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EVALUATION OF VARIABLE BALANCE AC SUBMERGED ARC WELDING AND METAL CORED ELECTRODE TECHNOLOGY FOR PANEL WELDING

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REPORT: Evaluation of Variable Balance AC Submerged Arc Welding and Metal Cored Electrode Technology for Panel Welding

DATE: April 2006

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EXECUTIVE SUMMARY

High strength low alloy steels, such as HSLA-65 and HSLA-100, are being used in ship construction to optimize the weight and life-cycle costs of both naval and commercial vessels. Some shipyards have improved their productivity by employing one-sided, submerged arc welding (SAW) for long panel welds, in which two or three electrodes are used to fill the joint in a single run. However, the high heat input of these welding procedures can lead to large regions of coarse grain heat-affected zone (CG-HAZ) with poor impact toughness. For HSLA-100 steels, heat input restrictions are specified by NAVSEA to ensure minimum specified weld metal yield strengths are achieved, and, also maintain adequate HAZ toughness which can be a concern in the lean composition range for this grade of steel. One potential resolution, without sacrificing quality, is to make use of welding power sources with wave form control technology and metal cored electrodes.

Digital square wave alternating current (AC) SAW power sources, with independent control of the positive and negative polarity dwell times (i.e., variable balance waveform control) in the AC welding cycle have the potential to improve deposition rates and thus productivity of one-sided welding (OSW) operations in US shipyards. The positive polarity of a welding power source output transfers a greater portion of heat to the work piece to enhance melting of the base metal and provide welds with deep penetration. The negative polarity promotes a greater portion of heat to the electrode for enhanced melting of the continuously fed electrode. A conventional AC welding sine wave provides a 50/50 balance of negative and positive polarity, and therefore a balance between the characteristics of both DCEP and DCEN polarity welding. However, with variable balance AC (VBAC) waveform technology, the melt-off rate can be optimized for enhanced weld deposition and productivity by increasing the amount of negative polarity dwell time (i.e., the time the AC cycle spends in the negative polarity). Increasing negative polarity dwell time beyond 50% EN also reduces the amount of heat into the work piece compared to a conventional balanced sine wave output, thus promoting higher weld zone cooling rates (for improved impact toughness due to smaller CG-HAZ grain size). Furthermore, the square waveform is a much more stable arc compared to a conventional AC sine wave, leading to fewer weld defects.

In addition, newer generation metal cored electrodes for SAW are manufactured using a mild steel jacket with a core of specifically selected iron and other metal powders and alloys. Stabilizers and arc enhancers are added to its core, typically providing a wider operating window compared to welding with solid wires. Versatility is possible with these electrodes because of the infinite alloy compositions that can be easily made by electrode manufacturers. Special alloy combinations can be achieved that would be difficult or impractical with solid electrodes, including special types for welding high strength steels. Because the manufacturing process involves blending metal powders instead of creating a special melt of steel, small quantities are easier to produce, and minimum order quantities are much lower. As a result, metal cored electrodes can usually be produced within shorter turnaround times and at a lower cost than special ordered solid wire electrodes. The current is carried only by the thin sheath surrounding the electrode, thereby increasing resistive heating of the electrode, resulting in increased deposition rates for a given current level and thus higher productivity.

The benefits of this project to the sponsor group vary based upon the interests of the sponsoring organization. The National Shipbuilding Research Program (NSRP) will expect to increase the quality and economy of ship construction completed in US shipyards. This will both make naval platforms and commercial vessels more affordable and improve the structural integrity of ships built in US shipyards.

The sponsoring shipyards would expect to be able to reduce their fabrication costs, as well as extend their design build capabilities to include structures designed for high strength steels. In applying the technology and welding techniques demonstrated in this project, the shipyard will be better able to ensure that the minimum welded connection toughness requirements are consistently achieved. The shipyard sponsor will appreciate that the welding equipment can be easily implemented into any of their existing panel lines that use the SAW process, with minimal modifications, unlike other advanced hybrid welding processes. Deposition rates can be increased significantly over conventional DCEP power sources with the same welding parameters and wire types/sizes, and the projected return on the investment for most shipyard operations (due to higher productivity rates and lower consumable consumption and labor costs), can be as little as a few months after implementation of the technologies.

The main objective of this project was to utilize SAW with VBAC control and metal cored electrodes to enhance the productivity rates of OSW operations for ½” and 1” thick DH36 and HSLA-65 steels, whilst comfortably maintaining the minimum weld metal and HAZ mechanical property requirements. The second objective was to determine if the variable balance and metal cored electrode technologies could be utilized to extend the heat input restriction imposed by NAVSEA for HSLA-100 and produce procedures for one-sided and two sided welding that demonstrate higher productivity compared to current practice and meet the minimum mechanical property requirements.

The sponsoring shipyard Northrop Grumman Ship Systems (NGSS) and as well as the Naval Surface Warfare Center Carderock Division (NSWCCD), provided benchmark welding procedures for the current SAW practice for DH36, HSLA-65 and HSLA-100, so that the results of this project could be compared to demonstrate both productivity enhancements and cost reductions using the technologies evaluated.

OSW procedures onto a FCB were developed for DH36, HSLA-65, and HSLA-100 steels using the VBAC technology and metal cored electrodes. All of the OSW procedures for DH36 and HSLA-65 steels allowed for the weld joint to be completed in a single run, and the OSW procedure for the 1” thick HSLA-100 steel required as little as three passes to complete the joint. For each OSW procedure, the FCB design was modified to improve the consistency of penetration and root bead profile for use with the variable balance AC technology and metal cored electrodes. In addition, two sided “no back gouge” welding procedures were developed for both ½ and 1-inch thick HSLA-100 steels and each thickness only required a single pass per side without the need for back gouging.

The key findings are:

- Metal cored electrode formulations were developed for high heat input SAW of DH36, HSLA-65, and HSLA-100 steels.
- A modified FCB design was developed to improve the consistency of weld penetration and the root bead profile for one-sided welding.
- High heat input tandem welding procedures were developed for DH36 and HSLA-65 using VBAC technology and metal cored electrodes. The procedures developed for the 1” thickness allow for the joints to be welded from one side onto a flux filled copper backing in a single run. In each case the mechanical property requirements were comfortably met. The 1” thick OSW procedures demonstrated a fit-up tolerance of +/- 0.45” and 0”, respectively.

- OSW and two sided tandem welding procedures were developed for HSLA-100 using VBAC technology and metal cored electrodes. Multi-pass OSW procedures onto a FCB were developed that allowed for welding to be completed from one-side in as little as three runs, without having to flip the plate over, back gouge, and complete the weld from the second side. The OSW procedure demonstrated fit-up tolerance of +/- 0.45" and 0", respectively. Heat inputs as high as 100 kJ/in were produced in the two sided welding technique where the minimum mechanical property requirements were still satisfactorily met. In this case only one pass per side was required without the need for back gouging.
- Radiography results for each procedure met the requirements of MIL-STD 2035A.
- Balance settings of 66EP/34EN (60Hz) and 34EP/66EN (60Hz) were investigated for each application. It was found that the optimum AC balance setting for OSW was 66EP/34EN (60Hz), however a 34EP/66EN (60Hz) setting resulted in a significant wire feed speed increase and deposition rate enhancement. Under the conditions studied, varying the AC balance setting did not produce any significant changes in microstructure evolution or any significant enhancements to the weld zone mechanical properties. For example, at a constant heat input, each balance setting that was tested produced a coarse grain HAZ (CG-HAZ) grain size of approximately 100 microns in the 1" thick HSLA-100 steel. The areas examined were in the region where the all weld metal tensile and weld metal and HAZ impacts were extracted from. It is possible that all the heat inputs employed in these procedures exceeded a threshold where any changes to the dynamics of the arc (i.e., change in balance setting) may not have any influence on the prior austenite grain size and resulting final CG-HAZ microstructure upon cooling.
- The combination of variable balance AC and metal cored electrodes offer significant productivity enhancement (approaching 1200%) compared to current SAW practice that use conventional DC/AC technology and solid wire electrodes. Cost reductions (electrode and labor) demonstrated savings as much as 65% compared to current practice.

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ACRONYMS

AC	Alternating Current
AWS	American Welding Society
CTWD	Contact Tip to Work Distance
DCEN	Direct Current Electrode Negative
DCEP	Direct Current Electrode Positive
FCB	Flux Copper Backing
HAZ	Heat Affected Zone
NGSS	Northrop Grumman Ship Systems
NSWCCD	Naval Surface Warfare Center Carderock Division
OSW	One-sided Welding
SAW	Submerged Arc Welding
UTS	Ultimate Tensile Strength
VBAC	Variable Balance AC
WFS	Wire Feed Speed
YS	Yield Strength

1 INTRODUCTION

High strength low alloy steels, such as HSLA-65 and HSLA-100, were developed to optimize the weight and thus overall life-cycle costs of both naval and commercial vessels. Some shipyards have improved their productivity by employing one-sided, submerged arc welding (SAW) for long panel welds, in which two or three electrodes are used to fill the joint in a single run. However, the high heat input of these welding procedures can lead to large regions of coarse grain heat-affected zone (CG-HAZ) with poor impact toughness. For HSLA-100 steels, heat input restrictions are specified by NAVSEA for specific applications to maintain sufficient weld metal yield strength, and, also to maintain adequate HAZ toughness which can be a concern in the lean composition range for this grade of steel. For ½" thick and beyond HSLA-100 steel, NAVSEA specifies a maximum heat input restriction of 85kJ/in and it is for this reason, in practice, that several small weld passes are deposited to fill a joint. This practice is not very cost-effective and can also lead to significant welding induced distortion that requires further rework during subsequent fit-up operations later in the build process. There are no specified heat input restrictions for welding HSLA-65 although it is common practice to employ high heat input procedures using the same electrodes and fluxes designed for HSLA-100 steels.

In the SAW process, schematically shown in **Figure 1.1**, flux is laid in granular form on the unwelded seam ahead of the bare metal electrode to provide shielding. The electrode is fed from a coil to allow a continuous and uninterrupted welding operation. The flux is effective in preventing the atmosphere from contaminating the molten weld metal.

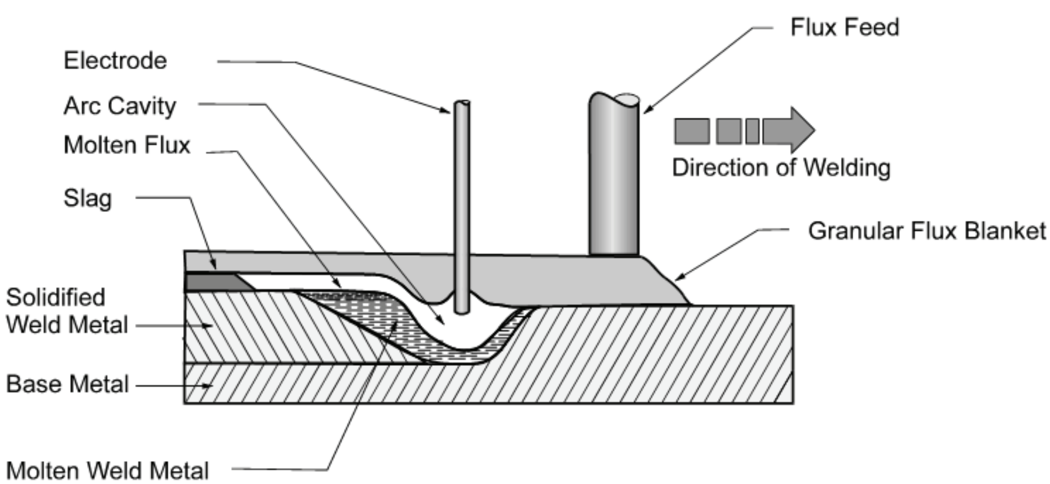


Figure 1.1: The SAW Process

The arc is struck beneath the flux between the bare electrode and the work piece, which melts a small amount of flux. The heat generated by the arc melts the end of the electrode, the flux, and part of the base metal at the weld seam. The arc transfers the molten metal from the tip of the melting electrode to the work piece where it becomes deposited metal. As the molten flux combines with the molten metal, chemical reactions occur that remove some impurities and/or adjust the composition of the weld metal.

While still molten, the flux which is lighter than the weld metal, rises to the surface of the weld pool and protects it from oxidation and contamination. On further cooling, the weld metal solidifies at the trailing edge of the moving weld pool, and the weld bead usually has a smooth surface due to the presence of the molten glass-like slag above it. The slag completely freezes next and continues to protect the weld as it cools. Solidified slag is readily removable, sometimes popping off the bead spontaneously. Excess, unmelted flux can be recovered and reused after proper processing.

The equipment set-up for single electrode SAW is shown in **Figure 1.2**.

