_09-07-05_14.59.36.txt	PURPOSE: Test same setup as W88-90 on a no-gap 5mm plate. APPROACH: Repeat W86, W87 parameters. No grinding of the primer on the root side. Use run-on/off tabs with little grinding and do not clamp to the run-on/off tabs as this is a direct path from the copper bar through the clamps. Copper bar isolated. RESULT: Ran much better than W87, lead arc was stable, but bead appearance is irregular. Most of weld good penetration. but some places where it not penetrated well. Inconsistent.	40.9	59	135		0.0375
W92	9/7/05	5	0	N/A	0.15625	0	1.00	CC sq, bal=50%, DCOffs=0	650	35							32	_09-07-05_15.55.35.txt	PURPOSE: Test single wire AC param's on the round .75" x .090" backing groove. APPROACH: Similar to Nick's parameters, but Square Wave and using 5/32" wire and the round back groove. No run-on/off tabs. I ground off primer from the back to get plate grounded, but left primer in the joint area. RESULT: Very stable. Very good bead front side and back.	42.7	59	0		0.0354
W93	9/7/05	5	0	0.78	0.15625	0	1.25	CC DC+	650	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	400	32	45	_09-07-05_17.18.13.txt	PURPOSE: Try to improve on consistency of W91, no-gap tandem. APPROACH: Reduce travel speed and try to keep same deposit area as W91. RESULT: Some improvement over W91. Burned the copper and stuck some on the run-on tab. Fully penetrated all the way. Front side somewhat inconsistent. This is not the level of quality that the single wire procedure (W92) produced.	46.5	51	140		0.0432
																			Try develop base procedures on 10 mm that utilize AC/AC					

WELD ID	Date	Nominal Plate Thickness (mm)	Gap (mm)	Wire Separation (in.)	------LEADING WIRE PARAMETERS------						------TRAILING WIRE PARAMETERS------						TRAVEL SPEED (ipm)	DATA ACQ FILENAME	COMMENTS	Combined Heat Input (kJ/inch)	WFS (lead)	WFS (trail)	%over	Combined Deposit Area (in2)
					Wire Diameter (in.)	Travel Angle (deg.)	Tip -to- Work (in.)	Waveform, %EP, DCOffst	AMP or WFS SETPOINT	VOLT SETPOINT	Wire Dia. (in.)	Travel Angle (deg.)	Tip -to- Work (in.)	Waveform, %EP, DCOffst	AMP or WFS SETPOINT	VOLT SETPOINT								
W94	9/14/05	10	3.8 to 4.0	0.78	0.15625	0	1.25	CC sq, 45 Hz, bal=50%, DCOffs=0	800	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0, Phase=90	500	34	30	_09-14-05_13.40.44.txt	APPROACH: Same param's as baseline 10 mm (W76), but Balanced AC on lead torch. RESULT: Note 45 Hz frequency. Ran a little unstable, flare ups. Penetrated all the way, but penetration is not as strong as W76. In some places negative reinforcement or sucked back a little.	88.4	87	185		0.0982
W95	9/14/05	10	3.6 to 3.9	0.78	0.15625	0	1.25	CC sq, 45 Hz, bal(+)=70 %, DCOffs=+ 7500	800	34	0.125	9.5	1.250	CC sq, bal=50%, DCOffs=0, Phase=123	500	35	30	_09-14-05_15.19.43.txt	APPROACH: Positive balance and some positive offset on lead torch to get more penetration. RESULT: Note 45 Hz frequency. Ran more unstable than W94. Flare ups and spiking of the slag. In some places negative reinforcement or sucked back a little.	89.4	75	185		0.0905
																			Taking distortion measurements of baseline welds					
W96	10/21/05	5	1.9 to 2.0	0.78	0.15625	0	1.25	CC sq, bal=50%, DCOffs=0	650	33	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	55	_10-21-05_10.06.59.txt	Good weld. A lot of bowing distortion in the opposite direction expected.	41.9	60	180		0.0435
W97	10/21/05	8	3.4 to 3.3	0.78	0.15625	0	1.25	CC DC+	750	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	35	_10-21-05_11.01.49.txt	Good bead. Minimal distortion.	72.9	62	175		
W98	10/21/05	10	3.8 to 4.0	0.78	0.15625	0	1.25	CC DC+	800	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	30	_10-21-05_13.03.36.txt	Good bead. Minimal distortion.	88.4	70	175		
																			Test baseline 8mm & 10mm parameters on small & large gaps					
W99	10/21/05	8	2.1 to 2.2	0.78	0.15625	0	1.25	CC DC+	750	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	35	_10-21-05_14.54.07.txt		72.9	61	172		
W100	10/21/05	8	5.2 to 5.0	0.78	0.15625	0	1.25	CC DC+	750	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	35	_10-21-05_15.56.05.txt		72.9	63	182		
W101	10/24/05	10	3.0 to 2.9	0.78	0.15625	0	1.25	CC DC+	800	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	30	_10-24-05_10.00.04.txt		88.4	68	173		
W102	10/24/05	10	5.9 to 6.0	0.78	0.15625	0	1.25	CC DC+	800	34	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34	30	_10-24-05_12.36.22.txt	Ran a little unstable. Stuck to copper backing in a few places. Good penetration, front face is somewhat ropey with little or no reinforcement	88.4	73	185		
W103	10/24/05	10	3.8 to 3.9	0.78	0.15625	0	1.25	CC sq, 65 Hz, bal(+)=70 %, DCOffs=+ 7500	700	32	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0, Phase=123 deg	400	32	25	_10-24-05_16.36.08.txt	APPROACH: More conservative parameters (less current, slower travel). Positive balance and some positive offset on lead torch to get more penetration. RESULT: Note 65 Hz frequency. Ran stable. A little less penetration than the procedure with DC+ lead torch. Penetrated all the way. but minimal root side reinforcement and some suck-back at 2/3 of the way where gap has pulled in most.	84.5	62	135		0.0850
																			Try reduce heat input for 5 mm plate					
W104	10/25/05	5	3.1 to 3.2	0.78	0.15625	0	1.25	CC sq, bal=50%, DCOffs=0	550	32	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	33	55	_10-25-05_14.26.07.txt	PURPOSE: Improve on baseline 5mm plate parameters (W73). Foremost, reduce heat input, secondly, decrease the height-to-width ratio of the underbead. APPROACH: Wider gap so that it can penetrate at lower current. RESULT: Ran very stable. There were two holes (skips) in the weld. Underbead good except for the holes where it skipped. Data shows that arc was ok, wfs was ok, and the hole simply from lacking enough fill. Some sticking to the copper. Plenty of penetration.	37.2	48	180		0.0393
W105	10/25/05	5	3.3	0.78	0.15625	0	1.25	CC sq, bal=50%, DCOffs=- 8200	550	32	0.09375	12	1.250	CC sq, bal(+)=45%, DCOffs=-8200, Phase=100 deg	500	33	55	_10-25-05_16.17.20.txt	PURPOSE: Improve on baseline 5mm plate parameters (W73). Eliminate holes seen on W104. APPROACH: Increase EN (wfs should increase) on both wires. RESULT: Ran very stable. Again there were two holes (skips) in the weld but further apart this time. Underbead good except for the holes where it skipped. Data shows that arc was ok, wfs was ok, and the hole simply from lacking enough fill. No sticking to the copper. Still plenty of penetration. This seems to have helped, but it didn't have as much effect on adding more wire as I had hoped for.	37.2	50	185		0.0407
W106	10/26/05	5	3.1 to 3.4	0.78	0.15625	0	1.50	CC sq, bal=50%, DCOffs=- 8200	550	32	0.09375	12	1.250	CC sq, bal(+)=40%, DCOffs=-8200, Phase=105 deg	500	33	55	_10-26-05_08.53.46.txt	PURPOSE: Improve on baseline 5mm plate parameters (W73). Eliminate holes seen on W104. APPROACH: Increase EN on trail wire and increase stickout on lead wire (wfs should increase) RESULT: Ran very stable. This time just one hole (skip) in the weld which took longer before it developed. Underbead good except for the hole where it skipped. Data shows that arc was ok, wfs was ok, and the hole simply from lacking enough fill. No sticking to the copper. Still plenty of penetration. This seems to have helped again, but again the effect of adding more wire is smaller than desired.	37.2	51	190		0.0416
W107	10/26/05	5	1.9 to 2.1	0.78	0.15625	0	1.25	CC sq, bal=50%, DCOffs=- 8200	550	32	0.09375	12	1.250	CC sq, bal(+)=40%, DCOffs=-8200, Phase=105 deg	500	33	55	_10-26-05_13.22.10.txt	PURPOSE: Improve on baseline 5mm plate parameters (W73). See how lower heat input param's work on the 2 mm gap.. APPROACH: Try same param's on 2 mm gap. RESULT: Somewhat unstable. No holes. Underbead started out good but penetration went away. No sticking to the copper. Not enough heat to penetrate this gap.	37.2	50	185		0.0407

WELD ID	Date	Nominal Plate Thickness (mm)	Gap (mm)	Wire Separation (in.)	------------------------------LEADING WIRE PARAMETERS------------------------------						----------------------------TRAILING WIRE PARAMETERS----------------------------						TRAVEL SPEED (ipm)	DATA ACQ FILENAME	COMMENTS	Combined Heat Input (kJ/inch)	WFS (lead)	WFS (trail)	%over	Combined Deposit Area (in2)
					Wire Diameter (in.)	Travel Angle (deg.)	Tip -to- Work (in.)	Waveform, %EP, DCOffst	AMP or WFS SETPOINT	VOLT SETPOINT	Wire Dia. (in.)	Travel Angle (deg.)	Tip -to- Work (in.)	Waveform, %EP, DCOffst	AMP or WFS SETPOINT	VOLT SETPOINT								
																			Conclusion: It seems that reducing the heat input from the nominal 43 kJ/inch (W73) makes a tight window on the gap tolerance. At 3mm gap, holes, at 2mm, not enough penetration. Try the 43 kJ/inch parameters with some EN. This should give a little more deposit which would help widen the gap tolerance.					
W108	10/27/05	5	1.9 to 2.0	0.78	0.15625	0	1.25	CC sq, bal=50%, DCOffs=-8200	650	33	0.09375	12	1.250	CC sq, bal(+)=40%, DCOffs=-8200, Phase=105 deg	500	33	55	_10-27-05_08.35.19.txt	PURPOSE: Improve on baseline 5mm plate parameters (W73). APPROACH: Try similar to W73 param's but with added EN similar to W105 on 2 mm gap. RESULT: Ran stable. Good balance of bead size on front & back. Plate can buckle either direction. Good bead shape front & back. No sticking to the copper.	41.4	60	190		0.0448
W109	10/27/05	5	1.3 to 1.4	0.78	0.15625	0	1.25	CC sq, bal=50%, DCOffs=-8200	650	33	0.09375	12	1.250	CC sq, bal(+)=40%, DCOffs=-8200, Phase=105 deg	500	33	55	_10-27-05_09.20.26.txt	PURPOSE: Test gap tolerance of parameters W108. APPROACH: Same as W108, but narrower gap. RESULT: Ran somewhat unstable. Penetrated all the way, but penetration is minimal with little or no reinforcement on root side. Most of the weld deposited on the front causing a lot of distortion in that direction.. No sticking to the copper.	41.4	60	190		0.0448
W110	10/27/05	5	2.9 to 3.0	0.78	0.15625	0	1.25	CC sq, bal=50%, DCOffs=-8200	650	33	0.09375	12	1.250	CC sq, bal(+)=40%, DCOffs=-8200, Phase=105 deg	500	33	55	_10-27-05_10.43.12.txt	PURPOSE: Test gap tolerance of parameters W108. APPROACH: Same as W108, but wider gap. RESULT: Ran stable. Good balance of bead size on front & back. Plate can buckle either direction. Good bead shape front & back. A hole formed at end of weld just before the run-off tab. I don't know if this is due to the transition to the run-off or if because procedure not tolerant to 3 mm gap. No sticking to the copper.	41.4	60	194		0.0453

Appendix C – DC Offset Trends

Tandem Trials :	Lead 750A/34V , Trail 500A/34V , Travel=35ipm				
BOP #	Offset Value	Resulting WFS	Average Current	Average V,I,WFS data file (.txt)	HS data file (.dat)
2	19599	140		9/8/2005 9:53	
3	32767	133		9/8/2005 10:12	
4	-32767	168		9/8/2005 10:24	
5	0	168		9/8/2005 12:48	
6	-24500	165		9/8/2005 12:58	
7	24500	133		9/8/2005 13:10	
8	16500	143		9/8/2005 13:27	
9	7500	156		9/8/2005 14:07	
10	0	168		9/8/2005 14:35	
11	-7500	171	-114	9/8/2005 15:10	Test1
15	-16500	167	-240	9/9/2005 8:18	Test5
16	-24500	167	-245	9/9/2005 8:37	Test6
17	-32767	169	-250	9/9/2005 8:58	Test7
18	0	171	-18	9/9/2005 9:14	Test8
19	5000	158	51	9/9/2005 9:30	Test9
20	10000	156	116	9/9/2005 10:06	Test10
21	24500	135	240	9/9/2005 10:40	Test11
Single Wire trials:		**500A/34V , Travel=22 ipm**			
12	0	150	22	9/8/2005 15:21	Test2
13	-7500	150	-80	9/8/2005 15:33	Test3
14	-16500	147	-218	9/8/2005 15:38	Test4

Appendix D – ROMER Arm Distortion Measurements: 5-mm Before Weld

RP 1		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	7.054	7.054	0.000	0.000
Target point	Y	0.000	0.000	28.220	28.220	0.000	
	Z	0.000	0.000	0.252	0.252	0.000	0.000
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 2		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	10.046	10.046	0.000	
Target point	Y	0.000	0.000	28.195	28.195	0.000	
	Z	0.000	0.000	0.266	0.266	0.000	0.000
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 3		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	13.193	13.193	0.000	
Target point	Y	0.000	0.000	28.206	28.206	0.000	
	Z	0.000	0.000	0.275	0.275	0.000	0.000
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 4		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	16.334	16.334	0.000	
Target point	Y	0.000	0.000	28.270	28.270	0.000	
	Z	0.000	0.000	0.280	0.280	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 5

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	19.491	19.491	0.000	
Target point	Y	0.000	0.000	28.342	28.342	0.000	
	Z	0.000	0.000	0.281	0.281	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 6

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	22.659	22.659	0.000	
Target point	Y	0.000	0.000	28.304	28.304	0.000	
	Z	0.000	0.000	0.283	0.283	0.000	0.000
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 7

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	25.793	25.793	0.000	
Target point	Y	0.000	0.000	28.278	28.278	0.000	
	Z	0.000	0.000	0.271	0.271	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 8

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	28.945	28.945	0.000	
Target point	Y	0.000	0.000	28.325	28.325	0.000	
	Z	0.000	0.000	0.252	0.252	0.000	0.000
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 9

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	28.835	28.835	0.000	
Target point	Y	0.000	0.000	24.570	24.570	0.000	
	Z	0.000	0.000	0.261	0.261	0.000	0.000
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 10

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	25.760	25.760	0.000	
Target point	Y	0.000	0.000	24.552	24.552	0.000	
	Z	0.000	0.000	0.270	0.270	0.000	0.000
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 11

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	22.726	22.726	0.000	
Target point	Y	0.000	0.000	24.578	24.578	0.000	
	Z	0.000	0.000	0.282	0.282	0.000	0.000
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 12

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	19.463	19.463	0.000	0.000
Target point	Y	0.000	0.000	24.576	24.576	0.000	
	Z	0.000	0.000	0.279	0.279	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 13

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	16.345	16.345	0.000	0.000
Target point	Y	0.000	0.000	24.592	24.592	0.000	
	Z	0.000	0.000	0.278	0.278	0.000	0.000
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 14

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	13.239	13.239	0.000	
Target point	Y	0.000	0.000	24.592	24.592	0.000	
	Z	0.000	0.000	0.273	0.273	0.000	0.000
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 15

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	10.099	10.099	0.000	
Target point	Y	0.000	0.000	24.573	24.573	0.000	
	Z	0.000	0.000	0.263	0.263	0.000	0.000
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 16

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	6.980	6.980	0.000	0.000
Target point	Y	0.000	0.000	24.623	24.623	0.000	
	Z	0.000	0.000	0.250	0.250	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 17

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	7.013	7.013	0.000	0.000
Target point	Y	0.000	0.000	22.381	22.381	0.000	
	Z	0.000	0.000	0.249	0.249	0.000	0.000
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 18

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	10.114	10.114	0.000	0.000
Target point	Y	0.000	0.000	22.316	22.316	0.000	
	Z	0.000	0.000	0.260	0.260	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 19