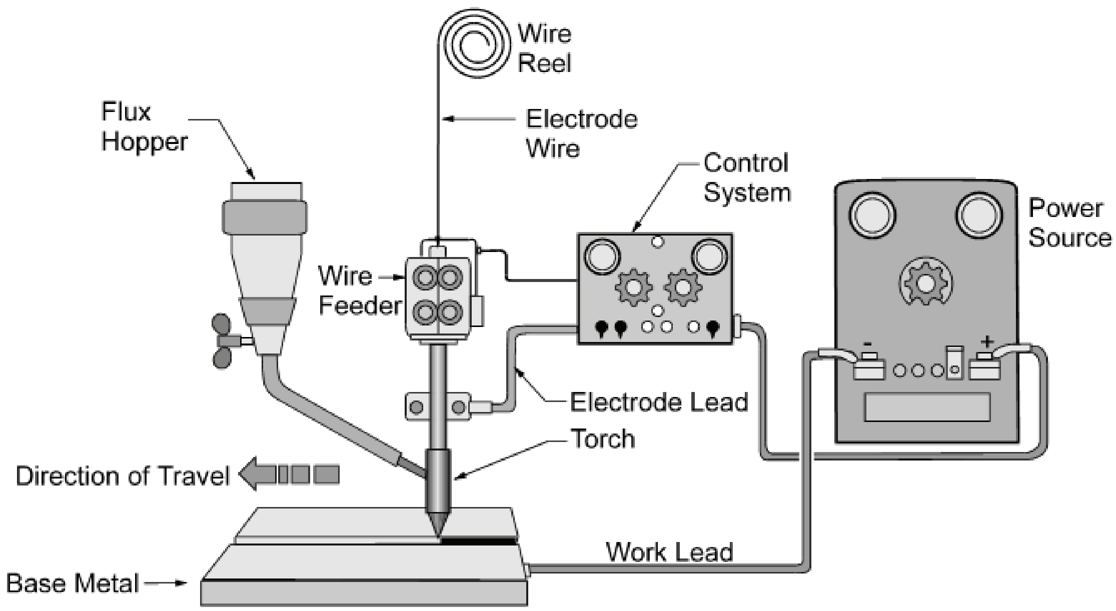


Figure 1.2: Equipment for SAW

One of the great advantages of the SAW process is its adaptation to the use of multiple electrodes fed into the same weld pool thus considerably increasing deposition rates and productivity. Some of the configurations for multiple electrodes SAW are shown in **Figure 1.3**.

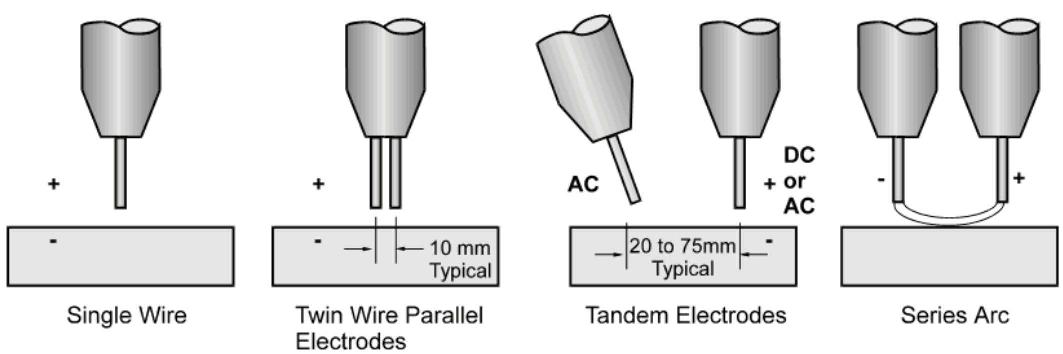


Figure 1.3: Sample SAW Configurations

With the high heat input one-sided welding (OSW) technique, a flux filled contoured copper backing bar (FCB) is used to support the weld pool on the back side of the joint. The flux protects the weld from atmospheric contamination and also serves to shape the weld back bead profile. The high heat input of these welding procedures can lead to large regions of CG-HAZ with poor impact toughness. One potential resolution to this problem, without sacrificing quality, is to make use of SAW welding power sources with wave form control technology and metal cored electrodes.

Digital square wave alternating current (AC) power sources with variable balance control (i.e., independent control of the positive and negative polarity dwell times in the AC welding cycle) have been developed for SAW. In SAW, a greater portion of heat is generated at the cathode (-), and therefore when the polarity is direct current electrode positive (DCEP), the work piece becomes the cathode and therefore a greater portion of the heat is generated at the work piece below the arc column. This is why when welding on DCEP polarity that welds with deep penetration characteristics are achieved, compared to DC electrode negative (DCEN). When welding on DCEN, the electrode then becomes the cathode and therefore a greater portion of the heat is generated at the electrode tip, and provides enhanced electrode melt-off and deposition rates compared to DCEP polarity. A conventional AC welding sine wave provides a 50/50 balance of negative and positive polarity, and therefore a balance between the characteristics of conventional DCEP and DCEN polarity welding. In **Figure 1.4**, conventional sine wave AC (in red) as well as the modified square wave AC waveform (in black) is shown. The square waveform was developed to increase the time at peak current, as well as eliminate the slope as the output passes through the neutral axis. Both of these modifications greatly enhanced arc stability compared to conventional sine wave output.

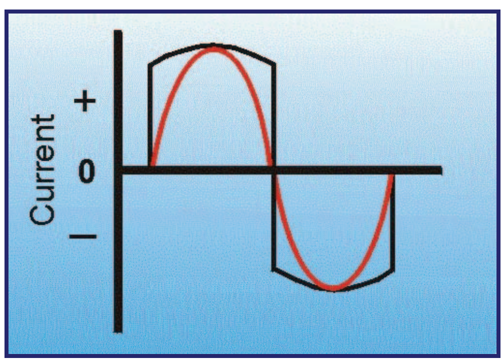


Figure 1.4: Conventional and Square AC Waveforms

Variable balance AC (VBAC) waveform technology was developed to allow welding procedures to be fine tuned for specific applications. VBAC can be used to control the duration the cycle spends in each of the EP and EN polarities, as shown in **Figure 1.5**.

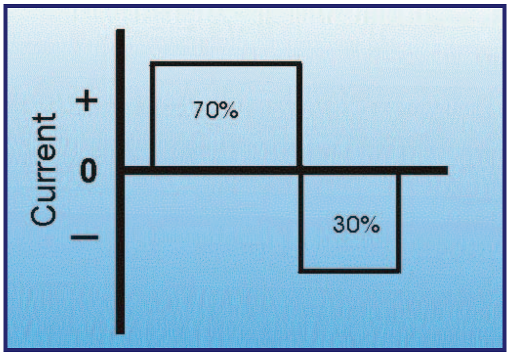


Figure 1.5: VBAC Waveform

The example shown in Figure 1.5 illustrates a 70% EP and 30% EN polarity setting, which will provide greater penetration compared to conventional AC welding however improved deposition rates compared to DCEP for the same current level.

Increasing negative polarity dwell time beyond 50% EN also reduces the amount of heat into the work piece compared to a conventional balanced sine wave output, thus promoting lower peak temperatures and higher weld zone cooling rates. This has the potential to improve the HAZ impact toughness, due to a smaller developed CG-HAZ grain size, as well as reduce dilution between the weld and base metal.

In addition, metal cored electrodes for SAW are manufactured using a mild steel jacket with a core of specifically selected iron and other metal powders and alloys. Stabilizers and arc enhancers are added to its core, typically providing a wider operating window compared to welding with solid wires. Versatility is possible with these electrodes because of the infinite alloy compositions that can be easily made by electrode manufacturers. Special alloy combinations can be achieved that would be difficult or impractical with solid electrodes, including special types for welding high strength steels. Metal cored electrodes are a more economical alternative to solid wire electrodes because the manufacturing process involves blending metal powders instead of creating a special melt of steel, and therefore small quantities are easier to produce, and minimum order quantities are typically much lower. As a result, metal cored electrodes can usually be produced within shorter turnaround times and at lower cost than special ordered solid wire electrodes. With metal cored electrodes approximately 90% of the current is carried by the thin sheath surrounding the electrode, thereby increasing resistive heating of the electrode which can demonstrate increases in weld metal deposition rate compared to a solid wire electrode of the same electrode diameter for the same current level.

2 PROJECT OBJECTIVES AND APPROACH

2.1 Project Objectives

The main objective of this investigation was to evaluate recent technological advancements in SAW power source and consumable design to improve the productivity rates of panel line welding and reduce the construction costs of both commercial and naval vessels in US shipyards. Secondly, panel line welds fabricated with the alternate technologies may benefit from improvements in weld zone mechanical properties and thus improve the integrity of ship structures.

The project metrics are shown in Table 2.1.

Table 2.1: Project Metrics

Metric	"As-is" Baseline	Project Goal	Tracking and Reporting Plan
Weld Completion Rate	Current Weld Metal Deposition Rates and Travel Speeds per Unit Length of Weld	Increase Weld Completion Rates by 40%	Select and evaluate current welding procedures for panel line welding of same materials and thickness; Compare results with those using the proposed technologies.
Welding Consumable Consumption Costs	Current Weld Metal Requirements (lb) per Unit Length of Weld Seam	Decrease Weld Metal Requirements and Costs by 20%	Determine the consumable consumption weights required per unit length of weld for current practice; Compare results with those using the proposed technologies; Calculate the percentage decrease in consumable consumption rates using the proposed technologies, and multiply by the actual consumable costs per pound.
Weld Zone Integirty	Inconsistent HAZ Toughness Properties	Improve Impact Energy and Consistency of Properties in HAZ's	Summarize the mechanical properties of benchmark weld procedure qualification tests; Compare to results of those using the proposed technologies; Calculate the percentage increase in mechanical properties.
Weld Defects	Various Levels of Weld Discontinuities Due to Arc Blow	Lower Defect Incidence Rate	Examine past NDT reports and determine the frequency of defects found on one side panel welding stations due to arc blow; Compare to defect frequency using the proposed technologies.

2.2 Approach

This project shall address the industry's need for achieving highly productive OSW with adequate mechanical properties fabricated in DH36, HSLA-65, and HSLA-100 steels. In addition, two-sided no back gouge welding procedures were developed and qualified in HSLA-100 steels. The approach was supported by the following tasks:

2.2.1 Task 1: Definition of Benchmark Welding Procedures

The first task was to collect and analyze results of OSW and other procedures developed specifically for SAW of DH36, HSLA-65, and HSLA-100 steels (½ and 1.0 inch thickness) using conventional output power sources and solid wire electrodes. These procedures were considered "state-of-the-art" in that they provided a balance between productivity and optimal mechanical properties. From this data, benchmark welding procedures were assembled to compare the results from subsequent tasks using the advanced VBAC equipment and metal cored electrodes.

2.2.2 Task 2: Development of Metal Cored Electrodes for High Heat Input Panel Welding

In the second task, metal cored electrode / flux combinations were developed for depositing high heat input welds in ½ and 1.0 inch thick DH36, HSLA-65, and HSLA-100 steels. The compositions were designed to achieve the minimum requirements for weld metal strength and toughness at high heat inputs using off-the-shelf highly basic fluxes.

2.2.3 Task 3: Development and Qualification of Welding Procedures for One-Sided Welding using Variable Balance Power Sources and Metal Cored Electrodes

The third task was to develop highly productive high heat input procedures for ½ and 1.0 inch DH36, HSLA-65, and HSLA-100 steels using the VBAC and metal cored electrode technologies. These procedures included:

- Single pass OSW onto FCB for ½" and 1" DH36
- Single pass OSW onto FCB for ½" and 1" HSLA-65
- Multi-pass OSW onto FCB for 1" HSLA-100
- Two sided welding of ½" and 1" HSLA-100, 1 pass per side, with no back gouging

This task also involved conducting a metallographic analysis on the HSLA-65 and HSLA-100 welds to characterize the resulting weld zone microstructures and mechanical properties.

2.2.4 Task 4: Productivity Enhancement and Cost Benefit Analysis

The fourth task was to summarize the productivity enhancements achieved using VBAC and metal cored electrodes and compare the results to current practice. A cost reduction, based on electrode and labor costs, was conducted to demonstrate the potential cost savings per foot of completed joint using the evaluated technologies.

3 RESULTS

3.1 Task 1: Definition of Benchmark Welding Procedures

In order to demonstrate potential improvements in productivity and mechanical properties using the VBAC and metal cored electrode SAW technologies, benchmarks needed to be made.

Northrop Grumman Ship Systems (NGSS) and the Naval Surface Warfare Center – Carderock Division (NSWCCD) provided panel line welding procedure data for ½ and 1-inch thick DH36, HSLA-65, and HSLA-100 steels, as part of their sponsorship to this project. These procedures are considered "state-of-the-art" for conventional output equipment and solid wire electrodes and were currently in use by major US shipyards. A summary of the information that was received from the project sponsors is provided in Sections 3.1.1, 3.1.2, and 3.1.3.

3.1.1 NGSS Welding Procedures – DH36 Steels

The welding procedure data provided by NGSS for ½ and 1-inch thick DH36 grade steels indicate that an AC power source with two electrodes connected in series are used for welding each thickness, with the ½"-thickness completed in one pass and the 1" thickness completed in five passes. In both thicknesses, the series arc configuration is used to complete the first pass onto an FCB. In the series arc configuration, the current path runs from one electrode to the other through the weld pool, as shown in **Figure 3.1**, with an additional ground lead running from the negative terminal of the power source to the work piece. The lead consists of a 3/16" diameter electrode and the trail is 1/8", and the typical electrode and torch arrangement is shown in **Figure 3.2**. The lead electrode has a travel drag angle of 30°, and the trail has a slight drag angle of 5°. The initial contact tip to work distance (CTWD) for both electrodes before welding is approximately 2 inches with no space between them, however when the arc is extinguished the spacing is approximately ½" which would be representative of the arc spacing during welding.