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	13.217	13.217	0.000	
Target point	Y	0.000	0.000	22.392	22.392	0.000	
	Z	0.000	0.000	0.264	0.264	0.000	0.000
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 20

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	16.396	16.396	0.000	
Target point	Y	0.000	0.000	22.424	22.424	0.000	
	Z	0.000	0.000	0.265	0.265	0.000	0.000
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 21

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	19.440	19.440	0.000	
Target point	Y	0.000	0.000	22.387	22.387	0.000	
	Z	0.000	0.000	0.261	0.261	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 22

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	22.677	22.677	0.000	
Target point	Y	0.000	0.000	22.355	22.355	0.000	
	Z	0.000	0.000	0.269	0.269	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 23

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	25.712	25.712	0.000	
Target point	Y	0.000	0.000	22.382	22.382	0.000	
	Z	0.000	0.000	0.271	0.271	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 24

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	28.867	28.867	0.000	
Target point	Y	0.000	0.000	22.372	22.372	0.000	
	Z	0.000	0.000	0.265	0.265	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 25

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	28.837	28.837	0.000	
Target point	Y	0.000	0.000	18.662	18.662	0.000	
	Z	0.000	0.000	0.251	0.251	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 26

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	25.789	25.789	0.000	
Target point	Y	0.000	0.000	18.650	18.650	0.000	
	Z	0.000	0.000	0.254	0.254	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 27

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	22.670	22.670	0.000	
Target point	Y	0.000	0.000	18.594	18.594	0.000	
	Z	0.000	0.000	0.259	0.259	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 28

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	19.475	19.475	0.000	
Target point	Y	0.000	0.000	18.617	18.617	0.000	
	Z	0.000	0.000	0.252	0.252	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 29

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	16.387	16.387	0.000	
Target point	Y	0.000	0.000	18.590	18.590	0.000	
	Z	0.000	0.000	0.257	0.257	0.000	0.000
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 30

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	13.310	13.310	0.000	
Target point	Y	0.000	0.000	18.579	18.579	0.000	
	Z	0.000	0.000	0.255	0.255	0.000	0.000
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 31

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	10.143	10.143	0.000	0.000
Target point	Y	0.000	0.000	18.595	18.595	0.000	
	Z	0.000	0.000	0.248	0.248	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 32

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	7.082	7.082	0.000	0.000
Target point	Y	0.000	0.000	18.583	18.583	0.000	
	Z	0.000	0.000	0.245	0.245	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

Appendix E – ROMER Arm Distortion Measurements: 5-mm After Weld

RP 1

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		0.394	0.394	0.000	
Target point	Y	0.000	0.000		28.050	28.050	0.000	
	Z	0.000	0.000		0.280	0.280	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 2

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		3.488	3.488	0.000	
Target point	Y	0.000	0.000		27.957	27.957	0.000	
	Z	0.000	0.000		0.438	0.438	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 3

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		6.687	6.687	0.000	
Target point	Y	0.000	0.000		28.011	28.011	0.000	
	Z	0.000	0.000		0.572	0.572	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 4

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		9.794	9.794	0.000	
Target point	Y	0.000	0.000		27.930	27.930	0.000	
	Z	0.000	0.000		0.658	0.658	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 5		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	12.839	12.839	0.000	
Target point	Y	0.000	0.000	27.999	27.999	0.000	
	Z	0.000	0.000	0.680	0.680	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 6		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	16.044	16.044	0.000	
Target point	Y	0.000	0.000	27.871	27.871	0.000	
	Z	0.000	0.000	0.635	0.635	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 7		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	19.222	19.222	0.000	
Target point	Y	0.000	0.000	27.949	27.949	0.000	
	Z	0.000	0.000	0.543	0.543	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 8		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	22.353	22.353	0.000	
Target point	Y	0.000	0.000	27.971	27.971	0.000	
	Z	0.000	0.000	0.422	0.422	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 9								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		22.277	22.277	0.000	
Target point	Y	0.000	0.000		24.187	24.187	0.000	
	Z	0.000	0.000		0.359	0.359	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 10								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		19.141	19.141	0.000	
Target point	Y	0.000	0.000		24.167	24.167	0.000	
	Z	0.000	0.000		0.471	0.471	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 11								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		16.091	16.091	0.000	
Target point	Y	0.000	0.000		24.227	24.227	0.000	
	Z	0.000	0.000		0.549	0.549	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 12								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		12.873	12.873	0.000	
Target point	Y	0.000	0.000		24.223	24.223	0.000	
	Z	0.000	0.000		0.586	0.586	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 13								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		9.787	9.787	0.000	
Target point	Y	0.000	0.000		24.314	24.314	0.000	
	Z	0.000	0.000		0.573	0.573	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 14								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		6.493	6.493	0.000	
Target point	Y	0.000	0.000		24.352	24.352	0.000	
	Z	0.000	0.000		0.502	0.502	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 15								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		3.508	3.508	0.000	
Target point	Y	0.000	0.000		24.343	24.343	0.000	
	Z	0.000	0.000		0.395	0.395	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 16								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		0.345	0.345	0.000	
Target point	Y	0.000	0.000		24.378	24.378	0.000	
	Z	0.000	0.000		0.239	0.239	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 17		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	0.312	0.312	0.000	
Target point	Y	0.000	0.000	22.221	22.221	0.000	
	Z	0.000	0.000	0.239	0.239	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 18		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	3.393	3.393	0.000	
Target point	Y	0.000	0.000	22.137	22.137	0.000	
	Z	0.000	0.000	0.383	0.383	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 19		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	6.594	6.594	0.000	
Target point	Y	0.000	0.000	22.212	22.212	0.000	
	Z	0.000	0.000	0.495	0.495	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 20		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	9.607	9.607	0.000	
Target point	Y	0.000	0.000	22.129	22.129	0.000	
	Z	0.000	0.000	0.557	0.557	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 21

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	12.874	12.874	0.000	
Target point	Y	0.000	0.000	22.004	22.004	0.000	
	Z	0.000	0.000	0.564	0.564	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 22

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	16.051	16.051	0.000	
Target point	Y	0.000	0.000	22.095	22.095	0.000	
	Z	0.000	0.000	0.525	0.525	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 23

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	19.172	19.172	0.000	
Target point	Y	0.000	0.000	22.032	22.032	0.000	
	Z	0.000	0.000	0.446	0.446	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 24

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	22.294	22.294	0.000	
Target point	Y	0.000	0.000	22.010	22.010	0.000	
	Z	0.000	0.000	0.335	0.335	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 25

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	22.290	22.290	0.000	
Target point	Y	0.000	0.000	18.297	18.297	0.000	
	Z	0.000	0.000	0.313	0.313	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 26

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	19.149	19.149	0.000	
Target point	Y	0.000	0.000	18.254	18.254	0.000	
	Z	0.000	0.000	0.429	0.429	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 27

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	16.049	16.049	0.000	
Target point	Y	0.000	0.000	18.321	18.321	0.000	
	Z	0.000	0.000	0.519	0.519	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 28

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	12.755	12.755	0.000	
Target point	Y	0.000	0.000	18.332	18.332	0.000	
	Z	0.000	0.000	0.577	0.577	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 29

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		9.659	9.659	0.000	
Target point	Y	0.000	0.000		18.354	18.354	0.000	
	Z	0.000	0.000		0.583	0.583	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 30

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		6.618	6.618	0.000	
Target point	Y	0.000	0.000		18.419	18.419	0.000	
	Z	0.000	0.000		0.524	0.524	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 31

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		3.398	3.398	0.000	
Target point	Y	0.000	0.000		18.374	18.374	0.000	
	Z	0.000	0.000		0.411	0.411	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 32

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		0.357	0.357	0.000	
Target point	Y	0.000	0.000		18.388	18.388	0.000	
	Z	0.000	0.000		0.270	0.270	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

Appendix F – ROMER Arm Distortion Measurements: 8-mm Before Weld

RP 1

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		3.618	3.618	0.000	
Target point	Y	0.000	0.000		28.727	28.727	0.000	
	Z	0.000	0.000		0.349	0.349	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 2

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		6.754	6.754	0.000	
Target point	Y	0.000	0.000		28.636	28.636	0.000	
	Z	0.000	0.000		0.361	0.361	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 3

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		9.940	9.940	0.000	
Target point	Y	0.000	0.000		28.618	28.618	0.000	
	Z	0.000	0.000		0.370	0.370	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 4

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		13.103	13.103	0.000	
Target point	Y	0.000	0.000		28.594	28.594	0.000	
	Z	0.000	0.000		0.371	0.371	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 5		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		16.151	16.151	0.000	
Target point	Y	0.000	0.000		28.599	28.599	0.000	
	Z	0.000	0.000		0.367	0.367	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 6		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		19.362	19.362	0.000	
Target point	Y	0.000	0.000		28.495	28.495	0.000	
	Z	0.000	0.000		0.357	0.357	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 7		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		22.451	22.451	0.000	
Target point	Y	0.000	0.000		28.452	28.452	0.000	
	Z	0.000	0.000		0.349	0.349	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 8		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		25.561	25.561	0.000	
Target point	Y	0.000	0.000		28.406	28.406	0.000	
	Z	0.000	0.000		0.338	0.338	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 9

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		25.511	25.511	0.000	
Target point	Y	0.000	0.000		24.739	24.739	0.000	
	Z	0.000	0.000		0.356	0.356	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 10

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		22.354	22.354	0.000	
Target point	Y	0.000	0.000		24.744	24.744	0.000	
	Z	0.000	0.000		0.363	0.363	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 11

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		19.226	19.226	0.000	
Target point	Y	0.000	0.000		24.825	24.825	0.000	
	Z	0.000	0.000		0.369	0.369	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 12

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		16.041	16.041	0.000	
Target point	Y	0.000	0.000		24.890	24.890	0.000	
	Z	0.000	0.000		0.374	0.374	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 13

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		12.945	12.945	0.000	
Target point	Y	0.000	0.000		24.941	24.941	0.000	
	Z	0.000	0.000		0.371	0.371	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 14

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		9.821	9.821	0.000	
Target point	Y	0.000	0.000		24.971	24.971	0.000	
	Z	0.000	0.000		0.365	0.365	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 15

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		6.721	6.721	0.000	
Target point	Y	0.000	0.000		25.054	25.054	0.000	
	Z	0.000	0.000		0.354	0.354	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 16

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		3.552	3.552	0.000	
Target point	Y	0.000	0.000		25.108	25.108	0.000	
	Z	0.000	0.000		0.340	0.340	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 17								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		3.442	3.442	0.000	
Target point	Y	0.000	0.000		22.925	22.925	0.000	
	Z	0.000	0.000		0.332	0.332	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 18								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		6.606	6.606	0.000	
Target point	Y	0.000	0.000		22.863	22.863	0.000	
	Z	0.000	0.000		0.344	0.344	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 19								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		9.807	9.807	0.000	
Target point	Y	0.000	0.000		22.798	22.798	0.000	
	Z	0.000	0.000		0.357	0.357	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 20								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		12.894	12.894	0.000	
Target point	Y	0.000	0.000		22.700	22.700	0.000	
	Z	0.000	0.000		0.364	0.364	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 21							
		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	16.037	16.037	0.000	
Target point	Y	0.000	0.000	22.668	22.668	0.000	
	Z	0.000	0.000	0.368	0.368	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 22							
		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	19.230	19.230	0.000	
Target point	Y	0.000	0.000	22.601	22.601	0.000	
	Z	0.000	0.000	0.363	0.363	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 23							
		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	22.277	22.277	0.000	
Target point	Y	0.000	0.000	22.543	22.543	0.000	
	Z	0.000	0.000	0.357	0.357	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 24							
		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	25.516	25.516	0.000	
Target point	Y	0.000	0.000	22.511	22.511	0.000	
	Z	0.000	0.000	0.346	0.346	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 25

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	25.416	25.416	0.000	
Target point	Y	0.000	0.000	18.733	18.733	0.000	
	Z	0.000	0.000	0.346	0.346	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 26

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	22.265	22.265	0.000	
Target point	Y	0.000	0.000	18.811	18.811	0.000	
	Z	0.000	0.000	0.355	0.355	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 27

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	19.243	19.243	0.000	
Target point	Y	0.000	0.000	18.836	18.836	0.000	
	Z	0.000	0.000	0.363	0.363	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 28

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	15.973	15.973	0.000	
Target point	Y	0.000	0.000	18.948	18.948	0.000	
	Z	0.000	0.000	0.361	0.361	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 29

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	12.835	12.835	0.000	
Target point	Y	0.000	0.000	18.909	18.909	0.000	
	Z	0.000	0.000	0.355	0.355	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 30

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	9.743	9.743	0.000	
Target point	Y	0.000	0.000	18.978	18.978	0.000	
	Z	0.000	0.000	0.342	0.342	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 31

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	6.525	6.525	0.000	
Target point	Y	0.000	0.000	19.108	19.108	0.000	
	Z	0.000	0.000	0.325	0.325	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 32

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	3.470	3.470	0.000	
Target point	Y	0.000	0.000	19.106	19.106	0.000	
	Z	0.000	0.000	0.311	0.311	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

Appendix G – ROMER Arm Distortion Measurements: 8-mm After Weld

RP 1		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	2.173	2.173	0.000	
Target point	Y	0.000	0.000	25.700	25.700	0.000	
	Z	0.000	0.000	0.383	0.383	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 2		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	5.339	5.339	0.000	
Target point	Y	0.000	0.000	25.738	25.738	0.000	
	Z	0.000	0.000	0.405	0.405	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 3		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	8.454	8.454	0.000	
Target point	Y	0.000	0.000	25.755	25.755	0.000	
	Z	0.000	0.000	0.420	0.420	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 4		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	11.576	11.576	0.000	
Target point	Y	0.000	0.000	25.681	25.681	0.000	
	Z	0.000	0.000	0.423	0.423	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 5

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	14.638	14.638	0.000	
Target point	Y	0.000	0.000	25.677	25.677	0.000	
	Z	0.000	0.000	0.414	0.414	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 6

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	17.849	17.849	0.000	
Target point	Y	0.000	0.000	25.735	25.735	0.000	
	Z	0.000	0.000	0.396	0.396	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 7

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	20.883	20.883	0.000	
Target point	Y	0.000	0.000	25.675	25.675	0.000	
	Z	0.000	0.000	0.384	0.384	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 8

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	24.106	24.106	0.000	
Target point	Y	0.000	0.000	25.666	25.666	0.000	
	Z	0.000	0.000	0.367	0.367	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 9

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	24.104	24.104	0.000	
Target point	Y	0.000	0.000	21.977	21.977	0.000	
	Z	0.000	0.000	0.402	0.402	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 10

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	20.892	20.892	0.000	
Target point	Y	0.000	0.000	21.936	21.936	0.000	
	Z	0.000	0.000	0.407	0.407	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 11

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	17.868	17.868	0.000	
Target point	Y	0.000	0.000	21.984	21.984	0.000	
	Z	0.000	0.000	0.416	0.416	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 12

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	14.647	14.647	0.000	
Target point	Y	0.000	0.000	22.089	22.089	0.000	
	Z	0.000	0.000	0.421	0.421	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 13

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	11.460	11.460	0.000	
Target point	Y	0.000	0.000	22.027	22.027	0.000	
	Z	0.000	0.000	0.419	0.419	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 14

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	8.448	8.448	0.000	
Target point	Y	0.000	0.000	22.073	22.073	0.000	
	Z	0.000	0.000	0.410	0.410	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 15

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	5.275	5.275	0.000	
Target point	Y	0.000	0.000	22.169	22.169	0.000	
	Z	0.000	0.000	0.391	0.391	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 16

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	2.145	2.145	0.000	
Target point	Y	0.000	0.000	22.000	22.000	0.000	
	Z	0.000	0.000	0.370	0.370	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 17								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		2.154	2.154	0.000	
Target point	Y	0.000	0.000		19.809	19.809	0.000	
	Z	0.000	0.000		0.366	0.366	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 18								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		5.218	5.218	0.000	
Target point	Y	0.000	0.000		19.842	19.842	0.000	
	Z	0.000	0.000		0.389	0.389	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 19								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		8.414	8.414	0.000	
Target point	Y	0.000	0.000		19.823	19.823	0.000	
	Z	0.000	0.000		0.412	0.412	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 20								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		11.431	11.431	0.000	
Target point	Y	0.000	0.000		19.772	19.772	0.000	
	Z	0.000	0.000		0.429	0.429	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 21

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	14.688	14.688	0.000	
Target point	Y	0.000	0.000	19.801	19.801	0.000	
	Z	0.000	0.000	0.439	0.439	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 22

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	17.920	17.920	0.000	
Target point	Y	0.000	0.000	19.807	19.807	0.000	
	Z	0.000	0.000	0.438	0.438	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 23