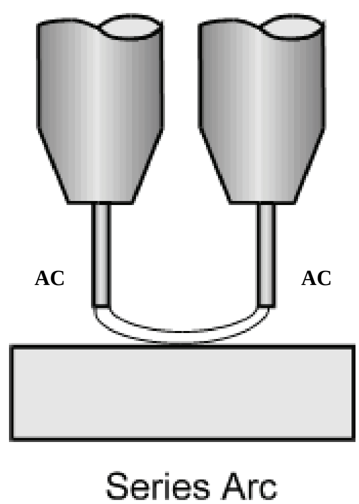


Figure 3.1: Series Arc Configuration

Figure 3.2: Series Arc Electrode Configuration

For the 1-inch thickness, the additional four passes (two passes per layer, two layers) are deposited using a single 5/32" diameter electrode on DCEP polarity. The welding electrodes are Lincoln Electric's L-61 with 780 flux (for both welding and backing), having a flux-electrode designation of F7A2-EM12K. As per AWS A5.17, this designation shall exhibit a deposited weld metal ultimate tensile strength (UTS) range between 70,000 and 90,000 psi and minimum yield strength (YS) of 58,000 psi. The A2 in the designation indicates that the weld metal shall exhibit a minimum of 20 ft-lbs of absorbed energy in a charpy V-notch impact test at -20°F when produced with an EM12K electrode under the testing conditions specified in AWS A5.17. In the EM12K electrode classification, the "E" indicates electrode, the "M" indicates a medium Mn content (as high as 1.25% maximum), the 12 indicates the nominal carbon content of the electrode (.12%C) and the "K" indicates that the electrode is made of silicon killed steel.

The flux depth in the FCB is approximately 3/32" whereas approximately ½" of flux depth between the nozzle and the plate is covering the arc. The ½" thick plate has a square groove preparation with a ¼" root opening, as shown in **Figure 3.3**. The 1 inch thick plate has a 45° included angle with a root face and opening dimension of ¼" and 5/32", respectively, as shown in **Figure 3.4**.

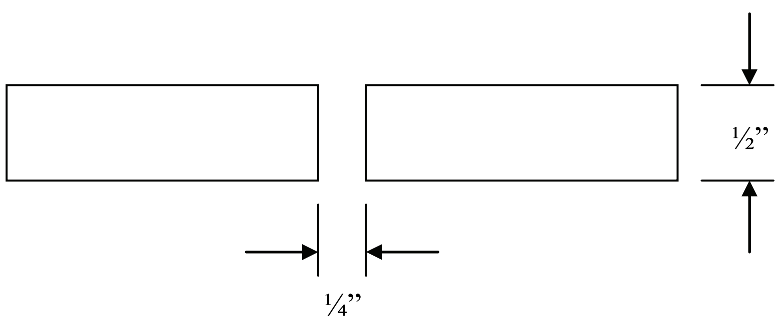


Figure 3.3: Square Groove Configuration – ½"-Thickness

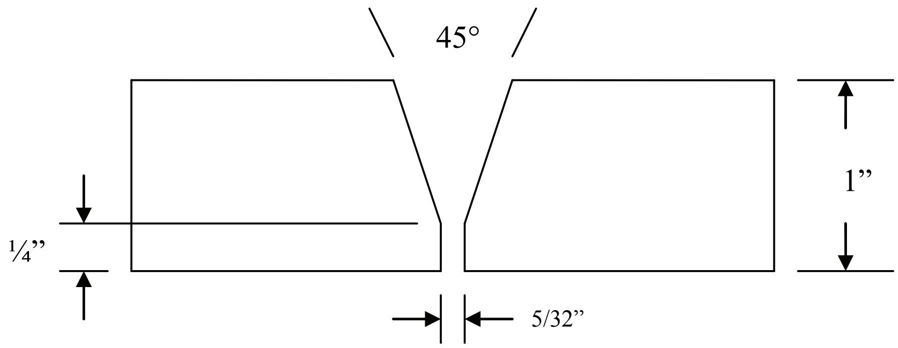


Figure 3.4: Single-V Joint Configuration – 1-inch Thickness

The welding parameters as well as number of passes and calculated “arc times per foot of joint” for each ½” and 1” DH36 procedures are provided in **Table 3.1**.

Table 3.1: DH36 Benchmark Procedures

Plate Thickness	Joint Preparation Details			Pass (#)	WFS (ipm)	Amps (A)	Volts (V)	Travel Speed (ipm)	Heat Input (kJ/in)	“Arc Time” (min/ft of joint) *
	Included Angle	Root Face	Root Opening							
½”	Square Groove	N.A.	¼”	1	60 Series Arc	780	41	12	160	1
1”	Single-V 45°	¼”	5/32”	1	60 Series Arc	780	41	12	160	4.4
				2 to 5	N.A. Single Arc	650	32	14	89	

** Note that arc time per foot of joint doesn’t include time required to carry out interpass welding operations (e.g. chipping, cleaning, re-alignment of electrodes, etc) typical for multi-pass welding procedures*

In production, the plates are normally just clamped, however in cases where misalignment between the plates is encountered the plates are tack welded and clamped with hydraulic hold downs. The panel line welder used at NGSS is an Air Liquide FRO one sided welder, model LT19.

3.1.2 NSWCCD Welding Procedure Information - HSLA-65 Steels

In both ½ and 1-inch thickness, a two electrode tandem set-up is used for welding the first pass, as shown in **Figure 3.5**. Each electrode is connected to its own constant voltage (CV) power source with the lead and trail electrode operating on DCEP and AC (sine wave) polarity, respectively. Both the lead and trail electrodes are 5/32” diameter and are spaced 5.5 inches apart. The lead electrode has a travel drag angle of 15°, and the trail has a drag angle 0-5°. The CTWD of the lead electrode is 1-1/8” and the trail is 1-1/2”.

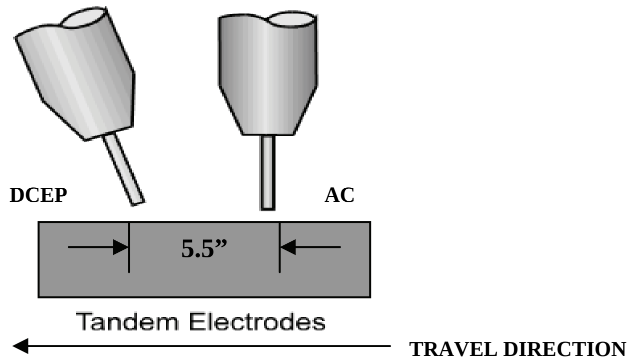


Figure 3.5: Tandem Set-up for HSLA-65 Steels

For the 1-inch thickness, the weld is completed with one additional fill pass using a single 5/32” electrode on AC (sine wave) polarity. All welding is conducted from one side onto an FCB using either Lincoln or ESAB MIL100S-1 of MIL-E-23765/2 and Lincoln MIL-800H flux of MIL-100S-2F. The backing bar flux is Nittetsu NSH-1R where the flux depth in the backing bar is approximately 1/8” with approximately ½” of flux depth between the supply nozzle and the plate is covering the arc. The ½” thick plate has a 45° included angle with a root face and opening dimension of 3/32” and 0 to 0.020”, respectively, as shown in **Figure 3.6**. The 1-inch thick plate has a 45° included angle with a root face and opening dimension of 5/32” and 0 to 0.020”, respectively, as shown in **Figure 3.7**.

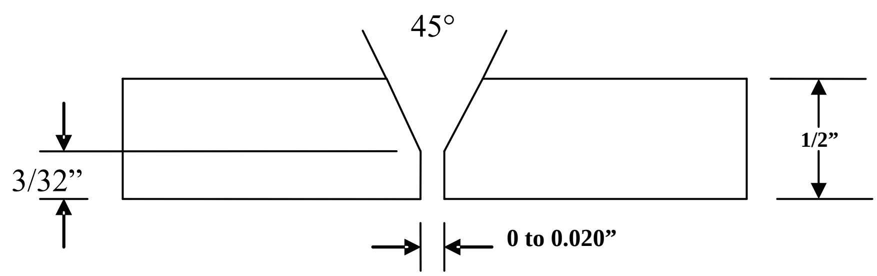


Figure 3.6: Single-V Joint Configuration for ½” Thick HSLA-65

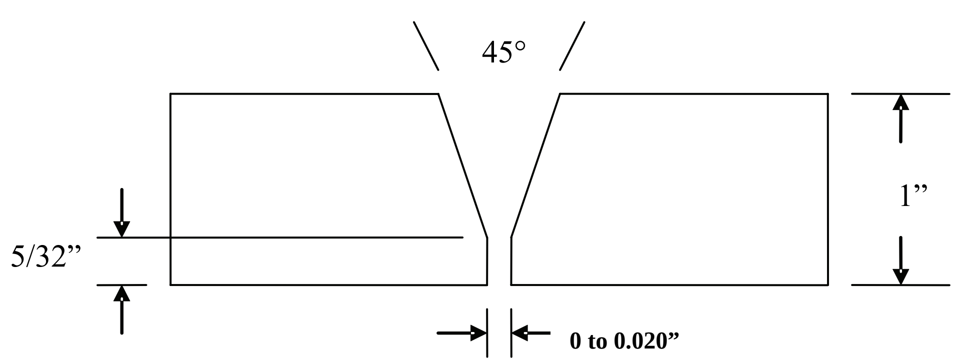


Figure 3.7: Single-V Joint Configuration for 1-inch Thick HSLA-65

The welding parameters as well as number of passes and calculated "arc times per foot of joint" for each ½" and 1" HSLA-65 procedures are provided in **Table 3.2**.

Table 3.2: HSLA-65 Benchmark Procedures

Plate Thickness	Joint Preparation Details			Pass (#)	WFS (ipm)	Amps (A)	Volts (V)	Travel Speed (ipm)	Total Heat Input (kJ/in)	"Arc Time" (min/ft of joint) *
	Included Angle	Root Face	Root Opening							
½"	Single-V 45°	3/32"	0"	1	N.A.	L-875	29	27.5	94.3	0.44
					N.A.	T-525	34			
1"	Single-V 45°	5/32"	0"	1	N.A.	L-1050	29	23.5	160.5	1.3
					N.A.	T-900	36			
				2	N.A.	825	34	15.5	108.6	

** Note that arc time per foot of joint doesn't include time required to carry out interpass welding operations (e.g. chipping, cleaning, re-alignment of electrodes, etc) typical for multi-pass welding procedures*

In production the plates are tack welded and clamped with hydraulic hold downs prior to welding. Small button tacks are deposited along the weld seam approximately 8 inches apart using the Gas Metal Arc Welding (GMAW) process.

3.1.3 NSWCCD Welding Procedure Information - HSLA-100 Steels

For both the ½" and 1 inch thickness, a single 1/8" diameter MIL-100S-1F electrode of MIL-E-23765/2 and a flux of MIL-100S-1F of MIL-E-23765/2 are used on DCEP. The typical parameter range for welding is as follows:

- Amperage (A): 475 - 650
- Voltage (V): 27 - 30
- Travel Speed (ipm): 12 - 18
- Minimum Preheat Temperature (°F): 60
- Maximum Interpass Temperature (°F): 300
- Maximum Heat Input: 85 kJ/in

The procedures for the ½" HSLA-100 steel typically consists of a square butt joint with no root opening, which requires one pass per side. The first weld is deposited on the first side and then the panel is flipped so that back gouging to sound weld metal can be completed from the back side before the second pass is deposited on the second side.

The procedures for the 1" HSLA-100 steel typically consists of a double-V joint configuration with no root opening and a root face of approximately 5/16" centered at the T/2 location. The included angle for each preparation is typically 60°. The first four weld passes are deposited from the first side and then the panel is flipped so that back gouging can be completed from the back side before the final four passes are deposited on the second side. There are typically eight passes in total deposited each at a heat input of approximately 83.5kJ/in to fill up the joint.

The typical welding parameters as well as number of passes and calculated "arc times per foot of joint" for each ½" and 1" HSLA-100 procedures are provided in **Table 3.3**.

Table 3.3: HSLA-100 Benchmark Procedures

Plate Thickness	Joint Preparation Details			Pass (#)	WFS (ipm)	Amps (A)	Volts (V)	Travel Speed (ipm)	Heat Input (kJ/in)	"Arc Time" (min/ft of joint) *
	Included Angle	Root Face	Root Opening							
½"	Square Groove	N.A.	N.A.	1	N.A.	650	30	14	83.5	1.7
				2	N.A.	650	30	14	83.5	
1"	Double-V 60°	5/16"	0"	1-4	N.A.	650	30	14	83.5	6.8
				5-8	N.A.	650	30	14	83.5	

** Note that arc time per foot of joint doesn't include time required to carry out interpass welding operations (e.g. chipping, cleaning, re-alignment of electrodes, etc) typical for multi-pass welding procedures*

3.2 Task 2: Development of Metal Cored Electrodes for High Heat Input Panel Welding

In the second task, metal cored electrode / flux combinations were developed for depositing high heat input welds in ½ and 1- inch thick DH36, HSLA-65, and HSLA-100 steels. The NAVSEA weld metal mechanical property requirements were as follows:

- **DH36 Targets – Modified AWS EC1 Classification**
  - Min. 58ksi YS, 71 to 95ksi UTS, and 20% Elongation
  - Impacts of 20ft-lbs @ -20F
- **HSLA-65 Targets – MIL-100S-1C per MIL-E-23765/2E**
  - Min. 65ksi YS, 20% Elongation
  - Impacts of 30 ft-lbs @ -20F
- **HSLA-100 Targets – MIL-100S-1C per MIL-E-23765/2E**
  - 88 to < 102ksi YS (under matching applications) and 18% Elongation
  - Impacts of 35 ft-lbs at -60F

The metal cored electrode compositions were developed using fundamental metallurgical principles and needed to be used with off-the-shelf highly basic fluxes. The combination of flux and electrode compositions, as well as the base plate chemistry and weld dilution, will determine the final composition of the deposited weld metal. The heat input, cooling rate, and any subsequent bead tempering and/or post weld heating for a given composition will thus determine the final microstructure and properties of the weld metal. The goal in this project was to achieve a balance between the weld strength and toughness, while demonstrating maximum productivity. A general literature review was conducted to examine references from past research that dealt primarily with welding of high strength steels. These steels included the quenched and tempered (QT) grades, HY-80, HY-100, and HY-120, as well as the high-strength, low-alloy (HSLA) steels with yield strengths of 80 ksi (550 MPa) and higher. These references aided in the electrode compositions developed in this project, and a summary of the literature review is provided in **Appendix A.**

3.2.1 Preliminary Electrode Formulations

With some guidance from the references reviewed in Task 2, the first series of electrode formulations were developed for each of the steels in this project. The preliminary electrode formulation developed for the DH36 electrode was within the compositional range requirements for an EC1 electrode classification per AWS A5.17. The formulations developed for the HSLA-65 and HSLA-100 electrodes were within the compositional range requirements for MIL-100S-1C and MIL-120S-1C electrode classifications per MIL-E-23765/2E, respectively. It should be noted that the composition range for cored electrodes are for deposited weld metal and not sampled from the actual electrode.

To achieve baseline mechanical properties as well as deposited weld metal chemistry, each of the electrodes were used to fabricate all weld metal test assemblies in accordance with standard AWS A5.17/23 requirements, at a heat input of 57.5 kJ/in, two (2) passes per layer and five (5) layers. The maximum interpass temperature was maintained below 325°F. The DH36, HSLA-65 and HSLA-100 base materials received from the project sponsors were used as test plate material with each of the applicable electrodes. Hobart HPF-N90 flux was initially used with the DH36 composition whereas Lincoln Electric's MIL800-H flux was selected for the HSLA-65 and HLSA-100 compositions based on its ability to demonstrate low weld metal diffusible hydrogen levels to reduce the susceptibility to hydrogen cracking. This flux also is considered highly basic that can promote low weld metal oxygen levels which is essential for achieving good low temperature impact properties with alloyed consumables.

The preliminary compositions, including the deposited weld metal results, are provided in **Table 3.4**. The deposited weld metal sample was extracted from the reduced area of the fractured tensile specimen and tested in accordance with ASTM 1019.

Table 3.4: Preliminary Target Electrode Formulations and Resulting Weld Metal Results

	Target Electrode Chemical Compositions																
Base Metal	C	Mn	Si	S	P	Ni	Cr	Mo	Al	B	Cu	Zr	Nb	Ti	V	N	O	Pcm
HSLA-100	0.045	1.700	0.350	0.002	0.001	2.000	0.150	0.550	0.005	0.005	0.010	0.004	0.004	0.014	0.001	0.005	0.006	0.245
HSLA-65	0.035	1.500	0.350	0.002	0.001	1.250	0.070	0.350	0.005	0.005	0.010	0.004	0.004	0.010	0.001	0.005	0.006	0.195
DH-36	0.070	1.800	0.550	0.004	0.001	0.150	0.020	0.100	0.005	0.001	0.020	0.001	0.001	0.007	0.001	0.005	0.006	0.195
	Electrode Formulations																	
Base Metal	C	Mn	Si	S	P	Ni	Cr	Mo	Al	B	Cu	Zr	Nb	Ti	V	N	O	Pcm
HSLA-100	0.063	1.692	0.312	0.001	0.006	1.950		0.465	0.008									0.222
HSLA-65	0.021	1.320	0.300	0.001	0.007	1.200		0.372	0.008									0.142
DH-36	0.120	1.070	0.614	0.001	0.006	0.300		0.149	0.015									0.209
	Weld Metal Results																	
	C	Mn	Si	S	P	Ni	Cr	Mo	Al	B	Cu	Zr	Nb	Ti	V	N	O	Pcm
HSLA-100	0.047	1.253	0.375	0.012	0.017	1.434	0.039	0.377	0.007	0.001	0.094	0.002	0.003	0.002	0.001	0.009	0.061	0.182
HSLA-65	0.033	1.082	0.348	0.010	0.016	0.914	0.038	0.312	0.004	0.001	0.082	0.002	0.003	0.002	0.002	0.013	0.046	0.147
DH-36	0.033	1.429	0.528	0.009	0.018	0.247	0.041	0.144	0.007	0.000	0.060	0.001	0.008	0.001	0.003	0.005	0.056	0.142

Macro sections were extracted from each test plate, polished, and etched with a solution of 10% nital, and these are shown in **Figures 3.8**, **3.9**, and **3.10**.

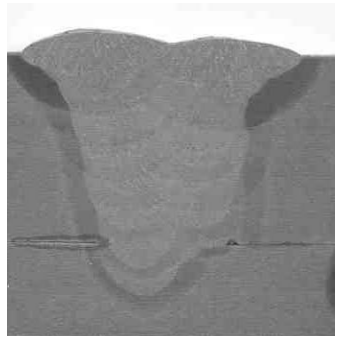


Figure 3.8: DH36 Macro Section

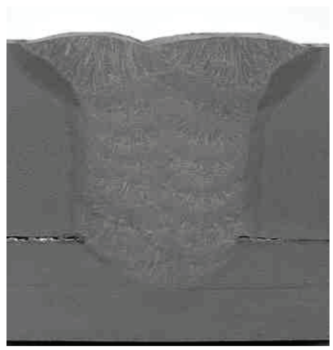


Figure 3.9: HSLA-65 Macro Section

Figure 3.10: HSLA-100 Macro Section

One round all weld metal tensile and five charpy V-notch impact specimens were extracted from each of the fabricated weldments and tested in accordance with ASTM E8 and ASTM E23, respectively. The results were as follows:

Tension Tests Results

The results of the tension tests are shown in **Table 3.5**. The stress-strain curve for each tension test is provided in **Appendix B.**

Table 3.5: All Weld Metal Tension Test Results

Specimen	Diameter (in.)	Area (in^2)	Yield Load (lbs)	Yield Strength (psi)	Maximum Load (lbs)	Ultimate Tensile Strength (psi)	Elongation (%)
DH36	.500	.196	13,500	68,755	16,380	83,423	29
HSLA-65	.503	.198	14,335	72,400	16,540	83,535	27
HSLA-100	.503	.198	17,444	88,100	19,860	100,303	21

Charpy V-notch Impact Test Results

The results of the impact tests are shown in **Table 3.6**.

Table 3.6: Charpy V-notch Impact Test Results

Specimen	Test Temperature (°F)	Energy (ft-lbs)	Average (ft-lbs)
DH36-1	-20	65	67
-2		65	
-3		82	
-4		68	
-5		24	
HSLA-65-1	-20	99	84
-2		88	
-3		85	
-4		80	
-5		70	
HSLA-100-1	-60	40	35
-2		35	
-3		38	
-4		28	
-5		31	

Each of the mechanical test results met the minimum strength and toughness requirements however, the HSLA-100 strength and impact properties were marginally acceptable even when welded well below the 85kJ/in heat input restriction. It should be noted that the results achieved with the preliminary formulations were from standard weld metal conformance tests and that the properties from actual high heat input OSW's could differ due to the increased levels of dilution with the base plate and thus the expected higher levels of weld metal alloying contents. Because yield strength and heat input are directly linked and that yield strength typically diminishes with increasing heat input, a second series of electrode formulations were manufactured to ensure that sufficient strength and impact properties could be achieved under the conditions of high heat input welding compared to those of the standard all weld metal test assemblies.

These revised electrode formulations are shown in **Table 3.7**.

Table 3.7: Revised Electrode Formulations for Testing

	C	Mn	Si	S	P	Ni	Cr	Mo	Al	B	Cu	Zr	Nb	Ti	V	N	O	Pcm
HSLA-100-2	0.0646	1.9207	0.4510	0.0010	0.0053	2.8500	0.2400	0.5580	0.0185	0.0039	0.0300	0.0081	0.0099	0.0297	0.0117			0.2945
HSLA-65-2	0.0386	1.5907	0.4510	0.0012	0.0060	1.8300	0.0960	0.3348	0.0184	0.0039	0.0300	0.0081	0.0099	0.0297	0.0047			0.2123
DH36-2	0.0632	1.3800	0.5260	0.0012	0.0062	0.5100	0.0030	0.1488	0.0204	0.0039	0.0600	0.0081	0.0099	0.0148	0.0117			0.1920

3.2.2 Revised Electrode Formulation Testing

The revised electrode formulations were subjected to all weld metal qualification testing, utilizing the same welding parameters as the first round of tests. For the second round of testing, the DH36 and HSLA-65 plates were welded with ESAB's OK10.62 flux, which is also a highly basic agglomerated flux that was recommended by NGSS. In addition, the HSLA-65 and HSLA-100 second round tests were conducted with Lincoln MIL800-H flux as previously used. The revised electrode formulations as well as the weld metal chemical analysis results are both shown in **Table 3.8** for comparison. It should be noted that the level of alloy content in each of the weld metals increased compared to the actual electrode formulation, a trend that was opposite to what was achieved during the first round of tests.

Table 3.8: Revised Electrode Formulations and Weld Metal Chemical Analysis Results

	Formulation																	
	C	Mn	Si	S	P	Ni	Cr	Mo	Al	B	Cu	Zr	Nb	Ti	V	N	O	Pcm
HSLA-100-2	0.0646	1.9207	0.4510	0.0010	0.0053	2.8500	0.2400	0.5580	0.0185	0.0039	0.0300	0.0081	0.0099	0.0297	0.0117			0.2945
HSLA-65-2	0.0386	1.5907	0.4510	0.0012	0.0060	1.8300	0.0960	0.3348	0.0184	0.0039	0.0300	0.0081	0.0099	0.0297	0.0047			0.2123
DH36-2	0.0632	1.3800	0.5260	0.0012	0.0062	0.5100	0.0030	0.1488	0.0204	0.0039	0.0600	0.0081	0.0099	0.0148	0.0117			0.1920
	Weld Metal Results																	
HSLA-100-2 / MIL800-H	0.0700	1.8300	0.3600	0.0090	0.0140	2.8300	0.3500	0.6100	0.0360	0.0018	0.2700	0.0100	0.0230	0.0090	0.0230	0.0100	0.0320	0.3036
HSLA-65-2 / MIL800-H	0.0600	1.6800	0.3600	0.0080	0.0150	1.7500	0.1200	0.3600	0.0240	0.0013	0.0890	0.0050	0.0250	0.0100	0.0450	0.0100	0.0370	0.2306
HSLA-65-2 / ESAB OK 10.62	0.0400	1.6100	0.3600	0.0080	0.0170	1.6600	0.1200	0.3400	0.0230	0.0015	0.0850	0.0050	0.0240	0.0110	0.0440	0.0100	0.0340	0.2050
DH36-2 / ESAB OK 10.62	0.0700	1.5100	0.4100	0.0090	0.0170	0.4800	0.0510	0.1600	0.0230	0.0017	0.1100	0.0050	0.0210	0.0120	0.0300	0.0100	0.0400	0.1974

The macro sections from each test plate are shown in **Figures 3.11**, **3.12**, **3.13, and 3.14**.

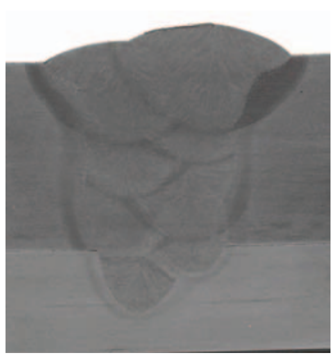


Figure 3.11: DH36-2 Macro Section, OK10.62 Flux

Figure 3.12: HSLA-65-2 Macro Section, Lincoln MIL800-H Flux

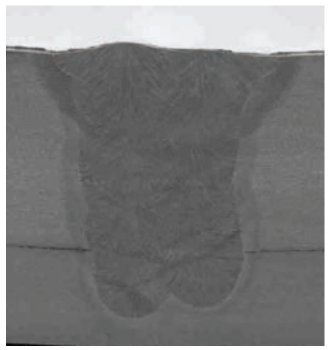


Figure 3.13: HSLA-65-2, ESAB 10.62 Flux

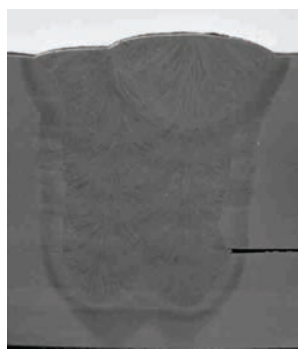


Figure 3.14, HSLA-100-2, Lincoln MIL-800-H Flux

During the extraction and machining of the mechanical test specimens from the HSLA-100 plate, transverse cracks were discovered at approximately 5/8” below the top surface. Transverse cracks occur when the critical combination of hydrogen, tensile stress, and a susceptible microstructure are present. A combination of each variable needs to reach a critical level for cracking to occur, and each condition needs to be engineered to preclude cracking. It was possible that the weld metal alloy content and resulting weld metal hardness was in a range that was sensitive to cracking.

To determine if excessive hydrogen values were the cause of cracking, standard diffusible hydrogen tests were conducted in accordance with AWS A4.3 using the same flux and electrode used in the weld metal test assemblies. The flux was stored at a constant temperature of 300°F after removing from the sealed container. The results of the diffusible hydrogen tests yielded an average of 3.6 ml of hydrogen per 100g of weld metal, which is below the average maximum requirement of 5.5ml/100g as per NAVSEA Technical Publication T9074-BCGIB-010/0200 for a 100S-1 or 120S-1 electrode classification. Although not considered a relatively high value, the hydrogen level could have been sufficient to cause this type of cracking in the highly alloyed weld metal.

The remaining two options that were considered to reduce the susceptibility of cracking were to increase the preheat level (a method used to drive off moisture and also provide more time for hydrogen to diffuse from the weld zone to a non-critical level before returning to ambient temperature) then subject the test assembly to a post-weld hydrogen removal heat treatment, or, to reduce the alloy content of the weld metal to a level that will produce a lower hardness microstructure that is less susceptible to cracking. The first option of pre and post-weld heating would significantly increase the cost of welding if this practice was applied in production; therefore reducing the alloy content of the weld metal appeared to be the more economical choice. The HSLA-100 electrode formulation was revised for the third time and is shown in **Table 3.9**.