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	20.939	20.939	0.000	
Target point	Y	0.000	0.000	19.804	19.804	0.000	
	Z	0.000	0.000	0.433	0.433	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 24

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	24.104	24.104	0.000	
Target point	Y	0.000	0.000	19.807	19.807	0.000	
	Z	0.000	0.000	0.426	0.426	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 25

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	23.991	23.991	0.000	
Target point	Y	0.000	0.000	15.937	15.937	0.000	
	Z	0.000	0.000	0.463	0.463	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 26

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	20.910	20.910	0.000	
Target point	Y	0.000	0.000	16.050	16.050	0.000	
	Z	0.000	0.000	0.468	0.468	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 27

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	17.863	17.863	0.000	
Target point	Y	0.000	0.000	16.016	16.016	0.000	
	Z	0.000	0.000	0.469	0.469	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 28

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	14.663	14.663	0.000	
Target point	Y	0.000	0.000	15.994	15.994	0.000	
	Z	0.000	0.000	0.460	0.460	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 29

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		11.457	11.457	0.000	
Target point	Y	0.000	0.000		16.015	16.015	0.000	
	Z	0.000	0.000		0.439	0.439	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 30

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		8.412	8.412	0.000	
Target point	Y	0.000	0.000		16.319	16.319	0.000	
	Z	0.000	0.000		0.410	0.410	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 31

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		5.354	5.354	0.000	
Target point	Y	0.000	0.000		16.012	16.012	0.000	
	Z	0.000	0.000		0.380	0.380	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 32

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		2.260	2.260	0.000	
Target point	Y	0.000	0.000		16.264	16.264	0.000	
	Z	0.000	0.000		0.351	0.351	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

Appendix H – ROMER Arm Distortion Measurements: 10-mm Before Weld

RP 1

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	2.413	2.413	0.000	
Target point	Y	0.000	0.000	27.618	27.618	0.000	
	Z	0.000	0.000	0.403	0.403	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 2

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	5.544	5.544	0.000	
Target point	Y	0.000	0.000	27.635	27.635	0.000	
	Z	0.000	0.000	0.412	0.412	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 3

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	8.650	8.650	0.000	
Target point	Y	0.000	0.000	27.586	27.586	0.000	
	Z	0.000	0.000	0.416	0.416	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 4

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	11.680	11.680	0.000	
Target point	Y	0.000	0.000	27.619	27.619	0.000	
	Z	0.000	0.000	0.417	0.417	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 5								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		14.753	14.753	0.000	
Target point	Y	0.000	0.000		27.554	27.554	0.000	
	Z	0.000	0.000		0.416	0.416	0.000	0.000
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 6								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		17.984	17.984	0.000	
Target point	Y	0.000	0.000		27.507	27.507	0.000	
	Z	0.000	0.000		0.415	0.415	0.000	0.000
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 7								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		20.958	20.958	0.000	
Target point	Y	0.000	0.000		27.566	27.566	0.000	
	Z	0.000	0.000		0.414	0.414	0.000	0.000
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 8								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		24.052	24.052	0.000	
Target point	Y	0.000	0.000		27.463	27.463	0.000	
	Z	0.000	0.000		0.415	0.415	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 9

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		24.007	24.007	0.000	
Target point	Y	0.000	0.000		23.729	23.729	0.000	
	Z	0.000	0.000		0.440	0.440	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 10

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		21.033	21.033	0.000	
Target point	Y	0.000	0.000		23.715	23.715	0.000	
	Z	0.000	0.000		0.434	0.434	0.000	0.000
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 11

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		17.930	17.930	0.000	
Target point	Y	0.000	0.000		23.826	23.826	0.000	
	Z	0.000	0.000		0.434	0.434	0.000	0.000
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 12

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		14.775	14.775	0.000	
Target point	Y	0.000	0.000		23.859	23.859	0.000	
	Z	0.000	0.000		0.434	0.434	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 13

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		11.564	11.564	0.000	
Target point	Y	0.000	0.000		23.942	23.942	0.000	
	Z	0.000	0.000		0.431	0.431	0.000	0.000
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 14

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		8.569	8.569	0.000	
Target point	Y	0.000	0.000		24.024	24.024	0.000	
	Z	0.000	0.000		0.426	0.426	0.000	0.000
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 15

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		5.481	5.481	0.000	
Target point	Y	0.000	0.000		24.011	24.011	0.000	
	Z	0.000	0.000		0.417	0.417	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 16

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		2.383	2.383	0.000	
Target point	Y	0.000	0.000		24.073	24.073	0.000	
	Z	0.000	0.000		0.407	0.407	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 17		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	2.281	2.281	0.000	
Target point	Y	0.000	0.000	21.780	21.780	0.000	
	Z	0.000	0.000	0.413	0.413	0.000	0.000
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 18		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	5.443	5.443	0.000	
Target point	Y	0.000	0.000	21.749	21.749	0.000	
	Z	0.000	0.000	0.416	0.416	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 19		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	8.542	8.542	0.000	
Target point	Y	0.000	0.000	21.698	21.698	0.000	
	Z	0.000	0.000	0.422	0.422	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 20		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	11.647	11.647	0.000	
Target point	Y	0.000	0.000	21.659	21.659	0.000	
	Z	0.000	0.000	0.429	0.429	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 21								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		14.764	14.764	0.000	
Target point	Y	0.000	0.000		21.646	21.646	0.000	
	Z	0.000	0.000		0.434	0.434	0.000	0.000
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 22								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		17.928	17.928	0.000	
Target point	Y	0.000	0.000		21.576	21.576	0.000	
	Z	0.000	0.000		0.436	0.436	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 23								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		20.981	20.981	0.000	
Target point	Y	0.000	0.000		21.607	21.607	0.000	
	Z	0.000	0.000		0.436	0.436	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 24								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		24.030	24.030	0.000	
Target point	Y	0.000	0.000		21.563	21.563	0.000	
	Z	0.000	0.000		0.435	0.435	0.000	0.000
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 25		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		24.015	24.015	0.000	
Target point	Y	0.000	0.000		17.860	17.860	0.000	
	Z	0.000	0.000		0.424	0.424	0.000	0.000
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 26		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		20.952	20.952	0.000	
Target point	Y	0.000	0.000		17.933	17.933	0.000	
	Z	0.000	0.000		0.421	0.421	0.000	0.000
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 27		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		17.834	17.834	0.000	
Target point	Y	0.000	0.000		17.913	17.913	0.000	
	Z	0.000	0.000		0.422	0.422	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 28		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		14.680	14.680	0.000	
Target point	Y	0.000	0.000		17.969	17.969	0.000	
	Z	0.000	0.000		0.415	0.415	0.000	0.000
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 29							
		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	11.474	11.474	0.000	
Target point	Y	0.000	0.000	18.087	18.087	0.000	
	Z	0.000	0.000	0.407	0.407	0.000	0.000
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 30							
		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	8.505	8.505	0.000	
Target point	Y	0.000	0.000	18.089	18.089	0.000	
	Z	0.000	0.000	0.399	0.399	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 31							
		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	5.430	5.430	0.000	
Target point	Y	0.000	0.000	18.094	18.094	0.000	
	Z	0.000	0.000	0.391	0.391	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 32							
		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	2.240	2.240	0.000	
Target point	Y	0.000	0.000	18.178	18.178	0.000	
	Z	0.000	0.000	0.384	0.384	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

Appendix I – ROMER Arm Distortion Measurements 10-mm After Weld

RP 1

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	0.900	0.900	0.000	
Target point	Y	0.000	0.000	27.446	27.446	0.000	
	Z	0.000	0.000	0.430	0.430	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 2

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	3.930	3.930	0.000	
Target point	Y	0.000	0.000	27.515	27.515	0.000	
	Z	0.000	0.000	0.423	0.423	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 3

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	7.084	7.084	0.000	
Target point	Y	0.000	0.000	27.494	27.494	0.000	
	Z	0.000	0.000	0.417	0.417	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 4

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	10.048	10.048	0.000	
Target point	Y	0.000	0.000	27.414	27.414	0.000	
	Z	0.000	0.000	0.411	0.411	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 5								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		13.147	13.147	0.000	
Target point	Y	0.000	0.000		27.510	27.510	0.000	
	Z	0.000	0.000		0.409	0.409	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 6								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		16.287	16.287	0.000	
Target point	Y	0.000	0.000		27.478	27.478	0.000	
	Z	0.000	0.000		0.413	0.413	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 7								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		19.338	19.338	0.000	
Target point	Y	0.000	0.000		27.582	27.582	0.000	
	Z	0.000	0.000		0.422	0.422	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 8								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		22.454	22.454	0.000	
Target point	Y	0.000	0.000		27.672	27.672	0.000	
	Z	0.000	0.000		0.434	0.434	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 9

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	22.575	22.575	0.000	
Target point	Y	0.000	0.000	23.837	23.837	0.000	
	Z	0.000	0.000	0.465	0.465	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 10

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	19.509	19.509	0.000	
Target point	Y	0.000	0.000	23.628	23.628	0.000	
	Z	0.000	0.000	0.450	0.450	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 11

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	16.341	16.341	0.000	
Target point	Y	0.000	0.000	23.564	23.564	0.000	
	Z	0.000	0.000	0.438	0.438	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 12

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	13.274	13.274	0.000	
Target point	Y	0.000	0.000	23.595	23.595	0.000	
	Z	0.000	0.000	0.431	0.431	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 13		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	10.050	10.050	0.000	
Target point	Y	0.000	0.000	23.522	23.522	0.000	
	Z	0.000	0.000	0.429	0.429	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 14		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	7.006	7.006	0.000	
Target point	Y	0.000	0.000	23.713	23.713	0.000	
	Z	0.000	0.000	0.430	0.430	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 15		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	3.875	3.875	0.000	
Target point	Y	0.000	0.000	23.587	23.587	0.000	
	Z	0.000	0.000	0.434	0.434	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 16		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	0.890	0.890	0.000	
Target point	Y	0.000	0.000	23.390	23.390	0.000	
	Z	0.000	0.000	0.442	0.442	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 17

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		0.752	0.752	0.000	
Target point	Y	0.000	0.000		21.748	21.748	0.000	
	Z	0.000	0.000		0.448	0.448	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 18

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		3.946	3.946	0.000	
Target point	Y	0.000	0.000		21.629	21.629	0.000	
	Z	0.000	0.000		0.440	0.440	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 19

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		7.120	7.120	0.000	
Target point	Y	0.000	0.000		21.700	21.700	0.000	
	Z	0.000	0.000		0.437	0.437	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 20

		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		10.074	10.074	0.000	
Target point	Y	0.000	0.000		21.532	21.532	0.000	
	Z	0.000	0.000		0.438	0.438	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 21

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	13.173	13.173	0.000	
Target point	Y	0.000	0.000	21.730	21.730	0.000	
	Z	0.000	0.000	0.442	0.442	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 22

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	16.328	16.328	0.000	
Target point	Y	0.000	0.000	21.710	21.710	0.000	
	Z	0.000	0.000	0.449	0.449	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 23

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	19.520	19.520	0.000	
Target point	Y	0.000	0.000	21.633	21.633	0.000	
	Z	0.000	0.000	0.460	0.460	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 24

		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	22.574	22.574	0.000	
Target point	Y	0.000	0.000	21.685	21.685	0.000	
	Z	0.000	0.000	0.470	0.470	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 25							
		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	22.544	22.544	0.000	
Target point	Y	0.000	0.000	18.119	18.119	0.000	
	Z	0.000	0.000	0.483	0.483	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 26							
		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	19.441	19.441	0.000	
Target point	Y	0.000	0.000	17.990	17.990	0.000	
	Z	0.000	0.000	0.475	0.475	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 27							
		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	16.298	16.298	0.000	
Target point	Y	0.000	0.000	17.954	17.954	0.000	
	Z	0.000	0.000	0.462	0.462	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 28							
		Lo. Tol.	Hi. Tol.	Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000	13.274	13.274	0.000	
Target point	Y	0.000	0.000	18.015	18.015	0.000	
	Z	0.000	0.000	0.450	0.450	0.000	
Distance To Target Point		-0.100	0.100	0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100	0.000	0.000	0.000	
Distance On Plane		-0.100	0.100	0.000	0.000	0.000	

RP 29								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		10.046	10.046	0.000	
Target point	Y	0.000	0.000		18.082	18.082	0.000	
	Z	0.000	0.000		0.443	0.443	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 30								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		7.162	7.162	0.000	
Target point	Y	0.000	0.000		18.019	18.019	0.000	
	Z	0.000	0.000		0.439	0.439	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 31								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		4.049	4.049	0.000	
Target point	Y	0.000	0.000		17.984	17.984	0.000	
	Z	0.000	0.000		0.441	0.441	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

RP 32								
		Lo. Tol.	Hi. Tol.		Nominal	Measured	Dev/Mean	Error
	X	0.000	0.000		0.891	0.891	0.000	
Target point	Y	0.000	0.000		18.042	18.042	0.000	
	Z	0.000	0.000		0.442	0.442	0.000	
Distance To Target Point		-0.100	0.100		0.000	0.000	0.000	
Distance to Target Plane		-0.100	0.100		0.000	0.000	0.000	
Distance On Plane		-0.100	0.100		0.000	0.000	0.000	

Appendix J – Data Acquisition Measurements for 5-mm Procedures

This appendix contains data acquired for 5-mm plate welded with preferred procedures. Figure J1 is the Current waveforms for the lead electrode (shown in red) and the trail electrode (shown in blue). Table J1 is the welding parameter data captured at four times per second.

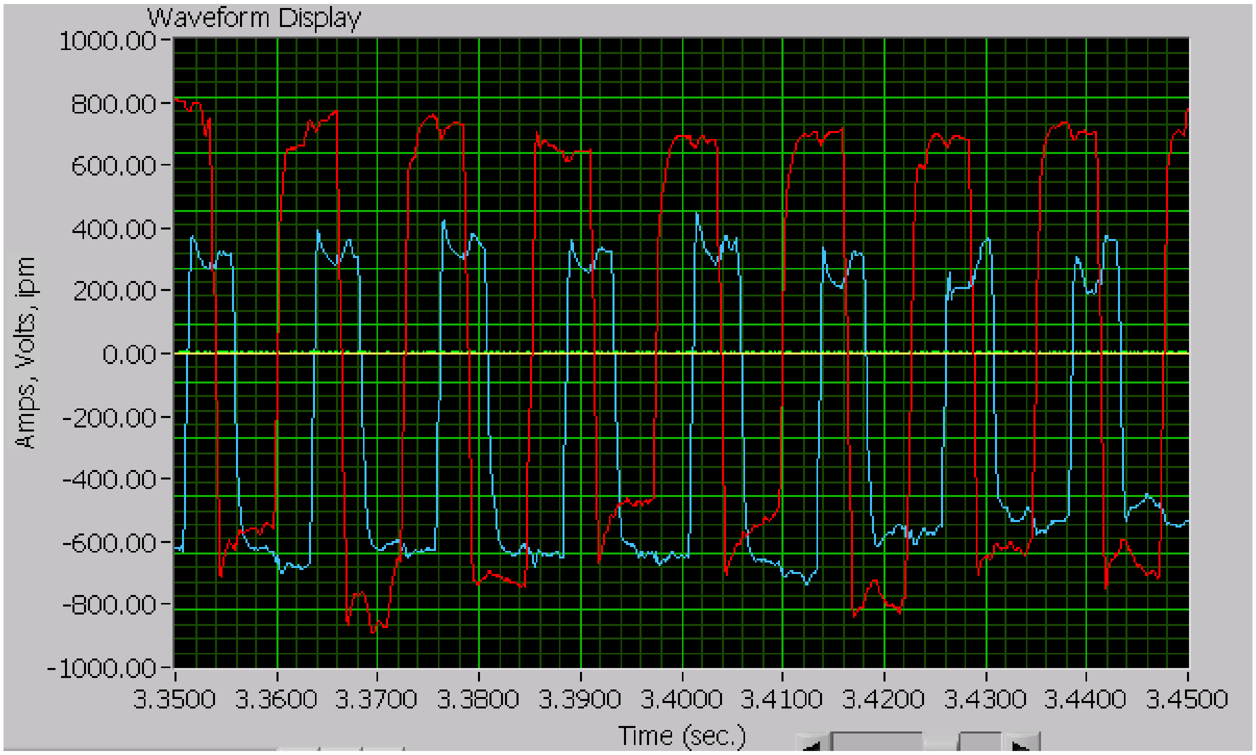


Figure J1 - Current Waveforms for 5-mm Procedures

Table J1 - Data Acquired from 5-mm Procedure Four Times per Second

Time Stamp	Arc 1 Current	Arc 2 Current	Arc 1 Voltage	Arc 2 Voltage	Arc 1 Wire Feed Speed	Arc 2 Wire Feed Speed
0	0	0	0	0	0	0
1	0	0	0	0	24.3	89.5
2	380.1	0	81.7	0	29.5	137.9
3	671.3	0	47.6	0	59.5	140.1
4	618.9	0	41.6	0	62.4	139.9
5	615.4	0	38.4	0	63.2	139.9
6	620.4	0	36.7	0	62.7	140
7	582.1	324	36.6	92.4	75.7	84.7
8	642.2	429	35.9	52.9	71.2	140.3
9	642.7	403.5	35.1	45.9	64.4	156.5
10	649.6	456.3	34.8	40.7	65	152.6
11	660.9	422.3	34.3	39	64.1	160.2

12	664.1	443.3	33.6	37.3	63.3	151.1
13	659.6	483.2	33.6	36.3	64.2	172.4
14	647.7	473.3	33.7	36	64.2	144.3
15	646.7	480.1	33.8	35.9	64.5	156.1
16	659.5	489.4	33.2	35.6	62.9	155.5
17	653.1	473.5	33.2	36	63.7	184.9
18	661.7	504.7	33.2	35.7	64	163.3
19	660.6	489.9	33	35.8	63.6	151.8
20	651.1	497.8	32.9	36	64	204.5
21	655.7	491.1	32.7	35.7	63.6	155.4
22	654.8	508	32.8	35.9	63.5	186.6
23	637.9	490.5	33.3	36	64.8	150.2
24	625.7	492.3	33.7	36.3	66.5	198.4
25	654.4	487.4	33.1	36	64.1	175.1
26	657.9	507.1	32.9	35.8	63.8	160.3
27	668.8	495.5	32.4	36.3	62.7	204.5
28	659.8	486.8	32.4	36.5	63.1	157.3
29	660.2	497.6	32	36.1	62.5	182.9
30	665	487.6	32	36.1	62.3	189.9
31	647	479.4	32.6	36.3	62.6	173.8
32	650.9	495.6	32.3	36.1	62.2	159.9
33	659.7	493.7	32	36.4	62.1	183.7
34	654.3	492.7	32.1	36.7	62.1	151.5
35	657.1	497.9	31.9	36.3	61.7	161.3
36	661.2	487.4	31.8	36.4	61.1	200.6
37	655.4	499.3	31.8	36.5	61.5	161.1
38	657	498.1	32	36.5	60.6	166.8
39	650.7	493.9	31.9	37	61.1	206.2
40	658	508	31.7	36.8	61	182.4
41	667.7	514	31.3	36.6	59.3	181.2
42	635.2	507	32.5	36.1	62.5	178.9
43	651.9	515.7	32.1	36	60.2	199.4
44	661	505.7	31.6	35.9	60.8	177.2
45	645.1	483.3	32.1	36.3	60.8	215
46	653.4	514.3	32	35.3	60.6	180.8
47	654.3	509.8	32	35.4	60.1	187
48	653.2	508	32	35.6	59.9	190.4
49	662.9	500.5	31.6	35.4	59.2	198.3
50	652.5	508.8	31.9	35.1	59.6	183.5
51	641.7	515.2	32.3	35.1	60.1	178.9
52	657.2	519.6	32	35.1	59.7	184.4
53	654	512.2	32.2	34.9	59.9	188.4
54	644.9	507.8	32.1	34.9	58.8	192.8
55	640.7	512.5	32.6	34.7	59.7	188.5
56	640.3	512.7	32.7	34.5	60.2	188.6
57	638.8	483.8	32.7	34.8	60.5	188.8
58	654.4	513.3	32.5	34.4	59.6	181.3
59	656.9	491.3	32.4	34.7	59.3	193.6

60	643.1	501.7	32.7	34.4	60.4	189
61	634.2	516.6	33.2	34.2	61	187.9
62	644.1	509.3	33	34	59.6	191.9
63	649.2	513.2	33	33.8	60.5	191.6
64	655.1	506.8	33	34.2	60.2	194.8
65	663.5	499.7	32.7	34.3	60.3	189.3
66	658.8	521.3	32.7	34.1	59.7	191.6
67	669.6	521.2	32.5	33.8	59.9	190.2
68	650.8	510.8	32.9	33.4	60.5	186.7
69	655.4	513.7	32.6	33.3	59.2	190.2
70	649.8	510.1	32.7	33.2	60.3	187.2
71	652.4	515.9	32.7	33.1	59.4	186.5
72	646.5	515.2	32.9	33.3	60	191.2
73	655.6	496.2	32.9	33.7	60.3	189.8
74	644.5	499.8	32.9	33.4	59.7	190
75	640	517.1	33.2	33.1	60.7	185.4
76	649.2	519.5	33.3	32.8	60	186.1
77	649.8	498.4	33	33.1	60.3	190.7
78	654.3	523.1	32.9	32.8	60.1	184.7
79	646.1	518.7	33	32.5	59.8	185.3
80	647.2	491.9	33.3	33.2	60.2	190.4
81	647.9	492	33	33.2	60.1	191.1
82	646.2	510.8	33.1	33	60.7	186.6
83	659	496.1	32.9	33.2	59.6	190.7
84	639.1	497.2	33.2	33.1	60.2	188.1
85	656.6	500.2	32.8	32.9	59.1	187
86	656.3	516.5	32.9	32.4	60.9	184
87	645.5	509.7	33.1	32.6	60.1	186.6
88	640.8	513.9	33.2	32.8	60.4	188.4
89	653.2	491.7	32.8	33	60.5	190
90	651.4	504.9	32.8	33	60.3	192.1
91	648.1	523.2	32.8	32.5	59.5	186.1
92	650.1	498.8	32.8	33.1	60.7	187.5
93	647.6	499.9	32.7	33.1	58.5	193.6
94	649.8	511	32.8	32.9	59.7	186.3
95	646.8	502.2	33	32.9	60.1	187.2
96	647.2	492.1	33	34.1	60.2	204.7
97	633.9	502.8	33.3	33.6	61.4	187.8
98	651.1	501.8	32.9	33.1	59.6	190.3
99	653.1	502	32.8	33.1	59.8	189
100	642.6	503.8	33	33	60.2	192.1
101	642.6	501.7	33.4	32.9	61	193.9
102	678.2	496.1	32.6	33.4	58.7	197.7
103	637.7	506.2	33.2	33.2	61.2	189.3
104	652.4	495	33.2	33.4	59.7	192.1
105	629.7	494.2	33.3	33.7	61.7	192.2
106	653.6	498.8	33.3	33.5	61	190.4
107	639.7	482.9	33.7	33.7	62.2	193.6

108	655.5	514.9	33.7	32.9	62.1	187.1
109	647	489.4	33.6	33.3	61.4	190.6
110	642.3	507.8	33.8	33.1	61.5	188.5
111	650.6	521	33.6	32.7	61.4	188.1
112	657.6	492	33.2	33.3	61	193.8
113	658	516.3	33.2	33	61	189.7
114	668.1	520.2	32.7	32.6	60.5	188
115	655	476.5	33	33.4	60.9	193.8
116	654.1	505	33.1	32.9	60.8	186.9
117	648.7	499.7	33.1	33	61	194.9
118	655.1	504.6	32.9	32.8	61	186.8
119	665.1	499	32.5	33	59.5	191.9
120	652.6	492.3	32.5	33.2	60.4	191.9
121	644.1	506.2	32.7	32.8	60.8	187.8
122	645.6	507.8	32.9	32.8	60.9	185.9
123	683.8	496	31.8	33	58.6	194.4
124	672.9	506.5	31.8	33	57.6	186
125	646.2	504.2	32.2	32.5	59.8	186.9
126	630.2	496	32.8	32.7	61.1	189.7
127	634.5	491.5	33.1	32.6	60	188.5
128	632.8	496	33.5	32.5	60.4	183.9
129	661.7	503.7	33	31.9	59.8	185.5
130	644	509.1	33	31.6	60.8	180.9
131	642.7	468.2	33.1	32.7	60.5	192.2
132	649.1	502.3	33	32.5	60.1	186.2
133	650.9	490.1	32.8	32.9	60.3	187.7
134	657.9	475.7	32.9	33.3	60.4	187.6
135	648.4	491.6	32.9	33	60.6	188.1
136	651.5	507.3	33	32.5	60.3	184.9
137	647.1	503.5	33	32.1	60.2	183
138	649.9	479.9	32.9	32.5	60.1	185.7
139	664	489.8	32.5	32.7	59.7	189
140	663.1	513.1	32.4	32.7	58.8	188.3
141	641.2	515.5	32.9	32	60.3	182.6
142	666	498.8	32.5	32	58.9	183.3
143	652.5	514.9	32.8	31.9	59.8	182.8
144	643.5	482.1	32.9	32.2	60.1	182.3
145	649.9	505.8	32.9	32.1	60.2	184.5
146	637.7	503.3	33.1	32	60.2	182.3
147	650.2	503.9	33.2	32.1	59.9	182
148	644.2	492.1	33.4	32.4	60.7	185.1
149	643.3	495.9	33.2	32.2	60	181.7
150	646.2	498.1	33.3	32	60.7	180.6
151	637.2	516.1	33.4	31.8	61	179.1
152	643.3	506	33.5	31.8	61.2	180.1
153	659.7	492.8	33	32	60.5	180.2
154	631.9	497.8	33.2	33	60.6	0
155	570.7	0	34.1	0	56.4	0

156	612.9	0	36.4	0	0	0
157	557.1	0	41.3	0	0	0
158	405.9	0	48.7	0	0	0
159	0	0	0	0	0	0
160	0	0	0	0	0	0
161	0	0	0	0	0	0

Appendix K – Data Acquisition Measurements for 8-mm Procedures

This appendix contains data acquired for 8-mm plate weld with preferred procedures. Figure K1 is the Current waveforms for the lead electrode (shown in red) and the trail electrode (shown in blue). Table K1 is the welding parameter data captured at four times per second.

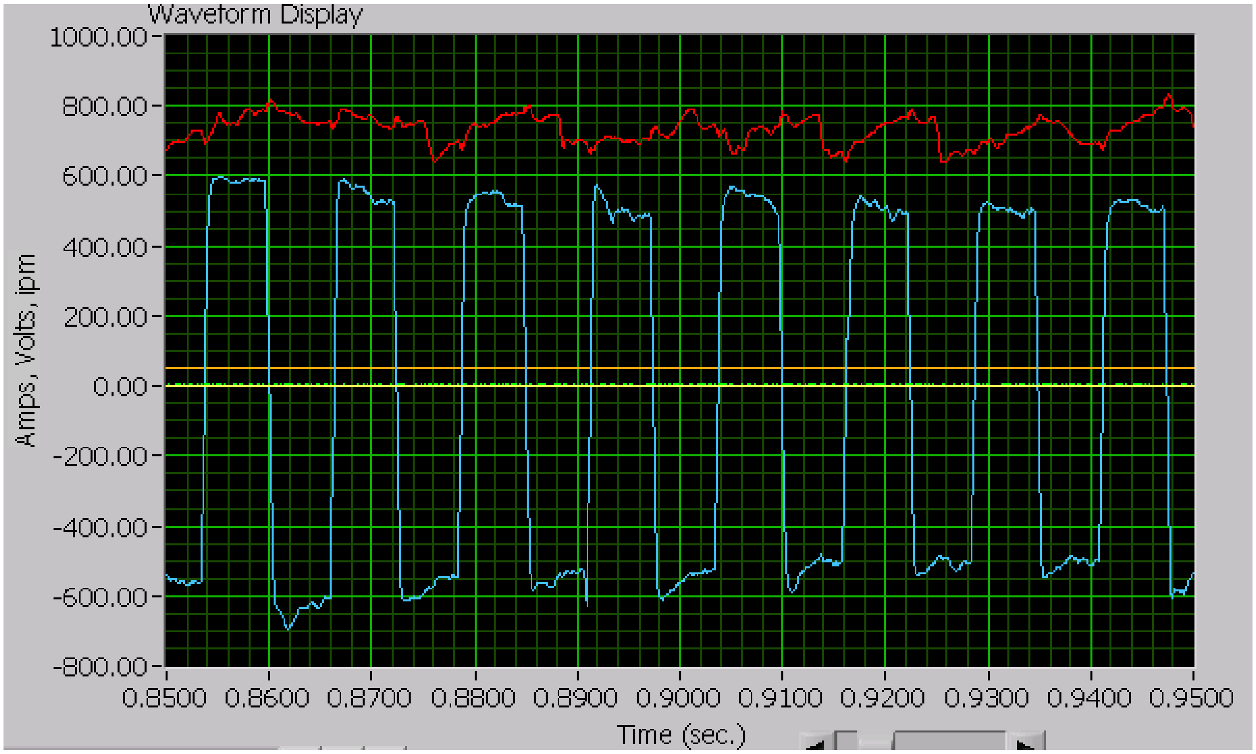


Figure K1 - Current Waveforms for 8-mm Procedures

Table K1 - Data Acquired from 8-mm Procedure Four Times per Second

Time Stamp	Arc 1 Current	Arc 2 Current	Arc 1 Voltage	Arc 2 Voltage	Arc 1 Wire Feed Speed	Arc 2 Wire Feed Speed
0	12.5	0	56	0	28.3	91.3
1	477.8	0	46.5	0	44.5	89.9
2	559	0	40.5	0	61.6	90.1
3	637.9	0	37	0	60	90
4	679.1	74.7	35.2	0	62.1	86.9
5	678.5	416.7	35.1	103	62.5	38.1
6	691.1	377.3	34.9	74	65.3	135.3
7	690.2	394.9	35.4	50.5	67.3	145.4
8	707.3	406.3	35.7	40.1	65.6	144.4
9	744	428.9	34.9	37.9	63.4	145.2
10	760.6	439.6	34.3	36.7	62.2	145.2
11	768.1	437.9	33.6	36.4	61.9	148.3

12	772.2	438.6	33.4	36.3	61.5	151.1
13	760.7	448.9	33.2	36.5	61.2	145.1
14	747.1	451.3	33.6	36.8	62.3	149.7
15	753.6	473.2	33.6	36.6	61.2	151.1
16	750.4	467.6	33.5	36.5	61.7	152.8
17	754.8	499	33.5	36.3	61	157.6
18	744	482.3	33.9	36.6	62.6	152.5
19	749.9	485.1	33.9	36.5	61.8	156.8
20	745.1	476.6	33.9	36.9	62	176.5
21	744.6	482.9	33.8	36.9	62.3	197.9
22	741.6	511.8	33.8	36.4	61.8	153.6
23	744.5	484.1	33.8	36.9	62	179.6
24	745.2	510.7	33.6	36.3	61.5	161.3
25	752	482.1	33.4	36.6	60.7	183.5
26	751.1	502.9	33.3	36.3	60.9	152.8
27	751.1	503.5	33.5	36.4	61	162.6
28	750.2	487.5	33.7	36.7	61.8	158.9
29	754.9	498.5	33.4	36.5	61.2	163.3
30	755.2	506.3	33.4	36.6	60.6	164.3
31	740.6	503.2	33.8	36.7	62.2	183.6
32	738.5	500.4	34.1	36.4	61.7	158.7
33	741.9	493	34	36.6	62.3	167.5
34	743.2	511.1	34.1	36.2	62.2	167
35	744.7	517.8	34.4	35.8	61.7	165.1
36	746.6	494.5	34.3	36.1	62.4	174.2
37	750.5	491.6	34.1	36.3	62.3	176.7
38	752.6	500.2	33.8	36.6	61.1	184.6
39	755.7	500.2	33.4	36.4	60.8	163.4
40	753.2	489.6	33.5	36.7	60.2	158
41	741.1	507	34.2	36.5	61.7	182.8
42	737.2	503.2	34.2	36.6	61.7	178.7
43	741.5	519.4	34.3	36.2	61.6	167.9
44	741.5	498.1	34.2	36.3	62.4	172.5
45	756.1	501.3	33.6	36.2	60.8	175.9
46	743.4	519.4	33.9	36.1	61.3	205.9
47	739.6	496.3	34.3	35.8	61.7	175.9
48	748.2	506.5	34	36.1	61.5	173.5
49	744.8	514.8	34.2	35.8	61.3	173.9
50	750.2	499.5	33.9	36.1	61	172.1
51	758.5	508.7	33.3	35.8	60.8	176.7
52	758	503.6	33.5	35.7	61.1	177.9
53	752.4	489.5	33.7	36	61	181.6
54	753.4	514.3	33.7	35.5	61.1	176.1
55	744.5	491.9	33.8	36.1	61.7	180.8
56	754.1	513.8	33.6	35.5	60.6	138.5
57	753.2	498.2	33.7	35.5	61.1	179.6
58	747	512.9	33.6	35.5	60.7	177.4
59	752.9	510.5	33.5	35.3	60.6	178.9