Table 3.9: Revised HSLA-100 Formulation, Third Revision

	C	Mn	Si	S	P	Ni	Cr	Mo	Al	B	Cu	Zr	Nb	Ti	V	N	O	Pcm
HSLA-100-3	0.0500	1.7500	0.4500	0.0020	0.0020	2.3000	0.1750	0.4500	0.0070	0.0040	0.0300	0.0080	0.0100	0.0300	0.0070			0.2518

An all weld metal test assembly was welded, using minimum preheat and maximum interpass temperatures of 150°F and 300°F, respectively, and the HSLA-100-3 electrode with MIL800-H flux. The macro section of the completed weld is shown in **Figure 3.15**.

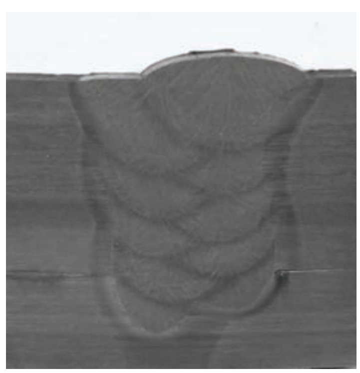


Figure 3.15: HSLA-100-3, Lincoln MIL800-H Flux

Tension Test Results

One all weld metal tensile specimen was extracted from each of the welded assemblies and tested in accordance with ASTM E8. The results of the previous tensile tests as well as those from the revised formulations are shown in **Table 3.10** for comparison. The stress/strain curves for each of the tests are shown in **Appendix C**. It should be noted that no transverse cracking was detected in the HSLA-100 welded test assembly.

Table 3.10: All Weld Metal Tension Test Results

Specimen	Diameter (in.)	Area (in^2)	Yield Load (lbs)	Yield Strength (psi)	Maximum Load (lbs)	Ultimate Tensile Strength (psi)	Elongation (%)
First Round of Testing							
DH36-1 N90	.500	.196	13,500	68,755	16,380	83,423	29
HSLA-65-1 MIL800-H	.503	.198	14,335	72,400	16,540	83,535	27
HSLA-100-1 MIL800-H	.503	.198	17,444	88,100	19,860	100,303	21
Second Round of Testing							
DH36-2 OK 10.62	.502	.198	17,958	90,698	19,850	100,253	27
HSLA-65-2 OK10.62	.497	.194	19,050	98,195	21,110	108,814	20
HSLA-65-2 MIL800-H	.479	.180	18,000	100,000	20,790	115,500	21
HSLA-100-3 MIL800-H	.502	.198	21,050	106,312	24,110	121,767	20

Charpy V-Notch Test Results

Five impact test specimens were extracted from each test assembly and tested in accordance with ASTM E23. The DH36 and HSLA-65 impact specimens were extracted 3/8" below the surface with the notch sampling the weld centerline, whereas the HSLA-100 impact specimens were extracted 1/16" below the surface. The results from the all weld metal impact tests, as well as those from the previous tests, are shown in **Table 3.11** for comparison.

Table 3.11: Charpy V-notch Impact Test Results

Specimen	Test Temperature (°F)	Energy (ft-lbs)	Average (ft-lbs)	Requirement (ft-lbs)
First Round of Tests				
DH36-1 (N90 Flux)				
-1	-20	65	67	20
-2		65		
-3		82		
-4		68		
-5		24		
HSLA-65-1 (MIL800-H Flux)				
-1	-20	99	84	30
-2		88		
-3		85		
-4		80		
-5		70		
HSLA-100-1 (MIL800-H Flux)				
-1	-60	40	35	35
-2		35		
-3		38		
-4		28		
-5		31		
Second Round of Tests				
DH36-2 (OK10.62 Flux)				
-1	-20	85	89	20
-2		87		
-3		95		
-4		94		
-5		74		
HSLA-65-2 (OK10.62 Flux)				
-1	-20	64	68	30
-2		66		
-3		76		
-4		62		
-5		75		
HSLA-65-2 (MIL800-H Flux)				
-1	-20	61	59	30
-2		58		
-3		58		
-4		62		
-5		54		
HSLA-100-3 (MIL800-H Flux)				
-1	-60	48	43	35
-2		43		
-3		38		
-4		43		
-5		43		

3.2.3 Revised DH36, HSLA-65, and HSLA-100 Electrode Composition Review

Significant improvements in tensile properties in each of the weld metals were achieved through revisions of the preliminary electrode formulations. A slight reduction in impact properties was demonstrated for each of the HSLA-65 weld metals, however this reduction was considered a trade off for the significant yield strength improvements that were achieved. The DH36 reformulated weld metal demonstrated the most enhancements in both tensile and impact properties by almost 25%. The HSLA-100 third revision resulted in crack free welds with a significant improvement in tensile properties over the initial formulation, while maintaining adequate impact properties at the specified -60°F test temperature.

The results of the electrode qualification testing were considered sufficient to carry forward into the next task involving the development and qualification of high heat input OSW of DH36 and HSLA-65 steels, as well as high heat input multi-pass welding of HSLA-100.

3.3 Task 3 - Welding Procedure Development and Qualification Testing for ½" and 1" Thick DH36, HSLA-65, and HSLA-100 Steels

The third task was to develop highly productive high heat input procedures for ½ and 1-inch DH36, HSLA-65, and HSLA-100 steels using the VBAC and metal cored electrode technologies. These procedures included:

- Single pass OSW onto FCB for ½" and 1" DH36;
- Single pass OSW onto FCB for ½" and 1" HSLA-65;
- Multi-pass OSW onto FCB for 1" HSLA-100; and
- Two sided welding of ½" and 1" HSLA-100, 1 pass per side, with no back gouging.

The chemical compositions and mechanical properties for each of the ½" and 1" thick DH36, HSLA-65, and HSLA-100 steels provided by the sponsors are shown in **Tables 3.12** and **3.13**, respectively.

Table 3.12: Chemical Compositions of Base Metals

		Composition (%)														
Base Metal	Thickness	C	Mn	Si	S	P	Ni	Cr	Mo	Al	B	Cu	Zr	Nb	Ti	V	Pcm
DH36	1/2"	0.08	1.31	0.252	0.006	0.012	0.01	0.03	0.005	0.029		0.011				0.049	0.161
	1"	0.07	1.34	0.252	0.003	0.011	0.01	0.03	0.005	0.033		0.013				0.051	0.153
HSLA-65	1/2"	0.07	1.45	0.31	0.005	0.011	0.005	0.021	0.005	0.036	0.0002	0.021	0.005	0.032	0.016	0.071	0.163
	1"	0.07	1.48	0.31	0.006	0.021	0.011	0.035	0.006	0.028	0.0002	0.021	0.005	0.029	0.013	0.071	0.166
HSLA-100	1/2"	0.06	0.87	0.28	0.005	0.008	1.74	0.62	0.34	0.047	0.0002	1.24	0.018	0.02	0.005	0.005	0.259
	1"	0.06	0.91	0.27	0.001	0.011	1.68	0.59	0.4	0.023		1.15			0.002	0.004	0.257

Table 3.13: Mechanical Properties of Base Metals

		Mechanical Properties		
Base Metal	Thickness	Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation (%)
DH36	1/2"	72.7	80.1	20
	1"	70.4	77.8	23
HSLA-65	1/2"	70	80	32
	1"	65.8	71.1	33
HSLA-100	1/2"	112.5	119.7	26
	1"	111.4	117.4	28

3.3.1 One-sided Single Run Welding Procedure Development – ½” Plate Thickness

The objective of this task was to increase the speed of single pass OSW’s in ½” thick DH36 and HSLA-65 steels compared to current practice, while comfortably maintaining the minimum specified weld zone mechanical property requirements.

As previously discussed, the DH36 steel NGSS series arc procedure consists of a square groove (no preparation) and ¼” root opening. The HSLA-65 steel tandem arc procedure provided by the NSWCCD consists of a 45° included angle with a 3/32” root face and no root opening. It was decided to examine the included angle, root geometry, and the leading arc welding parameters concurrently as any change in one of these variables can affect the success of the root bead deposit. Various welding fluxes (Oerlikon OP139, Lincoln 780 and 980, and ESAB OK10.62) were examined to determine their potential advantages and/or disadvantages for one-sided welding. Each of the 24-inch long test plates fabricated received precision machined bevels and were fit-up with button tack welds at every eight (8) inches using the GMAW process. The paint and mill scale was removed approximately two (2) inches in all directions from the groove location on both sides of the plate. The grooved copper backing bar typically used for one-sided welding was filled flush with flux and the test plate was clamped firmly onto the copper backing bar with rigid restraints. Prior to welding, flux was added manually to the joint for the leading arc however the flux hopper provided the additional flux depth required for the trailing arc during welding. The set-up for welding is shown in **Figure 3.16**.

The series of tests and parameters examined for DH36 steel as well as procedure notes are provided in **Table 3.14**. All welding parameters were monitored with calibrated digital volt and amperage meters and the speed of welding was verified using a stop watch and a tap measure.

Figure 3.16: Set-up for Tandem One-sided Welding

Table 3.14: ½” One-sided Welding Procedure Development

		Lead						Trail													
Weld	Flux	Electrode Diameter (in)	WFS (ipm)	Amperage (A)	Voltage (V)	ESO (in)	Travel Angle (deg)	Electrode Diameter (in)	WFS (ipm)	Amperage (A)	Voltage (V)	ESO (in)	Electrode Spacing (in)	Travel Angle (deg)	AC Balance (EP/EN)	Mode	Travel Speed (ipm)	Angle (deg)	Root Face (in)	Root Opening (in)	Notes
Benchmark	**MIL800-H**	**5/32**	**NA**	**875**	**29**	**1 1/8**	**15 drag**		**NA**	**525**	**34**	**1 1/2**	**5.5**			**CV**	**27.5**	**45**	**3/32**	**0**	
DH36-1	Oerlikon OP139	5/32	118	780	29	1 1/8	15 drag								66/34	CV+C	27.5	45	3/32	0	Produced sufficient penetration / inconsistent back bead profile
DH36-2	Oerlikon OP139	5/32	113	780	29	1 1/8	15 drag								66/34	CV+C	27.5	45	0	0	Produced sufficient penetration / inconsistent back bead profile with excessive reinforcment
DH36-3	Oerlikon OP139	5/32	100	780	29	1 1/8	15 drag								66/34	CV+C	27.5	30	3/32	0	Insufficient penetration
DH36-4	Oerlikon OP139	5/32	108	780	29	1 1/8	15 drag								66/34	CV+C	27.5	30	0	0	Insufficient penetration
DH36-5	Oerlikon OP139	5/32	130	780	29	1 1/8	15 drag								66/34	CV+C	27.5	30	0	1/8	Excessive penetration
DH36-6	Oerlikon OP139	5/32	140	800	27.5	1 1/4	15 drag								34/66	CV+C	35	30	0	1/16	Intermittent lack of penetration
DH36-7	Oerlikon OP139	5/32	145	850	27.5	1 1/4	5 drag								34/66	CV+C	38	30	0	1/16	Intermittent lack of penetration
DH36-8	Oerlikon OP139	5/32	150	870	28.5	1 1/4	5 drag								34/66	CV+C	38	45	0	0	Hour glass bead shape - possible CV+C effect i.e. wire feed speed fluctuation to keep current constant - switch to C
DH36-9	Oerlikon OP139	5/32	150	870	31	1 1/4	5 drag								34/66	CV	35	45	0	0	Improved Results
DH36-10	Oerlikon OP139	5/32	150	900	32	1 1/4	5 drag	5/32	130	650	36	2 1/2	2	10 lead	34/66	CV	35	45	0	0	Added trailing arc in tandem, root bead improved significantly
DH36-11	Oerlikon OP139	5/32	150	900	32	1 1/4	5 drag	5/32	150	700	38	3	4	10 lead	34/66	CV	37	45	0	0	Produced nicest back bead profile so far however still inconsistent when duplicating procedure
DH36-12	780	5/32	150	900	32	1 1/4	5 drag	5/32	150	700	38	3	4	10 lead	34/66	CV	37	45	0	0	Switched flux, produced adequate results however inconsistent when duplicating procedure
DH36-13	980	5/32	150	900	30	1	5 drag	5/32	160	720	42	3 1/2	4	0	34/66	CV	35	45	0	0	Switched flux, produced adequate results however inconsistent when duplicating the procedure
DH36-14	OK 10.62	1/8	200	850	33	1	10 drag	5/32	140	850	36	1 1/2	4	0	66/34	CV	35	45	0	0	Swithced flux, lead wire diameter, balance setting.
DH36-15	OK 10.62	1/8	200	850	33	1	10 drag	5/32	140	850	37	1 3/4	4	0	66/34	CV	33	45	1/16	0	Insufficient fill and inconsistent root
DH36-16	OK 10.62	1/8	170	800	33	1	10 drag	5/32	130	750	37	1 3/4	4	0	66/34	CV	30	45	1/16	0	Insufficient fill and inconsistent root
DH36-17	OK 10.62	1/8	185	830	33	1	15 drag	5/32	140	780	38	1 3/4	4	5 drag	66/34	CV	33	30	1/16	0	Insufficient fill and inconsistent root
DH36-18	OK 10.62	1/8	180	800	33	1	15 drag	5/32	145	740	37.5	1 3/4	4	5 drag	66/34	CV	33	30	1/16	0	Insufficient fill and inconsistent root

A range of joint configurations were examined in an attempt to reduce the weld metal volume requirements; as well, two sizes of electrode diameters and a range of welding parameters were investigated to determine if weld metal deposition rates could be significantly enhanced compared to current practice. The degree of helix and cast in the received electrodes did not allow for long stick out welding to be studied in detail, as the electrodes could not maintain suitable alignment in the weld joint. Each of the root welds produced in the above test matrix had demonstrated inconsistent results. In cases where a suitable root bead profile was achieved, the procedure showed varying results when duplicated on subsequent test plates. There were some unexplained improvements to the root bead characteristics when the trailing arc was introduced to the system however, the results were still inconsistent when the procedures were duplicated on subsequent test plates. In cases where excessive root reinforcement height (melt through) was experienced, there was insufficient fill to cap off the weld. In cases where there was sufficient fill for the cap, there was insufficient root bead penetration. This phenomenon was believed to be the result of the backing bar design and its inability to provide consistent flux compression between the backing bar and the test plate. Flux compression can influence the degree of weld melt through to the back side as well the ability of the flux to form the bead profile. Factors that can influence compression are flux particle size and distribution as well as the pressure exhibited between the copper backing bar and test plate.