60	753.1	505.7	33.6	35.2	60.8	180.4
61	746.2	515.6	33.9	34.9	61.1	177.6
62	754.7	497.2	33.7	35.1	61	180.5
63	745	514.4	33.8	34.6	60.5	178.7
64	740.7	508.7	33.8	34.8	60.8	178.8
65	743	516.4	33.8	34.2	61.4	178.9
66	743.2	500.5	33.9	34.6	61.3	179.5
67	736.8	503.2	34.1	34.5	61.3	179.2
68	743	491	34.1	34.9	61.2	181.1
69	744.8	511.3	34	34.5	61.2	180.4
70	751.9	515.4	33.7	34.3	60.2	178.1
71	750.3	501.6	33.8	34.5	61.1	182.2
72	752.4	517.5	33.7	34.1	60.8	178.1
73	751.6	503.6	33.7	33.9	60.8	175.9
74	755.8	503.1	33.7	34.1	60.8	180.6
75	757	509	33.7	33.9	61	178
76	749.7	506.7	33.9	34.3	60.5	174.8
77	744.3	492.7	34	34.2	61.5	182.6
78	748.3	509.3	34	33.7	60.9	176.5
79	742	517.6	34.3	33.5	60.9	174.8
80	745.4	503.7	33.9	33.3	60.7	175.9
81	739.9	484.3	34.3	33.6	61.6	181.5
82	741.9	502.7	34.1	33.5	61.8	176.5
83	745.4	499	33.9	33.8	60.9	176
84	751.8	486	34	34.1	61.3	183.8
85	748.8	502.7	34.1	33.9	61.4	176.3
86	742.8	514.1	34.4	33.5	61.2	177
87	747.8	471.3	33.8	34.5	61.9	183.5
88	749.5	498.3	33.7	34.5	60.6	178.7
89	754.6	517.8	33.6	33.8	61.5	174.2
90	753.1	514.3	34	33.6	61.5	172.9
91	747.3	513.8	33.9	33.3	61.9	173.7
92	746.6	504.4	33.9	33.4	60.3	175.6
93	766.5	503.7	33.2	33.7	60.1	179.4
94	762	483.1	33.4	34	60.1	178
95	750.9	498.4	33.7	33.7	62.3	177.7
96	748.7	499.6	33.9	33.7	60.8	174.5
97	754.8	478.4	33.8	33.7	61.7	192.1
98	752.4	499.1	34.1	34.4	61.1	170
99	744.4	488.6	34.2	34.1	62.1	180
100	743.2	493.5	34.7	33.8	61.9	177.7
101	743.2	513.6	34.4	33.4	61.3	174.1
102	748.8	503.7	34.2	33.6	61.8	175.6
103	753.9	494.2	34	34.3	62	179.8
104	748.1	491.2	34.3	34.2	62.1	178.4
105	753	500	34	33.9	61.6	175.6
106	754	507	33.9	33.8	60.8	172.4
107	755.7	505.5	33.9	33.8	60.4	177.4

108	750.4	494	33.9	34.1	60.4	175.5
109	763.7	513.7	33.6	33.6	60.4	174.4
110	761.5	494.9	33.6	33.5	62	176.8
111	756.1	493.5	33.7	33.7	61.3	173.1
112	755.9	501.2	33.7	33.4	61	174
113	746.6	495.8	34.2	33.6	61.3	173.8
114	751.4	497.1	34.1	33.9	61.6	176.1
115	748.3	475.9	34	34.4	60.2	184
116	749.5	479.8	33.8	34.6	60.3	189.9
117	763.2	490.1	33.4	34.6	60.4	175.9
118	753.6	507.4	33.7	34	60.9	173.5
119	757.7	509.1	33.4	33.7	60.5	174.2
120	755.1	498.1	33.6	33.9	60	176.7
121	756.7	503.3	33.4	33.7	60.1	173.6
122	754.8	487.5	33.5	33.9	59.8	177.5
123	745.5	504.8	33.8	33.8	60.7	174.8
124	752.7	508.5	33.8	33.4	60.7	173.1
125	755	493.5	33.6	33.8	60.1	176.5
126	741.3	504.7	34.2	33.7	61	175.2
127	744.7	487.9	34	33.9	61.6	178.6
128	744.6	506.1	34.3	33.7	61.5	172.7
129	750	502.9	34.1	33.9	60.6	174.7
130	743.7	494.9	34.2	34	61.3	176.1
131	748.9	504.9	34	33.9	60.6	174.7
132	746.2	479.2	34	34.9	61.1	178.9
133	744.3	503.7	34.1	34.5	61.1	172.7
134	754.3	516.8	33.9	33.3	60.8	171.9
135	756.4	475.1	33.8	34.4	62.3	181.3
136	757.1	500.9	33.6	33.9	60.8	172.8
137	755.1	474.2	33.7	34.3	61.7	177.3
138	767.7	508.9	33.4	33.8	60	175.1
139	755.5	507.2	33.7	33.7	60.1	175.9
140	757.7	489.9	33.7	34.3	60.7	179.3
141	741.4	507.4	34	33.7	60.7	174
142	735	505.4	34.3	34	61	176.2
143	743.3	503.6	34.2	33.7	60.9	173.9
144	749	486.4	34.1	34.5	61.2	180.3
145	746.7	501.7	34.3	34	61.4	174.8
146	754.2	497.7	34.1	34.2	60.7	177.4
147	753.6	495.9	34	33.9	60.5	177
148	754.5	477.3	34	34.7	60.4	181
149	745	489.1	34.1	34.6	61.2	176.9
150	739.2	497.1	34.2	34.3	61.5	178.7
151	741.9	486.2	34.1	34.5	60.8	180.7
152	751.7	512.3	34.1	34.1	60.9	173.7
153	744.7	491.7	34.2	34.1	61.9	179.6
154	745.2	516.7	34.4	33.6	62	174.9
155	753.4	498.8	34	34	61.6	179.3

156	751.7	484.3	34	34.2	61.8	179
157	754.4	494	34	33.9	61.4	178.1
158	755.8	514.4	33.9	33.7	60.6	172.9
159	751.2	507.6	34.2	33.8	61.1	178.9
160	751.7	493.2	34.1	34.4	60.9	177.7
161	748.5	508	34.2	34	61.1	176.1
162	754.1	502.7	34.3	33.7	61.5	174.4
163	757.1	503.6	34	33.6	60.8	172.2
164	748.5	487	34.1	34	61.4	178.7
165	747.3	481.7	34.4	34	61	176.8
166	750.4	495.7	34.3	34	61.8	177.2
167	754.2	507.6	34.3	33.4	61.3	172.4
168	750.6	497.7	34.3	33.3	61.4	176.3
169	746.1	504.9	34.3	33.6	61.5	174.4
170	748.7	492.7	34.3	33.5	61.6	178.7
171	750.6	496.3	34.1	34	62.3	175.9
172	762.4	510.6	33.9	33.7	62.9	173.1
173	757.7	488.4	33.9	34.2	61.9	179.1
174	751.1	490.4	34	34.5	62.3	175.7
175	746.7	485.9	34	35	61.2	178.6
176	746.5	500.4	34.2	34.7	61	177.2
177	743.6	523.9	34.6	33.3	61.8	171
178	748.7	494.8	34.2	33.5	62.6	178.1
179	748.8	511.8	34	33.2	62	173.5
180	750.3	504.5	33.8	33.6	61.3	173.9
181	752.5	495.2	33.7	33.8	62.3	177.3
182	755.5	486.3	33.7	34.3	61	175
183	756.9	501.5	33.8	33.8	61.7	178.9
184	755.2	486	34	34	62	180.2
185	752.4	508	34	34	61.2	173.3
186	757.2	511.4	33.8	33.7	60.8	174.3
187	749	493.4	34.2	33.7	62.5	175.6
188	746	506.9	34.3	33.3	62.3	172.5
189	749.5	498.2	34.4	33.5	62.5	178.4
190	763.3	508.2	34	33.4	61.7	172.6
191	759.6	502	33.9	33.3	61.4	173.5
192	771.2	508.2	33.3	33.2	60.5	171.5
193	758.2	481.6	33.6	33.8	62	176.5
194	760	499.9	33.5	33.6	60.5	174.4
195	758.9	497.2	33.5	33.8	60.5	173.6
196	749.4	502	33.7	33.6	60.9	172.3
197	752.5	500.1	33.9	33.6	61.2	173.5
198	749.1	509.1	33.7	33.3	61	170.9
199	753.1	508.4	33.8	33.4	60.5	171
200	755.9	491.7	33.4	33.7	60.6	176.3
201	747.5	466.7	33.6	34.3	61.1	179.9
202	742.9	506.2	33.9	34.2	61.1	173.6
203	751.6	495.4	34	33.9	61.5	175.9

204	762.1	503.4	33.7	33.7	60.5	172
205	755.9	491.9	34	34.6	60.7	176.4
206	755.7	480.9	33.8	34.5	61.1	177.7
207	763.5	520.2	33.4	33.8	61.7	174.6
208	749.3	510.5	33.8	33.8	61.3	175.6
209	750.8	498.7	33.9	34.1	61	174.7
210	749.3	506.7	33.9	33.8	60.8	172.5
211	750	475.2	33.7	34.8	61.4	182.9
212	747.3	498.9	34	34.9	61.1	175.9
213	747.6	506.7	33.8	34.3	60.9	175
214	745.6	515.5	33.8	34.1	60.9	172.9
215	749.5	491.4	33.7	34.5	60.4	175.7
216	754.3	507.5	33.4	34.1	60.5	176.6
217	763	489.9	33.3	34.2	59.6	176.9
218	755.7	498	33.3	34.3	59.7	181.9
219	748.8	497.5	33.3	34.4	60	177.7
220	760.1	502.9	33.3	34	59.2	176
221	739.5	508.2	33.9	33.6	60.6	173.8
222	741.9	506.6	33.6	33.4	59.5	172.9
223	739.6	484.2	33.9	34	59.7	180.1
224	738.3	494.8	34	33.9	61.2	176.1
225	749.8	495.2	33.6	33.7	60.4	177.2
226	746.1	500.9	33.6	33.5	60.7	174.5
227	744	484	33.7	34.1	60.6	178.7
228	746	493.9	34.1	33.9	60.7	176.9
229	742.7	504.8	34.2	34	61.1	173.8
230	656.9	538.3	33.5	33.9	45.4	63.5
231	643	350.4	32.5	40	44.8	63.5
232	621.7	0	33.9	0	0	0
233	610.7	0	38.7	0	0	0
234	0	0	0	0	0	0
235	0	0	0	0	0	0
236	0	0	0	0	0	0
237	0	0	0	0	0	0
238	0	0	0	0	0	0

Appendix L – Data Acquisition Measurements for 10-mm Procedures

This appendix contains data acquired for 10-mm plate weld with preferred procedures. Figure L1 is the Current waveforms for the lead electrode (shown in red) and the trail electrode (shown in blue). Table L1 is the welding parameter data captured at four times per second.

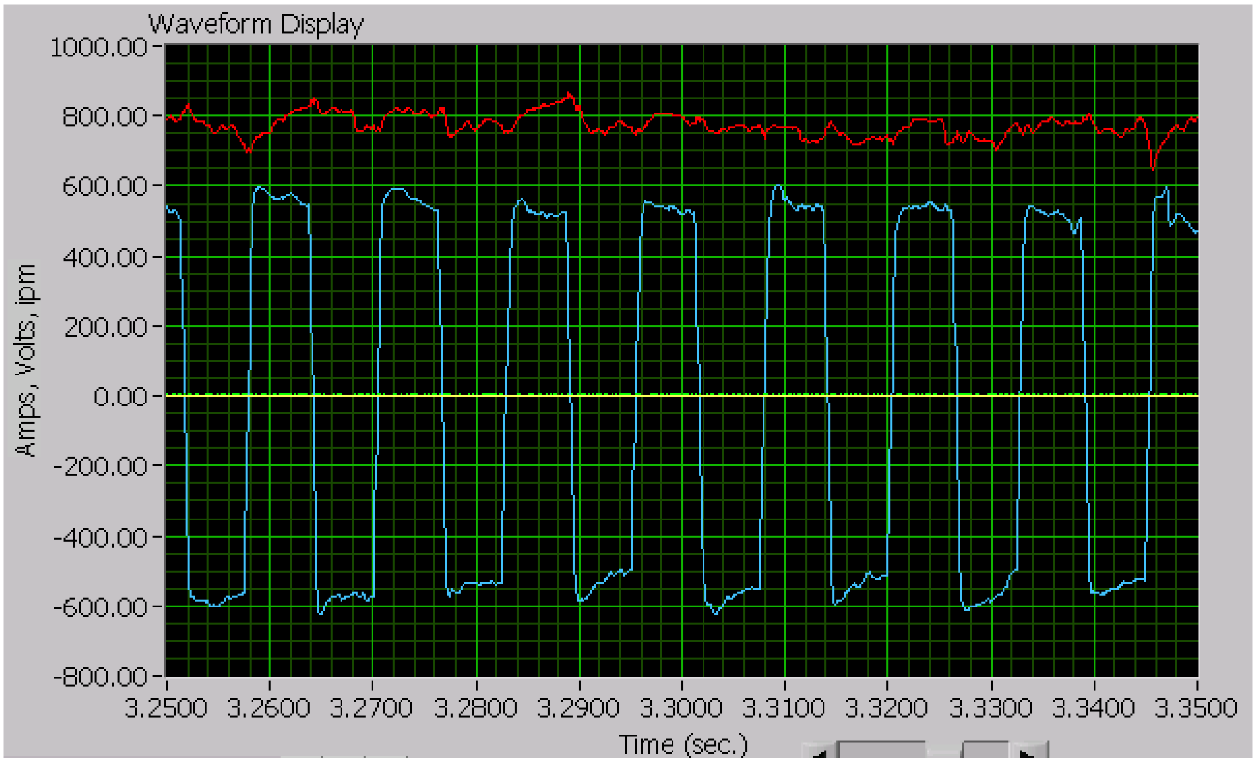


Figure L1 - Current Waveforms for 10-mm Procedures

Table L1 - Data Acquired from 10-mm Procedure Four Times per Second

Time Stamp	Arc 1 Current	Arc 2 Current	Arc 1 Voltage	Arc 2 Voltage	Arc 1 Wire Feed Speed	Arc 2 Wire Feed Speed
0	0	0	0	0	28.2	90.7
1	616	0	48	0	61.2	90.1
2	684.9	0	41.8	0	66.2	90
3	708.8	0	38.9	0	69.1	90
4	734.3	0	37.7	0	68.1	90
5	744.1	121.9	36.6	116.5	75.7	71.4
6	742.9	547.1	36.4	84.6	89.2	53.8
7	735.7	425.6	37	63.5	100.4	147.8
8	755.5	384.4	36.8	51.1	74	145.2
9	762.5	424.5	36.8	43.5	72.4	140.9
10	790.6	383.3	35.6	38.9	71	207.4

11	820.1	428.1	34.4	38	69.5	165.1
12	817	430.2	34.5	37.9	71	177.7
13	811	436.8	34.8	37.7	70.7	200.4
14	800.9	498.9	34.9	36.7	71.6	158.8
15	809.2	483.1	34.5	36.4	71.6	147.6
16	803.9	481.1	34.5	36.7	70.8	179.3
17	805.4	496.3	34.5	36.3	71.5	143.4
18	817.3	489.8	34.2	36.3	70.6	156
19	821.2	486.6	33.8	36.4	70.4	157.4
20	822	504	33.7	35.9	69.6	156.3
21	804	495.5	34.1	36.3	71	155.4
22	799.9	491.2	34.5	36.7	71.8	162.1
23	804.7	494.6	34.3	36.7	71.6	158.6
24	820.1	495.5	33.8	36.7	71.3	177.4
25	812.9	494.3	33.9	36.6	70.9	182.3
26	814.8	472.4	34	36.9	70.9	173.4
27	815.6	486.3	33.4	36.9	69.3	172.3
28	810.8	514.8	33.6	36.7	70.3	177.4
29	812.6	515	33.6	36.8	69.8	157.7
30	806.4	489.9	33.7	36.9	70	183.1
31	799.8	512.7	33.6	36.3	70.8	164.4
32	807.4	518.2	33.4	36.1	69.8	176.4
33	807	507.2	33.5	36.1	68.9	165.6
34	803.6	518.1	33.4	35.8	68.6	127.8
35	793.1	488.6	34	36.5	71.3	165.7
36	804.3	495.2	34	36.8	69.3	192.7
37	804.6	520.4	34	36	69.2	159.6
38	804.9	518.8	33.8	36.1	70	169.8
39	813.4	511.1	33.5	36.1	68.2	167.8
40	811.1	505.8	33.3	35.9	69.1	171.9
41	803.1	509.1	33.8	35.8	71.6	169.4
42	783.1	499.1	34.5	36.1	71.3	172
43	794.5	502.3	34.4	36.1	69.8	172.7
44	800.4	497.6	34.4	35.7	71.1	135
45	798.7	487.4	34.4	36.3	67.9	199.2
46	786.2	503	34.4	35.5	70.6	178
47	801.6	512.7	33.8	35.4	71	175.6
48	802.4	475.7	33.8	36.8	70.4	144.1
49	801.3	512.1	33.4	36.4	69.4	187.2
50	808.3	487.2	33.2	36.7	69.9	188.1
51	813	474.5	33.1	38	69.2	221
52	808	515.6	33.4	36.6	69.8	198.2
53	808.5	503.6	34.2	36.2	71	181.2
54	804.3	521.5	34.2	35.7	69.7	177.5
55	784.7	518.4	34.8	35.9	71.2	174.3
56	787.4	507.7	34.7	35.6	70.6	174.6
57	806.1	501.7	33.8	35.5	69.8	180.2
58	801.6	506.5	33.8	36	68.8	186

59	815	519.5	33.5	35.3	70.3	171.5
60	813	508.8	33.5	35.2	69.9	172
61	801.6	520.9	34	34.8	69.8	178.3
62	790.7	512.4	34.1	34.8	70.2	179
63	800	511.8	33.7	34.5	68.8	178.7
64	793.7	485.9	34.1	35.4	69.7	186.5
65	813.9	518.3	33.4	34.6	68.9	171.7
66	794.7	498.4	34.2	34.8	70.8	180.8
67	798.8	520.1	33.9	34.3	70.4	176.6
68	815.8	511.5	33.6	34.4	68.4	179.7
69	812.1	508.3	33.7	35.2	70.4	184.4
70	797.2	484.4	33.7	35.1	68.8	178.4
71	792.6	508	33.9	34.7	69.8	178.5
72	795.5	499.2	33.8	34.4	69.6	183.1
73	783	491.3	34	34.6	68.2	181.7
74	785.6	509.1	34.2	34.2	70.2	177.4
75	791.9	500.8	34.6	33.9	69.9	181.4
76	790.1	514.9	34.4	33.5	69.5	179.6
77	796.7	480.9	34.3	34.2	70.1	184.2
78	807	507	33.9	33.8	69.9	180.4
79	804.2	515	33.8	33.3	69.7	176.3
80	803.2	504.7	33.7	33.4	68.4	177.2
81	791.1	525.1	34.1	32.8	69.8	171.7
82	795.4	525.1	34.2	33.3	69.8	174
83	797.2	480.8	33.8	34.3	70.2	180.1
84	796.3	489.4	33.7	33.9	70.4	178.3
85	793.9	516.8	34	33.4	70.1	179
86	804.9	504.1	33.4	33.4	70.1	175.8
87	803.7	506.7	33.4	33.6	69.3	180.1
88	815.6	528.4	33.7	33.3	67.6	137.5
89	805.7	485.2	33.8	34.5	69.8	172.1
90	799.3	480.4	34.1	35.2	70.5	186.8
91	803.3	492.6	34.1	35.1	69.3	176.8
92	798.5	507.8	33.5	33.9	69.2	177.7
93	808.1	496.5	33.2	34	69.2	184.6
94	806.8	497.7	33.4	33.9	68.5	183.6
95	806	503.1	33.4	34.1	69.5	178.8
96	781.9	509.9	34.1	33.7	70.1	177.9
97	792.4	524	34	33.3	69.8	175.8
98	812.7	521.7	33.6	33.1	69.5	175
99	803.2	504.1	33.8	33.3	69.6	176.9
100	795.7	506.8	33.9	33.6	68.7	175.7
101	793.2	506.2	34.1	33.5	69.7	175.1
102	796.6	512.3	34.2	32.9	68.8	172.2
103	797.9	500.5	34.1	33.3	69.2	175.8
104	797.6	505.3	33.9	33	68.6	174.4
105	802.2	502.7	33.4	33.2	68.6	173.8
106	811.1	501.1	32.9	33.2	64.3	174.1

107	805.9	499.9	33.6	33.2	68.8	174
108	808.7	481	33.5	34.1	68	176.1
109	808.7	490.6	33.1	33.6	68.3	174.9
110	806.2	494.9	33.6	33.9	69.2	177.5
111	804.1	504.1	33.4	33.6	69.1	173.8
112	792.5	501.3	34.1	33.5	68.9	173.4
113	784.9	478.1	34.1	34	67.6	172.2
114	794.4	515.2	34.2	33.4	69	174
115	809.1	495.6	34	33.7	67.5	194.2
116	801	504.6	34	33.6	68.9	166.6
117	796.1	495.2	34.2	33.8	69.5	174.2
118	799	513.4	34.3	33.5	69.5	173.6
119	812.2	512.5	34.1	33.3	68.6	171
120	818	527.1	33.9	33.2	68.5	168.3
121	813.3	492.4	34	34	68.8	175.7
122	799.2	499.8	34.3	34.1	69.8	176
123	798.6	502.5	34.4	34.1	69.8	173.5
124	799.4	505.1	34.2	33.5	68.2	171.1
125	809.2	500.5	34	33.4	67.8	174
126	804	496.4	34.1	33.4	69.1	175
127	804	498.2	34.1	34.7	69.8	173.8
128	805	489.9	34.2	34.5	69	172.6
129	799.7	494.5	34.4	34.3	70.2	175.4
130	795.6	494.6	34.6	34.2	69.8	175.1
131	805.7	510.1	34.2	33.5	68.8	173.3
132	809.5	522.6	34.1	33.5	68.6	171.7
133	807.8	498.2	34.2	33.9	68.3	176.5
134	814.4	505.9	33.7	33.7	67.7	176
135	809.3	527.6	33.7	33.2	69.5	170.1
136	802.9	501.7	33.6	33.7	70	175.3
137	800.4	526.6	33.9	33.3	69.6	172.4
138	807.9	515.3	33.4	33.4	67.9	174.6
139	805.3	483.8	33.6	34.2	69.3	180.7
140	805	504.3	33.6	33.9	69.3	173.7
141	805.7	494.6	33.5	34.2	69.1	176.3
142	804.6	499.2	33.9	34.3	69.7	175.2
143	805.2	510.4	34	33.4	69.5	171.6
144	803.9	501.6	33.9	33.8	69	173.7
145	792.5	499.5	34	33.8	67.7	174
146	798.3	501.6	33.5	33.6	67.6	173.9
147	789.1	506.3	34	33.4	68.7	173
148	782.4	498.5	34.2	33.4	68.6	177.1
149	791.6	517.9	34	32.9	68.8	170.3
150	798.6	503.1	34.1	33.6	69	173
151	793.2	497.4	34.3	33.8	70	173.8
152	792.9	470.2	34.3	34.4	68.7	185.3
153	788.6	479.6	34.1	34.1	69.2	183.4
154	783.5	489.5	34.2	35	69.2	199.5

155	797.1	485.6	34.2	34.9	69.6	136.2
156	789.4	488.4	34.7	34.8	69.7	176
157	799.4	512.4	34.5	34.4	68.6	180.3
158	801.7	496	34.2	34.4	69	179.3
159	806	505.4	33.9	34.2	69.9	176.2
160	812.7	509.5	34	34.7	69.8	174.4
161	798.6	505.7	34.5	34.3	69.7	178.8
162	805.5	518.5	34.1	33.9	69.2	176.2
163	807.7	495.5	34	34.1	69.3	179.2
164	801.7	489.4	33.9	34.7	69.4	182.1
165	801.3	504.9	33.7	34.1	68.6	176.1
166	799.3	505.9	34.2	33.8	69.7	176.6
167	805.2	496.8	34.1	34.2	69	177.6
168	798	495.5	34.4	34.6	62.2	182.6
169	787.8	507.3	34.6	34.2	71.3	174.8
170	788.5	493.2	34.2	34.4	70.7	178.9
171	792.6	511.3	33.8	33.6	69.3	177
172	801.4	503.3	33.8	33.8	69	177.7
173	796.5	509.2	33.8	33.6	69.1	176.3
174	800.6	507	33.6	33.8	69	176
175	792.3	512.2	33.8	33.7	69.9	175.3
176	800.4	507.5	33.7	33.6	68.7	175.4
177	802.9	512	33.5	33.5	69.1	173.7
178	796.8	491.5	33.9	33.8	69.3	177.2
179	799	488	33.9	34.1	69.7	178.3
180	804.9	491.5	33.5	33.9	69.1	178.9
181	801.5	508.2	33.8	33.6	69.7	173.5
182	796.6	497.2	33.9	33.8	69	176
183	800.9	495.5	33.9	33.9	69.6	176.3
184	805.4	480.4	33.7	34	69.4	177.3
185	807.3	496.2	33.5	34.4	68.7	177.4
186	807.8	491.8	33.3	34.2	68.7	176.5
187	809.2	508.6	33.9	34.1	69.2	133.9
188	806.6	465.4	34.3	35.5	66.8	142.8
189	794.6	454.6	34.4	35.9	70.1	188.6
190	799.8	497.9	34.2	35	69.4	168.9
191	808.9	505.8	33.7	34.8	68.7	178.6
192	792.5	496.2	34.2	34.7	69.5	181.3
193	800.7	516.8	33.8	33.9	68.5	178.5
194	806.3	493.3	33.7	34.4	68.8	178.9
195	803.8	505.2	33.8	34.3	68.9	178.9
196	801.9	499.4	34.1	34.2	68.1	182
197	796.6	512.7	34.1	34	69.2	178.4
198	793.1	489.5	34.2	34	69.1	181.7
199	788.9	498.7	34.2	34.2	68.6	182.1
200	797.9	508.5	34.1	33.7	69.6	175.9
201	807.6	524.5	33.9	33.3	69.7	176.1
202	801.7	532.7	34.2	33.3	69.1	172.3

203	802.6	492	33.8	34.5	68.4	178.5
204	805.9	508.6	33.9	33.8	69.5	178.9
205	796	424	34	42.6	69.5	163.7
206	793.6	446	33.9	40.3	68.1	176.5
207	788.2	471.4	34.2	39.1	69.3	198.6
208	788.7	494.3	34.7	37.1	71	171.8
209	796.4	504.4	34.2	35	70.2	181.3
210	796.4	511.8	34.3	34.2	69.6	180.8
211	795.3	526.9	34.4	33.2	69.7	178.4
212	804.3	510.3	33.8	33.4	68.8	181.5
213	801.1	519.4	34	32.8	68.8	179.1
214	812.2	512.5	33.9	32.8	68	180.3
215	805.8	506.9	33.9	33.3	69.3	178.4
216	798	504.3	33.7	32.9	69.9	183.2
217	793.8	512.2	33.8	33.3	69.4	182.7
218	801.5	506.3	33.9	33.7	69	184.2
219	789.1	508.1	34.5	33.6	70.6	181
220	794.9	511.7	34.4	33.2	70.8	177.2
221	806.1	515.4	34.1	32.9	71.1	176.9
222	828.4	525.3	32.9	32.5	66.9	175.1
223	827.7	509.4	32.8	32.6	68	175.8
224	808.9	500.1	33.6	32.7	69.3	177.8
225	791.6	503.6	34.3	32.8	70.8	176.5
226	776.6	492.7	35.2	32.9	71.9	176.6
227	782.5	496.6	35.1	33.3	71	175.2
228	793.3	493.8	34.6	33.2	70.1	175.7
229	803.4	496.5	34.3	33.3	69.8	176.2
230	812.5	502.7	33.9	33	68.8	174.6
231	803.1	514.6	33.8	33	68.6	172.7
232	812.7	480.2	33.5	33.6	69.1	178.3
233	807.8	494.1	33.7	33.8	70.6	179.4
234	805.2	501.7	33.7	33.3	70	172.3
235	809.2	493.7	33.9	33.4	69.7	175.2
236	802	494.5	34	33.5	69.4	176.9
237	802	483.6	34	34.1	69.1	179.3
238	807.2	503.7	33.7	33.5	68	175.5
239	793.8	489	34.2	33.6	70.4	174.1
240	802.2	491.4	33.7	33.6	69.4	168.6
241	807.6	488.5	33.5	33.5	67.5	176
242	829.4	505.9	33.4	33.5	63.4	179.1
243	805.8	485.1	34	34	70.5	174.3
244	789.3	490.1	34.5	33.8	69.2	175.5
245	794	496.4	34.3	33.8	70.6	175.5
246	795.8	468.6	34.2	34.6	68.7	186.7
247	793.5	476.5	33.8	35	68.2	187
248	806.8	486.7	33.4	34.4	69.9	187.6
249	801.8	509.2	33.8	33.9	69.8	178.3
250	796.3	503.6	33.9	34.2	69.7	180.4

251	806.2	489.5	33.7	34.5	68.7	182.6
252	790.9	487.2	34.3	34.7	70.5	188.1
253	802	490	34	35.1	69.7	180.6
254	831.6	481.4	32.5	35	57	203.4
255	821.9	514.3	32.4	34.1	66.4	167.2
256	809.1	520.8	32.7	33.9	67.2	178.3
257	799.8	517.9	33.2	33.8	67.6	178.1
258	789.2	515.8	33.3	33.7	67.7	175.3
259	790.3	512.8	33.6	33.4	67.8	175.8
260	792.2	516.9	33.4	33.3	67.5	173.8
261	799.4	492.8	33	33.8	67.2	177.2
262	797.9	507.6	33.2	33.6	67.2	176.7
263	795.1	501.8	33.3	33.6	67.3	176.2
264	801.4	509	33.1	33.4	66.9	173.5
265	797.2	498.5	33.4	33.5	66.7	177.3
266	795.5	497	33.4	33.7	66.8	175.2
267	800.8	515.2	33.4	33.2	66.4	173
268	807.5	507.9	33.2	33.4	66.6	172.3
269	797.9	515	31.1	34.1	66.1	0
270	731.6	456.8	31.1	36.7	44.9	65.3
271	660	0	30.9	0	44.7	0
272	648.9	0	32.3	0	0	0
273	644.6	0	35.9	0	0	0
274	0	0	0	0	0	0
275	0	0	0	0	0	0
276	0	0	0	0	0	0
277	0	0	0	0	0	0
278	0	0	0	0	0	0

Appendix M – Thick Section Welding with Developed Procedures

At the request of NGNN, EWI attempted to weld 1-in. thick steel plates using the developed tandem SAW procedures. A butt joint configuration with each plate having a 45° bevel and a 5.5-mm root face was used. Root opening (gap) between the two plates was 3.0-mm.

The preferred procedure developed for the 8-mm plate thickness was used (Table M1). The resulting weld macrograph is shown in Figure M1. The bead profile was very nice, with complete penetration, good wetting into the joint, and consistent root bead reinforcement height. Future 1-in. thick butt joints may benefit from a reduced bevel angle joint design.