It was decided to reconfigure the backing bar to include a narrower and shallower contoured groove down the center. A smaller groove would require less flux and the shallower groove depth would restrict the weld penetration height. In addition, a smaller groove would provide more local support to the root weld on the back side of the joint instead of utilizing the flux itself to support and form the back bead profile. The original and revised backing bar designs are shown in **Figures 3.17** and **3.18**, respectively.

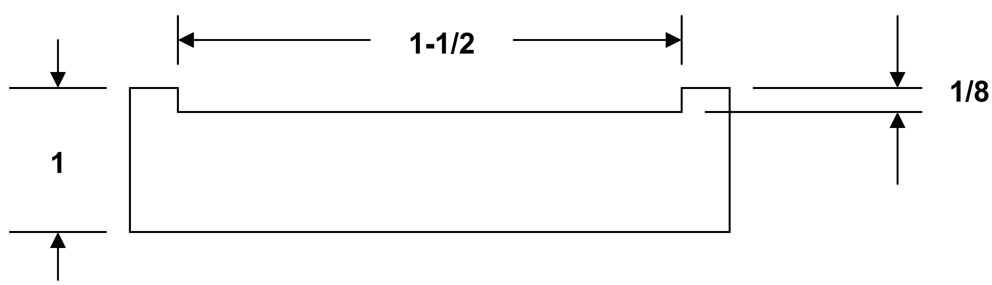


Figure 3.17: Original Copper Backing Design

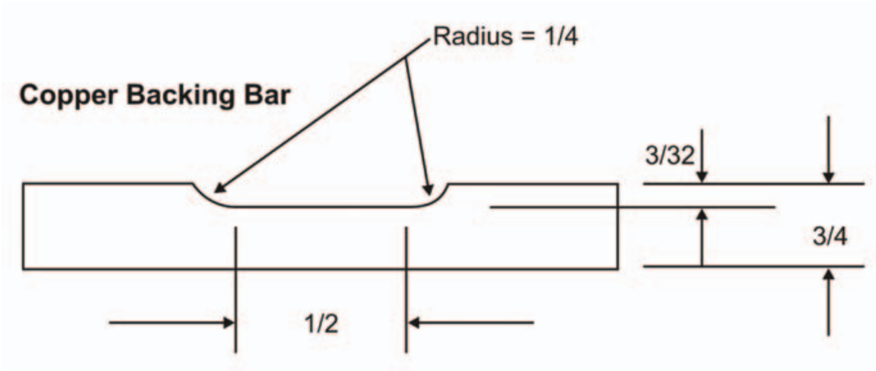


Figure 3.18: Revised Copper Backing Design

The parameters that were used with the revised backing bar design are shown in **Table 3.15.**

Table 3.15: ½" DH36 OSW Parameters

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	Single-V ϴ = 30°, Rf = 1/8", Rg = 3/32"	
Electrode Spacing	5 1/4"	
Flux	ESAB OK 10.62	
Welding Parameters		
	Lead Electrode	Trailing Electrode
Amperage (A)	800	700
Voltage (V)	37.5	37.5
WFS (ipm)	200	100
Travel Speed (ipm)	30	
Benchark Travel Speed (ipm)	12	
Travel Angle (°)	15 drag	5 push
CTWD (in)	3/4	1 3/4
Heat Input (kJ/in)	112.5 (combined)	
Benchmark Heat Input (kJ/in)	160 (combined)	

There was an immediate improvement in root bead shape and consistency, as well as fill and cap characteristics. This procedure was repeated several times without any significant variation in bead shape or size. The resulting cap and root bead profiles are shown in **Figures 3.19** and **3.20**, respectively, and the macro section is shown in **Figure 3.21**.

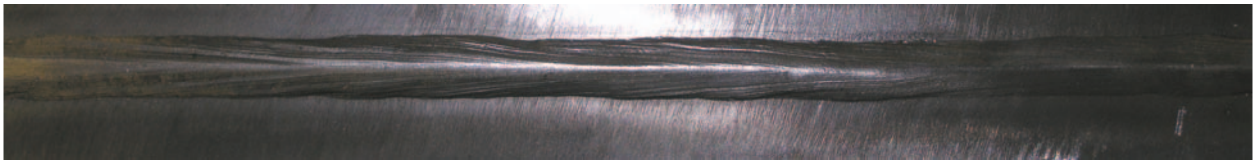


Figure 3.19: ½" One-sided Weld – Cap Side

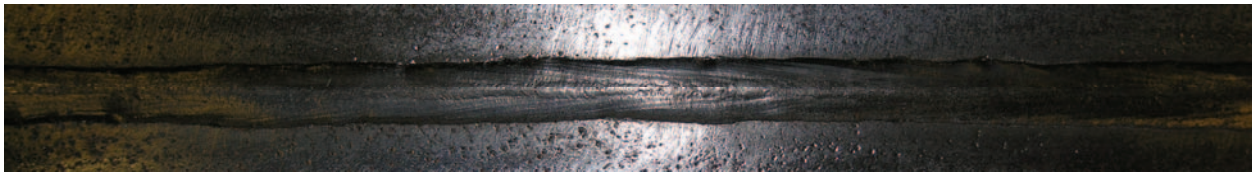


Figure 3.20: ½" One-sided Weld – Root Side

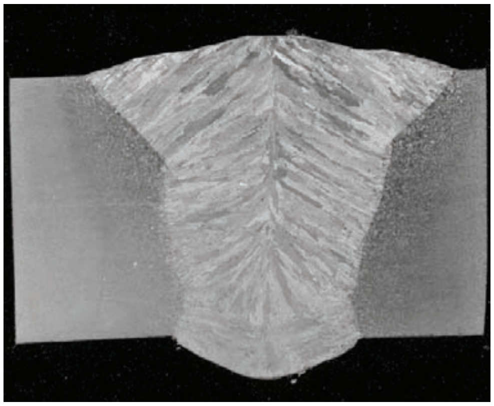


Figure 3.21: ½" One-sided Weld – Macro 2.5X Mag

The final welding procedure data sheet for the ½" thick DH36 one-sided single run welding procedure is provided in **Appendix D**.

The ½" DH36 procedure was applied with success to two separate ½" HSLA-65 test plates, one with ESAB OK 10.62 flux and the other with Lincoln MIL800-H, both using the HSLA-65-2 electrodes. The parameters are shown in **Table 3.16**.

Table 3.16: ½" HSLA-65 OSW Parameters

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	Single-V ϴ = 30°, Rf = 1/8", Rg = 3/32"	
Electrode Spacing	5 ¼"	
Flux	Lincoln MIL800-H	
Welding Parameters		
	Lead Electrode	Trailing Electrode
Amperage (A)	800	700
Voltage (V)	37.5	37.5
WFS (ipm)	200	100
Travel Speed (ipm)	30	
Benchark Travel Speed (ipm)	27.5	
Travel Angle (°)	15 drag	5 push
CTWD (in)	3/4	1 3/4
Heat Input (kJ/in)	112.5 (combined)	
Benchmark Heat Input (kJ/in)	94.3 (combined)	

The macro sections for the HSLA-65 welds using OK10.62 and Lincoln MIL800-H fluxes are shown in **Figure 3.22** and **3.23**, respectively, noting that each flux gave marginally different however acceptable results.

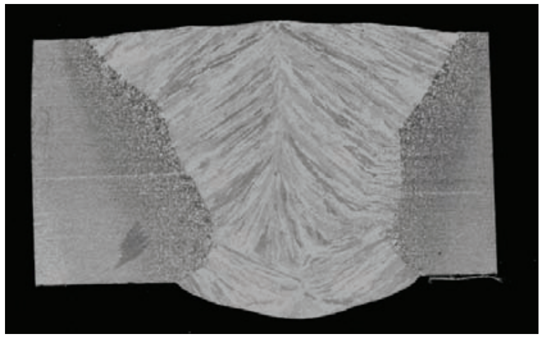


Figure 3.22: ½" HSLA-65 One-sided Weld, ESAB OK 10.62 – Macro – 2.5X Mag

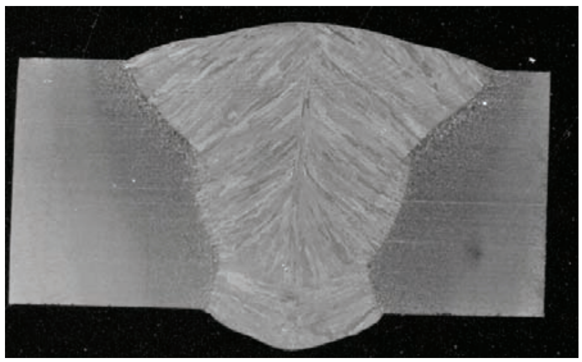


Figure 3.23: ½" HSLA-65 One-sided Weld, Lincoln MIL800-H – Macro 2.5X Mag

The final welding procedure data sheets for the ½" HSLA-65 single pass OSW procedure using both ESAB OK10.62 and Lincoln MIL800-H fluxes are shown in **Appendix E**.

3.3.2 One-sided Single Run Welding Procedure Development – 1" Plate Thickness

The objective of this task was to develop high heat input welding procedures for single pass OSW of DH36 and HSLA-65 steels while maintaining minimum weld zone mechanical property requirements. Current practice requires the use of multiple weld passes using a combination of multiple and single electrodes for each run. The benchmark welding procedures provided by NGSS for their series arc configuration consist of a 45° included angle joint preparation, a ¼" root face, and a 5/32" root opening. The benchmark procedures provided by NSWCCD for the tandem arc configuration for HSLA-65 steel consists of a 45° include angle, a 5/32" root face, and no root opening.

For single pass OSW, trials were performed with a 20° included angle in an attempt to reduce the amount of weld metal required to fill the joint which could have allowed higher travel speeds, however when used with 5/32" diameter electrodes, wide root openings (as much as ¼") were required to achieve sufficient lead electrode access and root penetration and was not considered economical. In addition, the deep and narrow characteristic of the resulting root bead (shown in **Figure 3.24**), would likely be sensitive to solidification cracking when applied into production under higher restraint conditions.

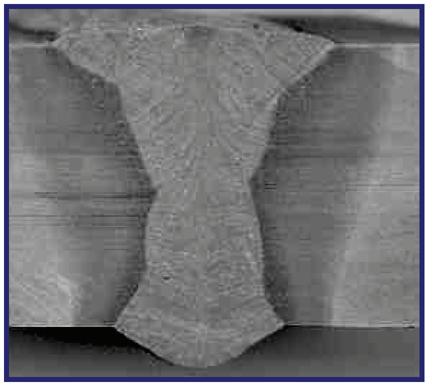


Figure 3.24: Macro-section of Weld Deposited with a 20° Included Angle – 1.5X Mag

Trials were also performed in a 20° included angle with a 1/8" electrode in an attempt to improve lead electrode access to the root location as well as enhance deposition rates, however inconsistent results were achieved. Joint preparation was increased from 20° to a 30° included angle which allowed a 5/32" lead electrode and high currents to be used with moderate root openings (3/32" to 1/8") and root faces (≤ 3/16"). Due to reasons discussed in the ½" procedure development, long stick-out welding could not be studied due to the effects of electrode wandering. The effect of electrode spacing was also studied however it was found that when welding at a spacing of less than four (4) inches there was too much interaction between the leading and trailing arcs resulting in poor arc characteristics. An electrode spacing as much as 6 inches was investigated without any problems, however, four (4) inches appeared to be an optimal distance.

The final single pass OSW procedures for 1" thick DH36 and HSLA-65 steels, utilizing the revised copper backing bar design and both ESAB OK10.62 and Lincoln MIL800-H fluxes, are provided in **Appendix F**. These procedures were repeated several times in 30 inch long plates without any significant variations in root and cap characteristics. The parameters for the 1" thick DH36 procedure are summarized in **Table 3.17**.

Table 3.17: 1" DH36 OSW Parameters

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	ϴ=30° Included Angle Rg = 3/32" Rf = 3/16"	
Electrode Spacing	4"	
Flux	ESAB OK 10.62	
Tandem Welding Parameters		
	Lead Electrode	Trailing Electrode
Amperage (A)	1150	980
Voltage (V)	32.5	36.5
WFS (ipm)	225	175
Travel Speed (ipm)	20.5 - 1 pass only	
Benchmark Travel Speed (ipm)	12 for1st pass, and 14 for 2nd, 3rd, 4th, and 5th passes	
Travel Angle (°)	15 drag	0
CTWD (in)	1/2	1 3/4
Heat Input (kJ/mm)	214.1 (combined)	
Benchmark Heat Input (kJ/in)	160.5 for 1st pass and 89 for 2nd, 3rd, 4th, and 5th passes	

The cap and root bead profiles for the completed DH36 weld are shown in **Figures 3.25 and 26.**

Figure 3.25: 1" DH36 One-sided Weld, ESAB OK10.62 – Cap Side

Figure 3.26: 1" DH36 One-sided Weld, ESAB OK10.62 – Root Side

The resulting macro-section of the DH36 weld with ESAB OK10.62 is shown in Figure 3.27.

Figure 3.27: 1" DH36 One-sided Weld, ESAB OK10.62 – Macro – 2.5X Mag

The parameters for the HSLA-65 welds are summarized in **Table 3.18**.

Table 3.18: 1" HSLA-65 OSW Parameters

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	ϴ=30° Included Angle Rg = 3/32" Rf = 3/16"	
Electrode Spacing	4"	
Flux	Lincoln MIL800-H	
Tandem Welding Parameters		
	Lead Electrode	**Trailing Electrode**
Amperage (A)	1180	950
Voltage (V)	32.5	36.5
WFS (ipm)	225	175
Travel Speed (ipm)	**20.5 - 1 pass only**	
Benchmark Travel Speed (ipm)	**23.5 for 1st pass and 15.5 for 2nd pass**	
Travel Angle (°)	15 drag	0
CTWD (in)	1/2	1 3/4
Heat Input (kJ/mm)	**214.1 (combined)**	
Benchmark Heat Input (kJ/in)	**160.5 for 1st pass and 108.6 2nd pass**	

The cap and root bead profiles for each of the completed welds are shown in **Figures 3.28**, **29**, **30**, and **31**.

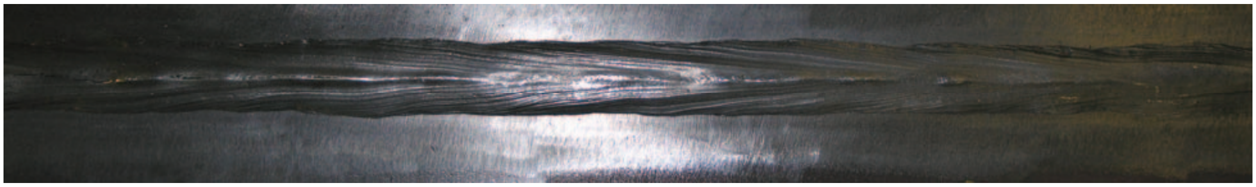


Figure 3.28: 1" HSLA-65 One-sided Weld, ESAB OK10.62 – Cap Side

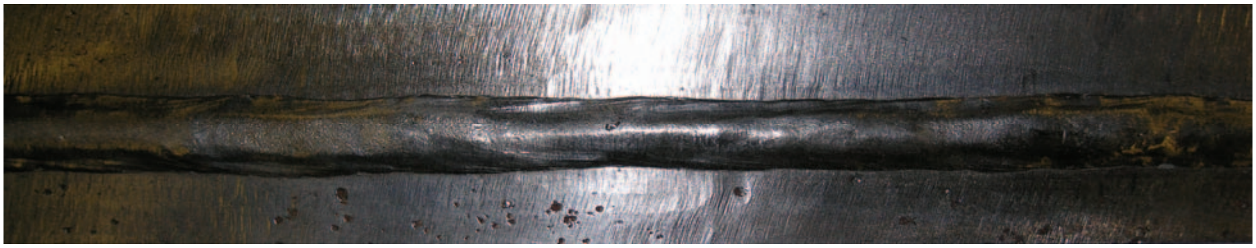


Figure 3.29: 1" HSLA-65 One-sided Weld, ESAB OK10.62 – Root Side

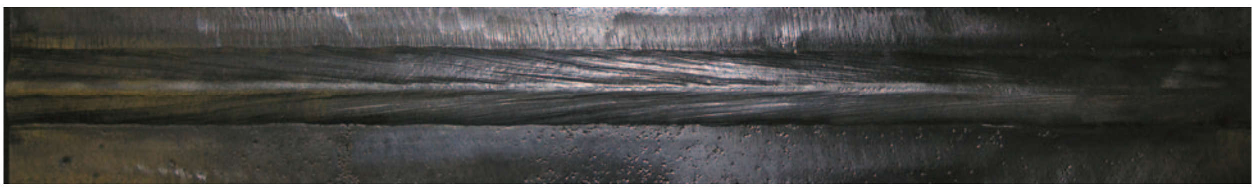


Figure 3.30: 1" HSLA-65 One-sided Weld, Lincoln MIL800-H – Cap Side

Figure 3.31: 1" HSLA-65 One-sided Weld, Lincoln MIL800-H – Root Side

The resulting macro-sections of the HSLA-65 welds with the ESAB and Lincoln fluxes are shown in Figures 3.32 and 3.33, respectively.

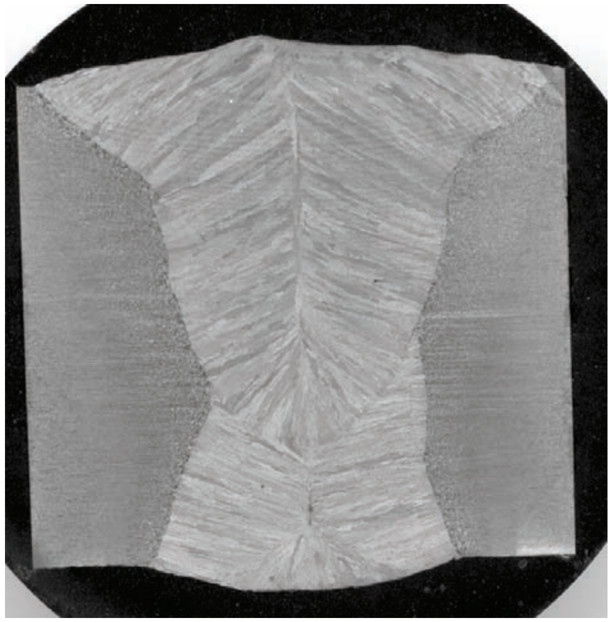


Figure 3.32: 1" HSLA-65 One-sided Weld, ESAB OK10.62 – Macro – 2.5X Mag

Figure 3.33: 1" HSLA-65 One-sided Weld, Lincoln MIL800-H – Macro – 2.5X Mag

It should be noted that arc flash through occurred frequently when welding with the ESAB OK10.62 flux and therefore required a greater flux depth compared to the Lincoln product. It was also found that all of the welds deposited with the Lincoln flux, at least under the conditions tested in this project, had demonstrated improved slag release characteristics as well as superior bead appearances in comparison to the ESAB product.

Sensitivity to electrode alignment was also investigated with these procedures. Using the DH36 steel, the trailing electrode alignment was increased from 0" offset to an offset of 1/8" using the identical welding parameters, and the resulting macro is shown in **Figure 3.34**. Each of the side bends in this procedure demonstrated acceptable results.

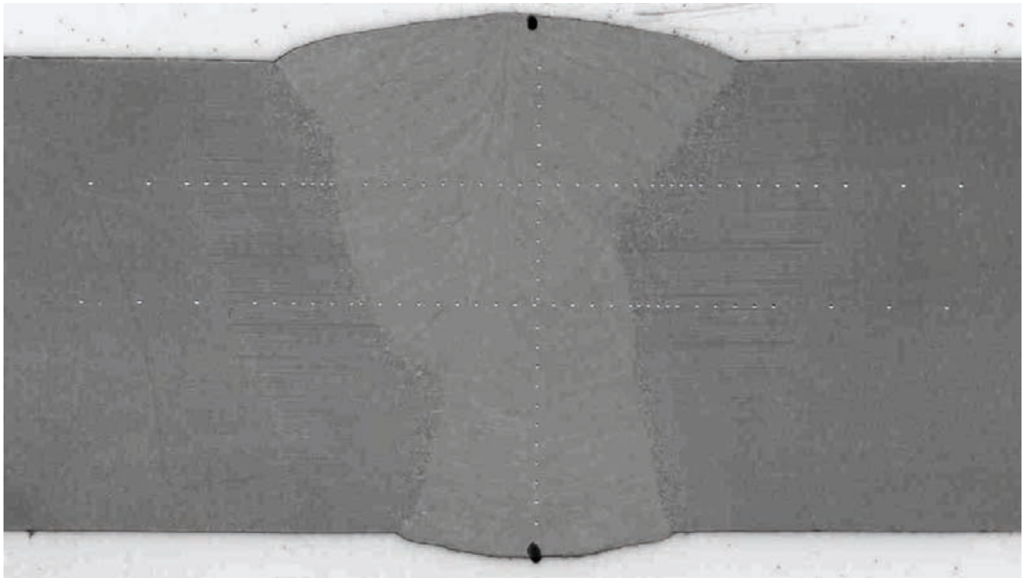


Figure 3.34: DH36 Procedure, 1/8" Electrode Misalignment (2.5X Mag.)

The tolerance of the single pass OSW procedure to fit-up was studied increasing the root gap from 3/32" to 5/32" using the same welding parameters. A macro of the weld produced in HSLA-65 with the 5/32" root gap is shown in **Figure 3.35**.

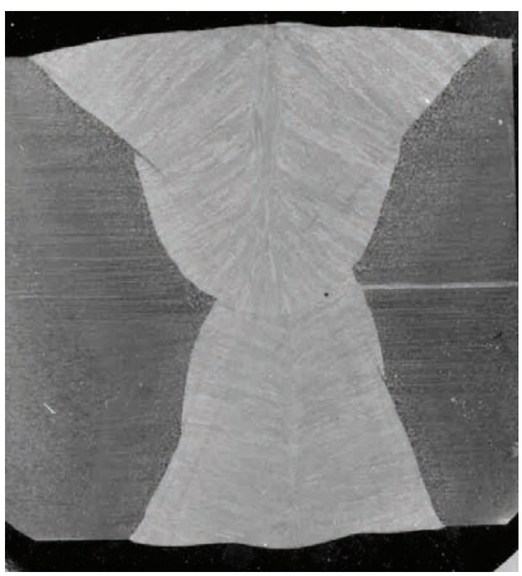


Figure 3.35: HSLA-65 OSW with 5/32" Root Gap (2.5X Mag)

3.3.3 High Heat Input Multi-Pass Welding Procedure Development for HSLA-100 Steel

The objective of this task was to increase joint completion rates for welding HSLA-100 steels using a tandem arc configuration, as well to determine if the VBAC technology could allow for the maximum 85kJ/in heat input restriction be extended for increased productivity rates while maintaining the minimum specified weld zone mechanical properties.

Two procedures were developed for 1-inch thick HSLA-100, a two-sided no back gouge welding technique where the plate is flipped to complete the weld on the second side, as well as the multiple pass OSW technique onto the optimized flux filled copper backing bar. For the ½" HSLA-100, the two sided no back gouge weld technique was the only procedure investigated. In each case the lead and trail electrodes were configured in a close tandem arrangement (electrode spacing of ¾") as shown in **Figure 3.36**.

Figure 3.36: Close Tandem Arrangement

In the 1-inch thick two-sided no back gouge welding technique, two sub-procedures were developed for one pass per side welding that investigated both 66/34 (EP/EN)-60 Hz and 34/66-60 Hz balance settings, in each case the first side was welded at a relatively high heat input (between 90kJ/in and 100kJ/in), and the second side at a lower heat input (between 75kJ/in and 84kJ/in). This approach allowed for the effect of balance setting to be studied as well as resulting weld zone mechanical properties in HSLA-100. Each no back gouge welding procedure provided a weld overlap between the first and second side of approximately 5/32". The welding procedure data sheets for each two sided weld are provided in **Appendix G**.

A procedure was developed that consisted of two passes on the first side, and a single pass on the second side, however the primary purpose of this weld was to evaluate the effect of multiple weld passes on microstructure evolution within the fist side of the joint. The results of the metallographic analysis for this weld, identified as 2P/1P (2 pass / 1 pass), are discussed later in the report in Section 4.

The welding parameters for the two-sided weld using 66/34 (EP/EN) balance are summarized in **Table 3.19**.

Table 3.19: 1" HSLA-100 Two-Sided Welding Parameters (66/34 Balance)

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	Θ1=70° Included Angle, Θ2=90° Included Angle, Rg = 0, Rf = 5/16, E1=7/16, E2=1/4	
Electrode Spacing	7/8"	
Travel Angle (°)	0 Lead	15 push Trail
CTWD (in)	1 1/4 Lead	1 1/2 Trail
Flux	Lincoln MIL800-H	
Welding Parameters		
	Lead Electrode	**Trailing Electrode**
Side 1		
Amperage (A)	1000	850
Voltage (V)	32.5	36
WFS (ipm)	175	195
Travel Speed (ipm)	**38 for 1st Pass**	
Side 2		
Amperage (A)	950	725
Voltage (V)	32.5	35
WFS (ipm)	160	160
Travel Speed (ipm)	**45 for 2nd Pass**	
Benchark Travel Speeds	**14 for 8 passes (4 per side)**	
Heat Input (kJ/in)	**99.6 (combined) for 1st Pass and 75 kJ/in for 2nd Pass**	
Benchmark Heat Input (kJ/in)	**83.5 each pass**	

The macro-section for the 66/34 weld is shown in **Figure 3.37**.