Table M1 - Parameters for 1-in. Plate (Same as 8-mm Preferred Procedures)

WELD ID	Plate Thickness (mm)	Root Face and Bevel Angle	Root Opening (mm)	Wire Separation (in.)	TRAVEL SPEED (ipm)	Combined Heat Input (kJ/inch)	Lead WFS (ipm)	Trail WFS (ipm)	DATA ACQ FILENAME
F01	1 inch	5.5mm, 45°	2.9	0.78	35.0	72.9	62	175	_11-07-05_16.27.24.txt
	------------------------------LEADING WIRE PARAMETERS------------------------------								
	Wire Dia (in.)	Trav. Angle (degr.)	Tip-to-Work (in.)	Waveform, %EP, DCOffst	RMS Current SETPOINT	VOLT SETPOINT			
	0.15625	0	1.25	CC DC+	750	34			
	----------------------------TRAILING WIRE PARAMETERS----------------------------								
	Wire Dia (in.)	Trav. Angle (degr.)	Tip-to-Work (in.)	Waveform, %EP, DCOffst	RMS Current SETPOINT	VOLT SETPOINT			
	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34			

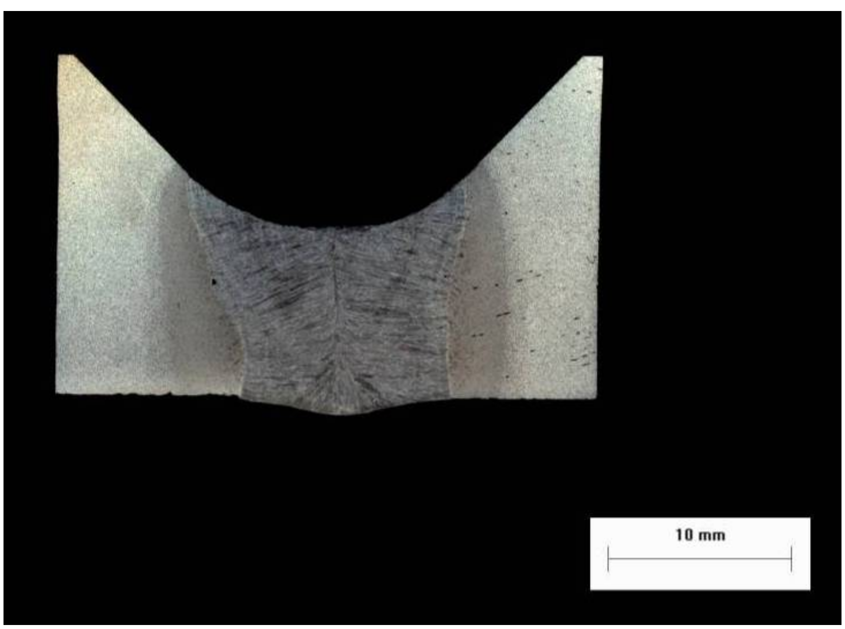


Figure M1 - Macrograph of Weld on 1-in. Thick Butt Joint

Appendix N – Project Results Presentation

Project team

- **NGSS**
  - Nick Evans
  - Lee Kvidahl
  - Tim Warren
- **NGNN**
  - Paul Hebert
- EWI
  - Brian Baughman
  - Jim Russell
  - Chris Conrardy
  - Nancy Porter

THE MATERIALS JOINING EXPERTS

Outline

- Introduction
- Objectives
- Task 1 – Evaluation of existing process (Series Arc)
- Task 2 – Tooling and Fixturing
- Task 3 – Tandem SAW procedure and development
- Comparison of Series Arc and Tandem SAW
- Cost Savings
- Conclusions
- Recommendations
- Questions and Demo

THE MATERIALS JOINING EXPERTS

Introduction

- Current and future ship programs will use more thin plate (3 to 10 mm) to optimize weight
- Submerged Arc Welding (SAW) with Flux/Copper Backing (FCB) is currently preferred for panel welding using single-sided welding procedures
  - Well established for thick steel plates requiring high heat input
- To minimize distortion, narrow-groove procedures are needed for thin panel welding
  - Implementation of milled joint preparation instead of oxyfuel or plasma cutting.
  - Use of Lincoln's Advanced Waveform SAW power sources

EWI THE MATERIALS JOINING EXPERTS

Program Objectives

- Reduce distortion on full penetration, single-sided groove welds
  - 5, 8 and 10mm steel plate thicknesses
  - Original proposal aimed at 3, 5 and 8mm, but 5-10 more representative
- Increase productivity of single-sided welds.
- Develop narrow-groove welding procedures utilizing FCB, waveform-control and carefully controlled root openings
  - Optimized procedures for each thickness of steel plate

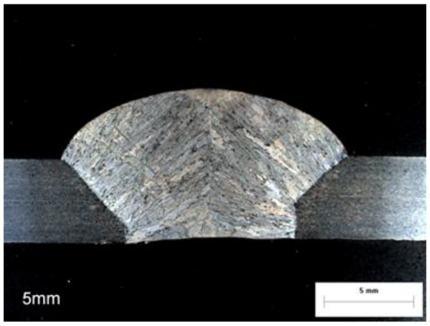
EWI THE MATERIALS JOINING EXPERTS

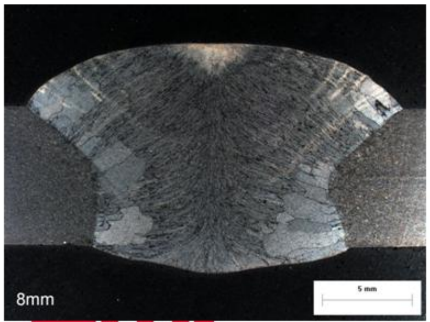
Task 1 – Modified Series Arc Evaluation

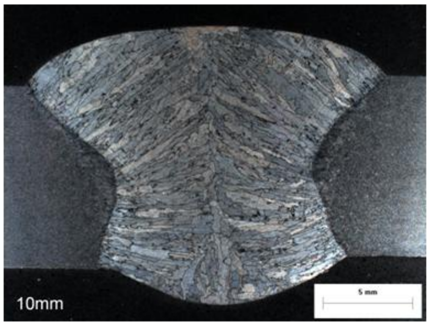
- Welds were made using current procedures and sent to EWI for analysis
  - Bead profile
  - Heat input
  - Distortion
- Flux bed raised to 3-mm above copper bar surface.
- Welds made were 4-ft. long.

Task 1 – Modified Series Arc Evaluation

- Observations:
  - 5-mm plate had a flat underbead
  - Excessive reinforcement at top and bottom surfaces
    - (exceeded Class 3 MIL-STD-2035A reinforcement limits).







EWI THE MATERIALS JOINING EXPERTS

Task 1 – Modified Series Arc Evaluation

- Parameter Measurements of Current Procedures
  - 3/16-in. dia. L-61 lead electrode (AWS EM12K)
  - 1/8-in. dia. L-61 trail electrode (AWS EM12K)
  - Lincoln 780 flux on topside and back (AWS F7A2)

Plate	Root Opening	Amperage	Voltage	WFS	Travel Speed	Heat Input (kJ/in)
5mm	3mm	600 amps	33.5 volts	48 ipm	21 ipm	60.3
8mm	4-5mm	725 amps	36 volts	54 ipm	16 ipm	97.875
10mm	5-6mm	800 amps	36 volts	60 ipm	14 ipm	123.4285714

  - Bead Shape Measurements

Plate Size	Top Reinforcement Height (mm)	Bottom Reinforcement Height (mm)	Total Weld Bead Area (mm^2)	Deposition Area (mm^2)	Top Bead Width (mm)	Root Bead Width (mm)	Base Metal Dilution %
5mm	3.83	-0.236	98.8	64.258	16.04	9.5	34.96
8mm	3.6	1.5	188.12	105.859	21.12	14.5	43.73
10mm	3.04	2.36	204.96	117.9	20.18	13.93	42.48

EWI THE MATERIALS JOINING EXPERTS

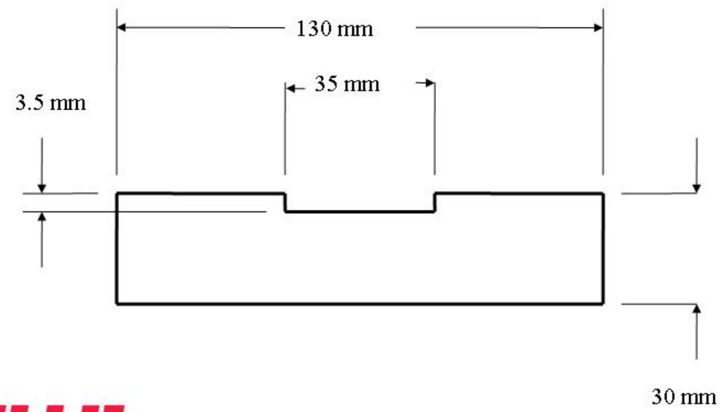
Task 1 – Modified Series Arc Evaluation

- Distortion Measurements of Series Arc Benchmark Welds
  [note: welds were made on large plates (8-ft. by 4-ft)]
  - 5mm
    - Exhibited transverse shrinkage between 1/32-in. and 1/16-in. (measured transverse to weld axis at both ends of plate).
    - Bowing (out-of-plane) distortion between 1/8-in. and 3/16-in. (measured at ends of plate relative to horizontal).
  - 8mm
    - Transverse shrinkage between 1/32-in. and 1/16-in.
    - Bowing distortion between 1/8-in. and 5/8-in.
  - 10mm
    - Transverse shrinkage between 3/32-in. and 1/8-in.
    - Bowing distortion between ¼-in. and 3/8-in.

EWI THE MATERIALS JOINING EXPERTS

Task 2 – Tooling and Fixture Development

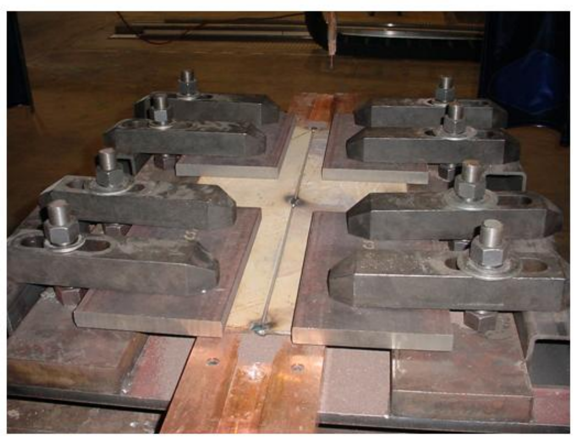
- Initial testing incorporated FCB groove used in Series Arc Procedure



THE MATERIALS JOINING EXPERTS

Task 2 – Tooling and Fixture Development

- Fixture Development
  - Fits provided plate size (24-in. by 6-in.)
  - Uses similar fixturing pattern and spacing of clamps as NGSS - Ingalls fixture.



THE MATERIALS JOINING EXPERTS

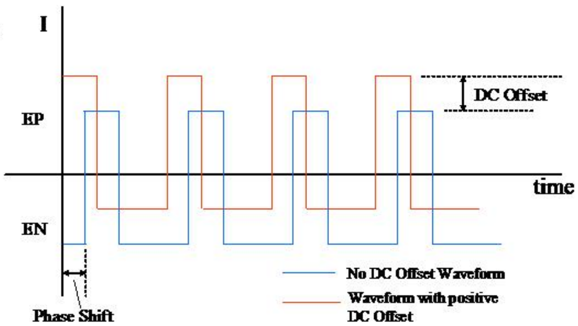
Task 3 – Tandem SAW Procedures

- Set-up and Equipment
  - Two Lincoln Electric PowerWave 500's per electrode
  - Power Feed 10S wire feeder.
  - Side-beam travel carriage
  - Microprocessor controller used to program waveform variables.

EWi THE MATERIALS JOINING EXPERTS

Task 3 – Tandem SAW Procedures

- Variables:
  - Electrode spacing
  - Contact tip-to-work distance
  - Voltage
  - Travel speeds
  - Root mean square (RMS) current level
  - Current balance
    - Ratio of time spent in EP to EN
  - Frequency of pulses
  - DC offset
    - Amount waveform current levels are shifted +/-
  - Phase shift

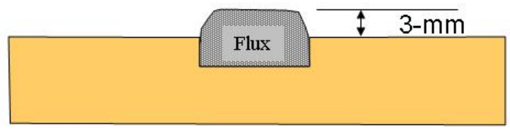


EWi THE MATERIALS JOINING EXPERTS

Original FCB groove design

Task 3 – Tandem SAW Procedures

- Tandem Development Procedure:
  - FCB was filled with and piled with flux up to 3mm above top surface of copper bar.
  - Test plates were pre-tacked with run-on and run-off tabs, then clamped (compressed) on flux bed.
  - 3/16-in. dia. Lead L-61 electrode
  - 1/8-in. dia. Trail L-61 electrode
  - Lincoln 761 Flux



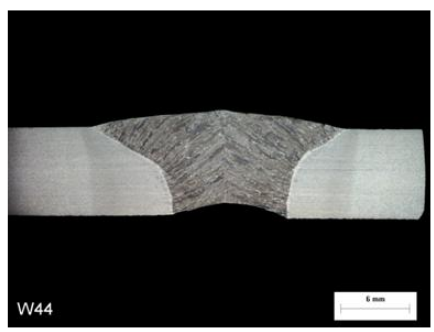
- Tests
  - AC/AC waveforms
  - DC/AC waveforms
  - Incorporated various root openings and travel speeds

EWI THE MATERIALS JOINING EXPERTS

Original FCB groove design

Task 3 – Tandem SAW Procedures

- Results
  - Inconsistent backbead was observed frequently.
    - Backbead depth and width varied over weld length.
  - Extreme suckback observed
    - Inconsistent also, varied with location and from weld to weld



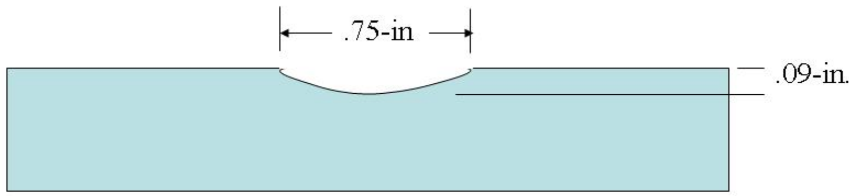
Same Parameters

EWI THE MATERIALS JOINING EXPERTS

New FCB groove design

Task 3 – Tandem SAW Procedures

- Consultation with Lincoln Electric
  - Suggested new backing bar groove design
  - New FCB groove:



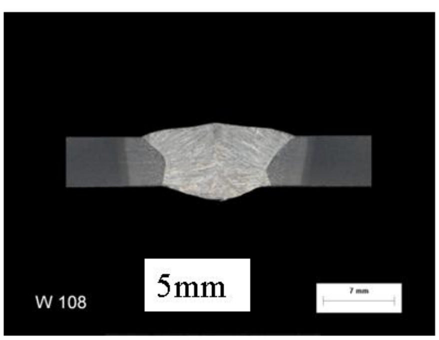
  - FCB was filled with flux but only to top surface of copper bar
  - Electrode size now 5/32-in. dia. lead and 3/32-in. dia. trail
    - (L-61 electrode, 761 flux)

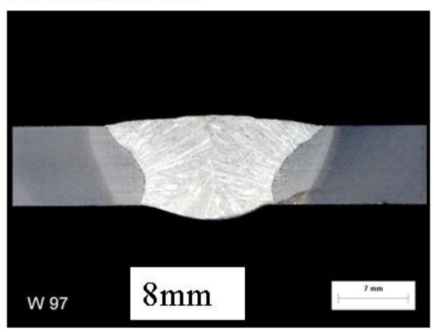
THE MATERIALS JOINING EXPERTS

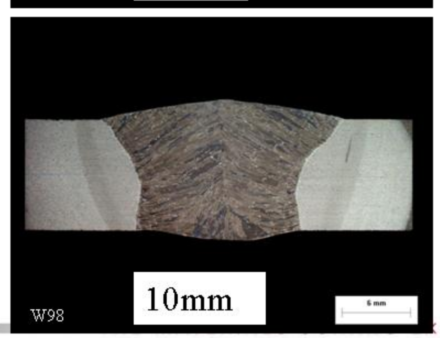
New FCB groove design

Task 3 – Tandem SAW Procedures

- Preferred Procedure Welds







New FCB groove design

Task 3 – Tandem SAW Procedures

5mm Plate

WELD ID	Plate Thickness (mm)	Root Opening (mm)	Wire Separation (in.)	TRAVEL SPEED (ipm)	Combined Heat Input (kJ/inch)	Lead WFS (ipm)	Trail WFS (ipm)	DATA ACQ FILENAME
W108	5	1.9 to 2.0	0.78	55	41.4	60	190	10-27-05 08.35.19.txt

LEADING WIRE PARAMETERS

Wire Dia (in.)	Trav. Angle (degr.)	Tip-to-Work (in.)	Waveform, %EP, DCOffst	RMS Current SETPOINT	VOLT SETPOINT
0.15625	0	1.25	CC sq, bal=50%, DCOffs=-8200	650	33

TRAILING WIRE PARAMETERS

Wire Dia (in.)	Trav. Angle (degr.)	Tip-to-Work (in.)	Waveform, %EP, DCOffst	RMS Current SETPOINT	VOLT SETPOINT
0.09375	12	1.250	CC sq, bal(+)=40%, DCOffs=-8200, Phase=105 deg	500	33

Plate Size	Top Reinforcement Height (mm)	Bottom Reinforcement Height (mm)	Total Weld Bead Area (mm^2)	Deposition Area (mm^2)	Top Bead Width (mm)	Root Bead Width (mm)	Base Metal Dilution %
5mm (W108)	1.31	1.34	77.66	30.853	15.3	11	62.5

THE MATERIALS JOINING EXPERTS

Task 3 – Tandem SAW Procedures

8mm Plate

WELD ID	Plate Thickness (mm)	Root Opening (mm)	Wire Separation (in.)	TRAVEL SPEED (ipm)	Combined Heat Input (kJ/inch)	Lead WFS (ipm)	Trail WFS (ipm)	DATA ACQ FILENAME
W97	8	3.4 to 3.3	0.78	35.0	72.9	62	175	10-21-05_11.01.49.txt

LEADING WIRE PARAMETERS

Wire Dia (in.)	Trav. Angle (degr.)	Tip-to-Work (in.)	Waveform, %EP, DCOffst	RMS Current SETPOINT	VOLT SETPOINT
0.15625	0	1.25	CC DC+	750	34

TRAILING WIRE PARAMETERS

Wire Dia (in.)	Trav. Angle (degr.)	Tip-to-Work (in.)	Waveform, %EP, DCOffst	RMS Current SETPOINT	VOLT SETPOINT
0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34

Plate Size	Top Reinforcement Height (mm)	Bottom Reinforcement Height (mm)	Total Weld Bead Area (mm^2)	Deposition Area (mm^2)	Top Bead Width (mm)	Root Bead Width (mm)	Base Metal Dilution %
8mm (W97)	1.34	1.25	137.03	50.53	21.05	11.4	63.1

THE MATERIALS JOINING EXPERTS

Task 3 – Tandem SAW Procedures

10mm Plate

WELD ID	Plate Thickness (mm)	Root Opening (mm)	Wire Separation (in.)	TRAVEL SPEED (ipm)	Combined Heat Input (kJ/inch)	Lead WFS (ipm)	Trail WFS (ipm)	DATA ACQ FILENAME
W98	10	3.8 to 4.0	0.78	30.0	88.4	70	175	_10-21-05_13.03.36.txt
	----LEADING WIRE PARAMETERS----							
	Wire Dia (in.)	Trav. Angle (degr.)	Tip-to-Work (in.)	Waveform, %EP, DCOffst	RMS Current SETPOINT	VOLT SETPOINT		
	0.15625	0	1.25	CC DC+	800	34		
	----TRAILING WIRE PARAMETERS----							
	Wire Dia (in.)	Trav. Angle (degr.)	Tip-to-Work (in.)	Waveform, %EP, DCOffst	RMS Current SETPOINT	VOLT SETPOINT		
	0.09375	12	1.250	CC sq, bal=50%, DCOffs=0	500	34		

Plate Size	Top Reinforcement Height (mm)	Bottom Reinforcement Height (mm)	Total Weld Bead Area (mm²)	Deposition Area (mm²)	Top Bead Width (mm)	Root Bead Width (mm)	Base Metal Dilution %
10mm (W98)	1.76	0.834	181	67.77	21.45	14.45	62.5

EWI THE MATERIALS JOINING EXPERTS

New FCB groove design

Task 3 – Tandem SAW Procedures

- Root bead consistency throughout whole weld length

EWI THE MATERIALS JOINING EXPERTS

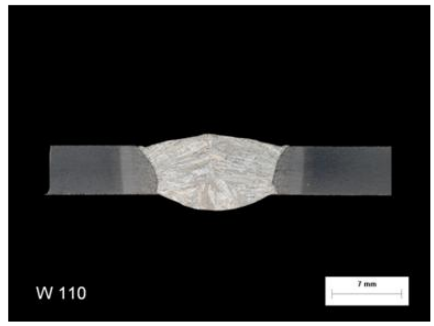
New FCB groove design

Task 3 – Tandem SAW Procedures

- Gap Tolerance of Baseline Parameters
  - Used same procedures but varied root opening
    - Nominal root opening of 2.0-mm.

5mm Plate

Root Opening: 1.4-mm



Root Opening: 3.0-mm

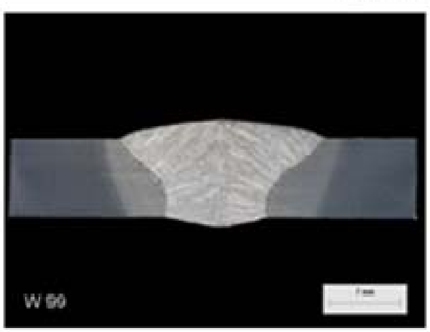
EWI THE MATERIALS JOINING EXPERTS

New FCB groove design

Task 3 – Tandem SAW Procedures

- Gap Tolerance of Baseline Parameters
  - Used same procedures but varied root opening
    - Nominal root opening of 3.0-mm.

8mm Plate



Root Opening: 2.0-mm

Root Opening: 5.0-mm

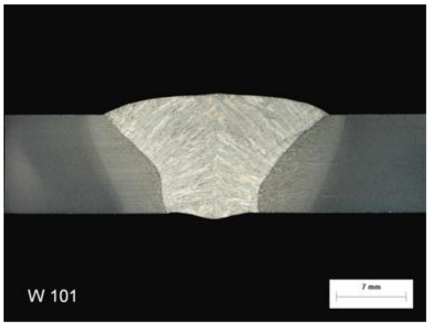
EWI THE MATERIALS JOINING EXPERTS

New FCB groove design

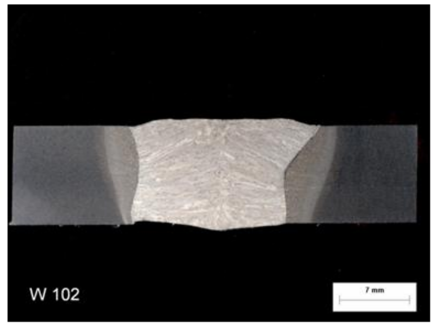
Task 3 – Tandem SAW Procedures

- Gap Tolerance of Baseline Parameters
  - Used same procedures but varied root opening
    - Nominal root opening of 4.0-mm.

10mm Plate



Root Opening: 3.0-mm

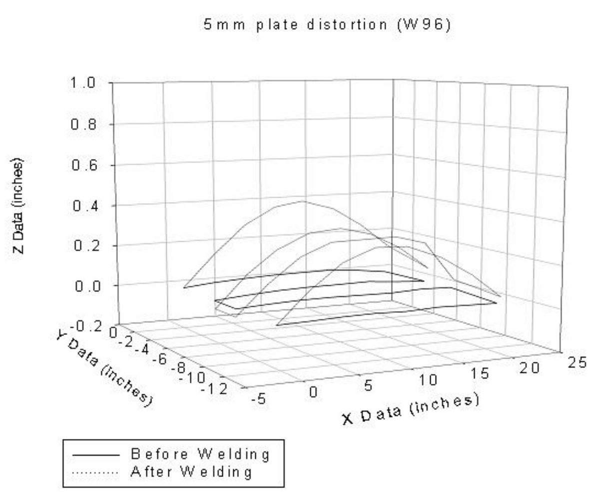


Root Opening: 6.0-mm

EWI THE MATERIALS JOINING EXPERTS

Task 3 – Tandem SAW Procedures

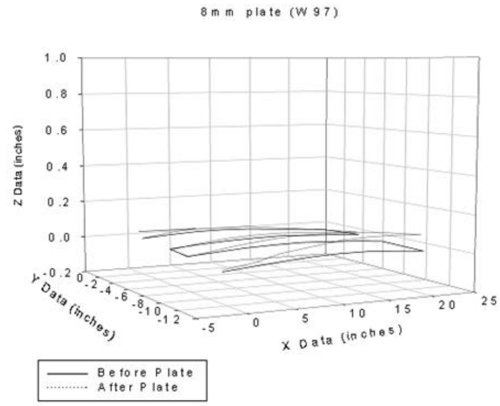
- Distortion Data
  - Out-of-plane distortion
  - Surface was 12-in. wide by 24-in. long
    - Two 6-in. by 24-in. plates.
  - Measured with ROMER Arm

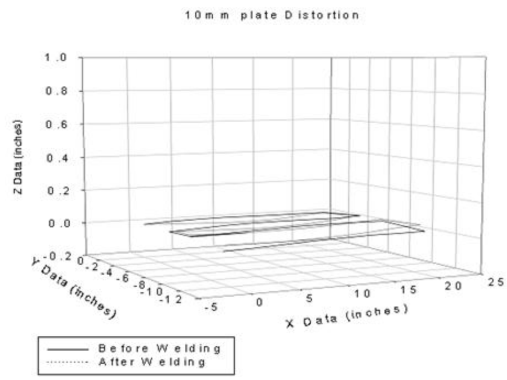


EWI THE MATERIALS JOINING EXPERTS

Task 3 – Tandem SAW Procedures

- Out-of-plane Distortion

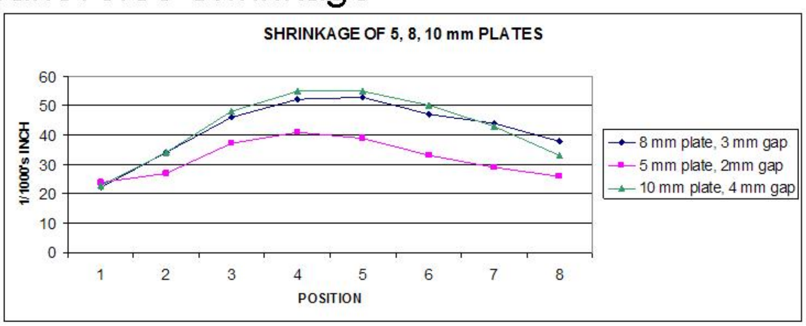


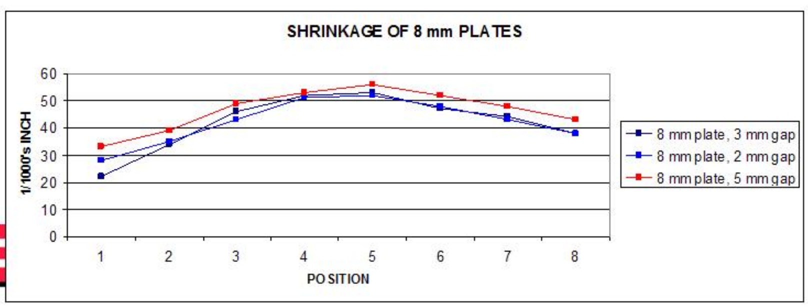


THE MATERIALS JOINING EXPERTS

Task 3 – Tandem SAW Procedures

- Transverse Shrinkage





EXPERTS

Task 3 – Tandem SAW Procedures

- Procedure Qualification
  - Performed in accordance to MIL-STD-248 and MIL-STD-2035A
  - 5mm
    - Passed visual observation, radiography, and magnetic particle testing
  - 8mm
    - Passed visual observation, radiography, and magnetic particle testing
  - 10mm
    - Passed visual observation, radiography, and magnetic particle testing
    - Passed mechanical testing per filler metal specs
      - Two face and root bends at 2T bend radius
      - Two transverse tensile specimens
      - Base metal, HAZ, and weld metal CVN

THE MATERIALS JOINING EXPERTS

Task 3 – Tandem SAW Procedures

CROSS WELD TENSION TEST RESULTS - ASTM E8

Technician: Kristen Merlo　　Test Date: November 3, 2005
Test Frame: H1938 UK18　　Loading Rate: 0.05 (in/min) 1.27 (mm/min)
Orientation: Cross Weld　　Test Temperature: Room Temperature

Spec.	Width	Thickness	Ultimate Strength		0.2% Yield Strength		Elongation	%RA	Failure
ID	(in.)	(in.)	(ksi)	(MPa)	(ksi)	(MPa)	(%)	(%)	Location
T-1	1.503	0.389	77.5	534.5	65.4	451.0	29.4	66.6	Base Metal
T-2	1.499	0.384	79.3	546.9	62.7	432.4	27.6	63.0	Base Metal

CHARPY IMPACT ENERGY TEST RECORD - ASTM E23

Technician: Kristen Merlo　　Test Date: November 3, 2005
Test Frame: 151297　　Notch Orientation: T-L per AWS B4.0

Spec.	Notch	Test Temperature		Absorbed Energy		Lateral Expansion		Shear
ID	Location	(°C)	(°F)	(J)	(ft-lbs)	(mm)	(mils)	(%)
1	Base Metal	-29	-20	40.7	30	1.02	40.2	60
2	Base Metal	-29	-20	40.7	30	0.91	35.8	60
3	Base Metal	-29	-20	48.8	36	0.96	37.8	61
4	HAZ	-29	-20	37.3	27.5	0.84	33.1	56
5	HAZ	-29	-20	37.3	27.5	0.81	31.9	51
6	HAZ	-29	-20	230.5	170	2.37	93.3	100
7	WCL	-29	-20	238.6	176	1.86	73.2	100
8	WCL	-29	-20	303.7	224	2.06	81.1	100
9	WCL	-29	-20	279.3	206	2.26	89.0	100
10	WCL	-29	-20	279.3	206	2.26	89.0	100
11	WCL	-29	-20	273.9	202	2.30	90.6	100

BEND TEST RECORD - ASTM E190

Technician: Kristen Merlo　　Test Date: November 3, 2005

Spec. ID	Thickness (in.)	Orientation	Mandrel Diameter (in.)	Results	Validity
FB-1	0.378	Face	1.5	No Visual Defects	Pass
FB-2	0.378	Face	1.5	No Visual Defects	Pass
RB-1	0.375	Root	1.5	No Visual Defects	Pass
RB-2	0.378	Root	1.5	No Visual Defects	Pass

THE MATERIALS JOINING EXPERTS

Process Comparison - Tandem SAW versus Series Arc

SERIES ARC

Plate Thickness (mm)	Electrode Dia. (in)		Root Opening (mm)	Current (A)	Voltage (V)	WFS (ipm)	Travel Speed (ipm)	Heat Input (kJ/in)
	Lead	Trail						
5	3/16	1/8	4.0	600	33.5	48	20	60.30
8	3/16	1/8	4 to 5	725	36	54	16	97.88
10	3/16	1/8	5 to 6	800	36	60	14	123.43

TANDEM SAW

Plate Thickness (mm)	Electrode Dia. (in.)		Root Opening (mm)	RMS Current (A)		Voltage (V)		WFS (ipm)		Travel Speed (ipm)	Heat Input (kJ/in)
	Lead	Trail		Lead	Trail	Lead	Trail	Lead	Trail		
5	5/32	3/32	2.0	650 - 50% EP	500 - 40% EP	33	33	60	190	55	41.40
8	5/32	3/32	3.0	750 - DC+	500- 50% EP	34	34	62	175	35	72.90
10	5/32	3/32	4.0	800 - DC+	500- 50% EP	34	34	70	175	30	88.40

SERIES ARC

Plate Size (mm)	Top Reinforcement Height (mm)	Bottom Reinforcement Height (mm)	Total Weld Bead Area (mm2)	Deposition Area (mm2)	Top Bead Width (mm)	Root Bead Width (mm)	Base Metal Dilution %
5	3.83	-0.236	98.8	64.258	16.04	9.5	34.96
8	3.6	1.5	188.12	105.859	21.12	14.5	43.73
10	3.04	2.36	204.96	117.9	20.18	13.93	42.48

TANDEM SAW

Plate Size (mm)	Top Reinforcement Height (mm)	Bottom Reinforcement Height (mm)	Total Weld Bead Area (mm2)	Deposition Area (mm2)	Top Bead Width (mm)	Root Bead Width (mm)	Base Metal Dilution %
5	1.31	1.34	77.66	30.853	15.3	11	62.56
8	1.34	1.25	137.03	50.53	21.05	11.4	63.12
10	1.76	0.834	181	67.77	21.45	14.45	62.56

S

Cost Savings

- Did not account for process set-up times, repair costs, or weight savings

Plate Size and Process	Flux Fill Cost		Electrode Cost		Process Cost		Total Cost ($/ft)
	Time (min./ft)	Labor Rate ($/hr)	Metal (lbs/ft.)	Cost ($/lb)	Speed (min/ft.)	Labor ($/hr)	
5mm - Series	0.5	55	0.3345	1.75	0.57	55	1.57
5mm - Tandem	0.25	55	0.1606	1.75	0.22	55	0.71
8mm - Series	0.5	55	0.5511	1.75	0.75	55	2.11
8mm - Tandem	0.25	55	0.2631	1.75	0.34	55	1.00
10mm - Series	0.5	55	0.6138	1.75	0.86	55	2.32
10mm - Tandem	0.25	55	0.3528	1.75	0.40	55	1.21

THE MATERIALS JOINING EXPERTS

Conclusions

- Tandem SAW successfully joined 5-, 8-, and 10-mm narrow groove butt joints.
  - Welds passed procedure qualification standards (MIL-STD-248 and 2035A)
- Tandem SAW procedures had several advantages over the modified Series Arc process.
  - Faster travel speed (over twice as fast)
  - Improved bead shape
  - Less filler metal deposition
  - Lower calculated heat input
  - Higher cost savings
- The preferred procedures for each plate had good gap tolerance.
  - 1-mm gap tolerance for 5-mm plate
  - 3-mm gap tolerance for 8- and 10-mm plates
- Distortion of the tandem SAW welds was found to be minimal.

EWI THE MATERIALS JOINING EXPERTS

Recommendations

- Tandem SAW implementation
  - Should evaluate performance in production environment and on large sized panels before full implementation
- Change design and flux fill procedure of FCB groove
- Change electrode diameters
  - Use 5/32-in. and 3/32-in. dia. on lead and trail, respectively.

EWI THE MATERIALS JOINING EXPERTS