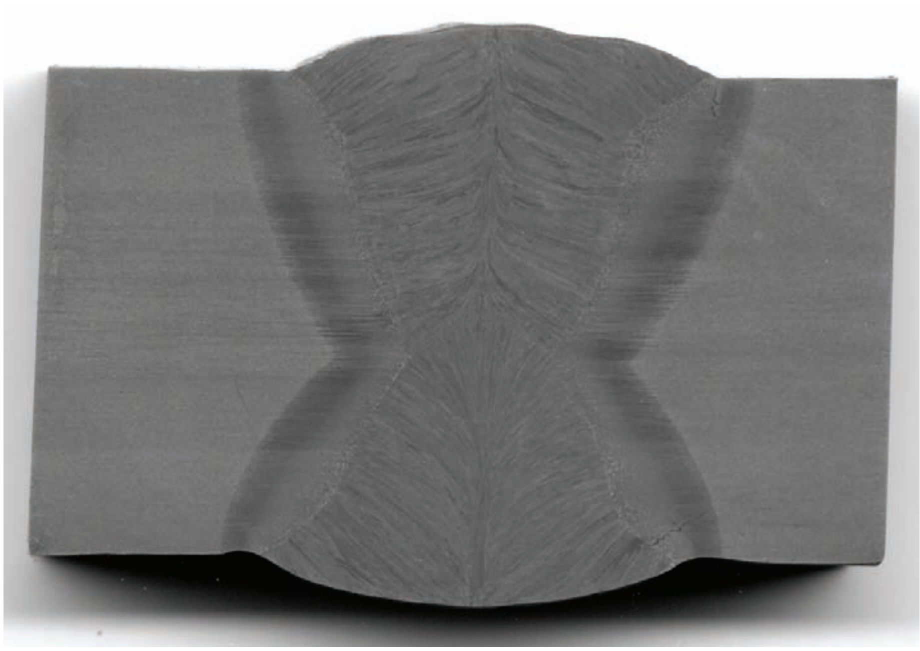


Figure 3.37: Two-sided No Back Gouge Weld, 66/34-60 Hz – One Pass per Side – Macro - 2.5X Mag

The welding parameters for the two-sided weld using 34/66 (EP/EN) balance are summarized in **Table 3.20**.

Table 3.20: 1" HSLA-100 Two-Sided Weld Parameters (34/66 Balance)

Mode	Constant Voltage	
Balance (EP/EN)	34/66	
Joint Preparation	Θ1=70° Included Angle, Θ2=90° Included Angle, Rg = 0, Rf = 5/16, E1=7/16, E2=1/4	
Electrode Spacing	7/8"	
Travel Angle (°)	0 Lead	15 push Trail
CTWD (in)	1 1/4 Lead	1 1/2 Trail
Flux	Lincoln MIL800-H	
Welding Parameters		
	Lead Electrode	Trailing Electrode
Side 1		
Amperage (A)	1000	680
Voltage (V)	32.5	36
WFS (ipm)	200	200
Travel Speed (ipm)	38 for 1st Pass	
Side 2		
Amperage (A)	1050	800
Voltage (V)	32.5	36
WFS (ipm)	200	200
Travel Speed (ipm)	45 for 2nd Pass	
Benchark Travel Speeds	14 for 8 passes (4 per side)	
Heat Input (kJ/in)	90 (combined) for 1st Pass and 83.9 kJ/in for 2nd Pass	
Benchmark Heat Input (kJ/in)	83.5 each pass	

The macro-section for the 34/66 weld is shown in **Figure 3.38**.

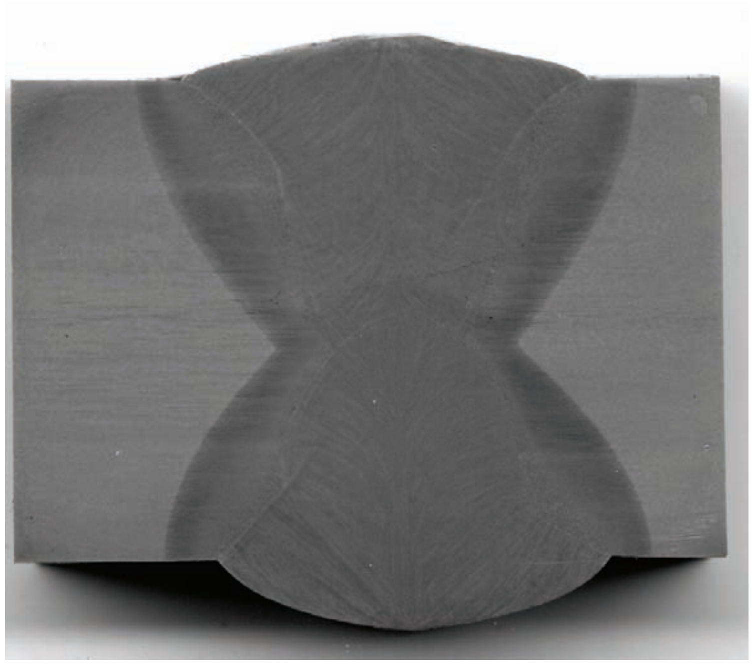


Figure 3.38: Two-sided No Back Gouge Weld, 34/66-60 Hz – One Pass per Side – Macro - 2.5X Mag

A high heat input multi-pass one-sided procedures was developed for 1-inch thick HSLA-100 using the modified flux filled grooved copper backing bar, where four passes were used to fill the joint at a heat input of each pass ranging from 71 kJ/in to 84 kJ/in. The welding procedure is summarized in **Table 3.21**.

Table 3.21: 1" HSLA-100 Multi-pass OSW – Four Pass Parameters

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	ϴ=45° Included Angle Rg = 1/8 Rf = 5/32	
Electrode Spacing	7/8"	
Travel Angle (°)	0 Lead	15 push Trail
CTWD (in)	1 1/4 Lead	1 1/4 Trail
Flux	Lincoln MIL800-H	
Tandem Welding Parameters		
	Lead Electrode	Trailing Electrode
Pass 1		
Amperage (A)	800	660
Voltage (V)	33	34
WFS (ipm)	145	145
Travel Speed (ipm)	35	
Pass 2		
Amperage (A)	860	680
Voltage (V)	33	34
WFS (ipm)	145	145
Travel Speed (ipm)	40	
Pass 3		
Amperage (A)	900	680
Voltage (V)	32.5	35
WFS (ipm)	145	145
Travel Speed (ipm)	45	
Pass 4		
Amperage (A)	920	700
Voltage (V)	32.5	35
WFS (ipm)	145	145
Travel Speed (ipm)	45	
Benchark Travel Speeds	Unknown for OSW'ing	
Heat Input (kJ/in)	83.8 1st Pass, 77.3 for 2nd, 70.7 for 3rd, and 72.6 for 4th	
Benchmark Heat Input (kJ/in)	Unknown for OSW'ing	

A macro of the root pass is shown in **Figure 3.29**, and the macro of the completed weld is shown in **Figure 3.30.** The welding procedure data sheet for this procedure is provided in **Appendix H**.

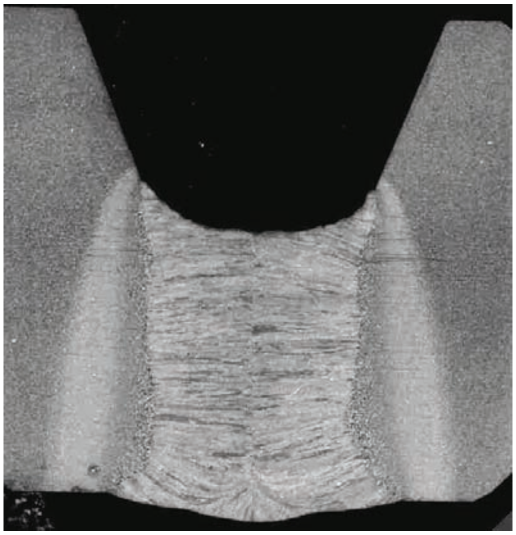


Figure 3.29: 1" HSLA-100 Tandem OSW Root Pass

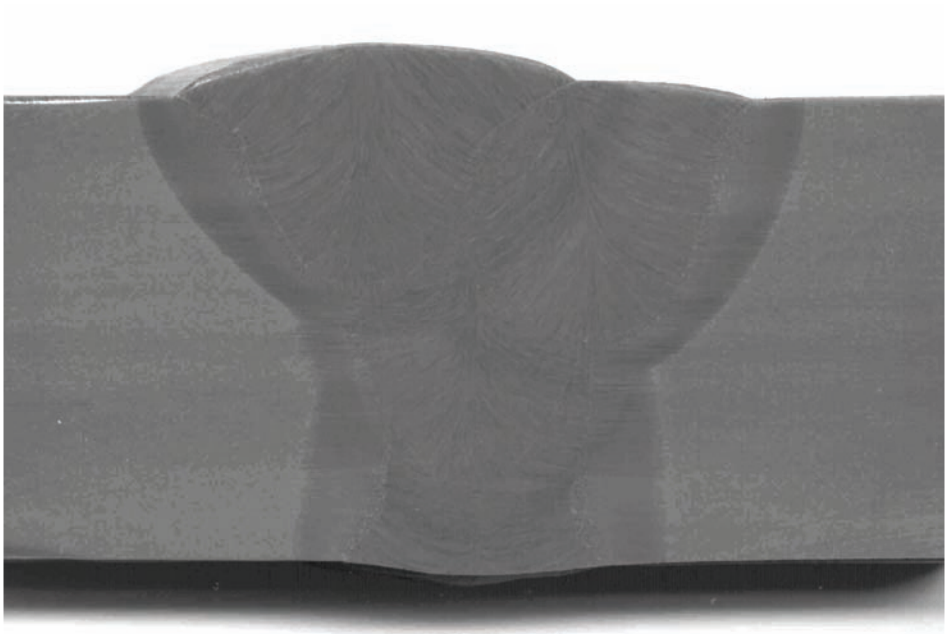


Figure 3.30: 1" HSLA-100 Tandem OSW – Four Passes

It should be noted that an additional procedure for multi-pass OSW was developed that completed the weld in only three passes, however the purpose of this weld was to evaluate the effect of multiple passes on microstructure evolution at a slightly higher heat input compared to the four pass procedure. The results of the metallographic analysis for this weld, identified as SS3, are discussed later in the report in Section 4.

A two-sided no back gouging welding procedure was also developed for the ½" HSLA-100 utilizing a square butt joint design with no root opening, and a 66/34 (EP/EN) – 60 Hz balance setting. This procedure does require the use of precision machined square butt joints to ensure a zero root opening is achieved, as any slight root opening would result in slag drop through which would require back gouging to sound weld metal before depositing the second pass on the second side. The welding procedure data sheet is provided in **Appendix I**, and the parameters are summarized in **Table 3.22**.

Table 3.22: ½" HSLA-100 Two-Sided Welding Parameters

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	Square Groove, Rg = 0	
Electrode Spacing	7/8"	
Travel Angle (°)	0 Lead	15 push Trail
CTWD (in)	3/4 Lead	1 3/4 Trail
Flux	Lincoln MIL800-H	
Welding Parameters		
	Lead Electrode	Trailing Electrode
Side 1		
Amperage (A)	950	600
Voltage (V)	30	35
WFS (ipm)	150	100
Travel Speed (ipm)	45 for 1st Pass	
Side 2		
Amperage (A)	950	600
Voltage (V)	30	35
WFS (ipm)	150	100
Travel Speed (ipm)	45 for 2nd Pass	
Benchark Travel Speeds	14 for 1st and 2nd Pass	
Heat Input (kJ/in)	66 (combined) for each pass	
Benchmark Heat Input (kJ/in)	83.5	

The macro section of the completed two sided weld is shown in **Figure 3.31**

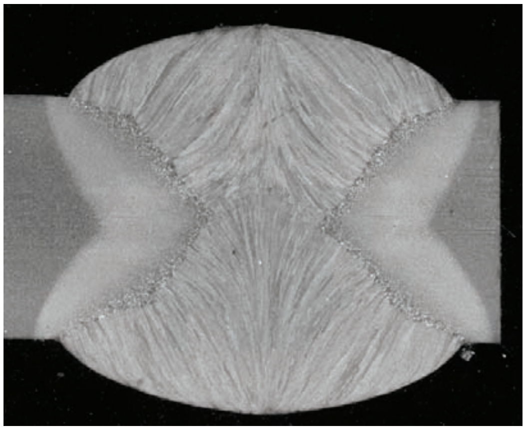


Figure 3.31: ½" Two-sided No Back Gouge Weld, 66/34–60 Hz – Macro – 2.5X Mag

3.3.4 Procedure Qualification Testing and Results

Each finalized welding procedure was used to weld the applicable final qualification test assemblies. The test assemblies for each ½" thick procedures measured 12" wide x 24" long and each of the 1" thick assemblies measured 12" wide x 30" long. The joint seams and angles were prepared by a milling machine with carbide cutters. Each welded assembly was radiographed at 90° and +/- 20° to the surface to examine for weld discontinuities at least 24 hrs after welding had been completed. From each of the procedure qualification test assemblies, the following test samples were extracted:

- **½" Plates**
  - Two (2) Cross Weld Tensile
  - One (1) Hardness
  - Four (4) Side Bends
  - Charpy V-notch Impact @ T/2
    - Five (5) Weld Centerline, Fusion Line, Fusion Line + 1mm, and Fusion Line + 3mm
- **1" Plates**
  - Two (2) Cross Weld Tensile
  - One (1) All Weld Metal Tensile (centered at ¼" below Side #1 surface)
  - One (1) Chemical Analysis from Reduced Area of Fractured All Weld Metal Tensile Specimen
  - One (1) Micro for Microstructure and Hardness Characterization
  - Four (4) Side Bends
  - Charpy V-notch Impact @ 1/16" from Side #1 surface
    - Five (5) Weld Centerline, Fusion Line, Fusion Line + 1mm, 5 Fusion Line + 3mm

The results for each of the radiography tests showed acceptable results in all completed weld joints with no cracks, slag inclusions or lack of fusion, and were considered acceptable under MIL-STD 2035.

Three (3) sets of five HAZ charpy V-notch impact specimens were extracted and tested in accordance with ASTM E23, with the notch sampling the fusion line (FL) as well at a distance of 1 mm and 3mm from the FL. For the ½" materials, the specimens were extracted from the T/2 location, however the samples were extracted 1/16" below the surface of side #1 of the 1" thick test plates. As required by NAVSEA Technical Specifications, the target minimum charpy V-notch impact energy requirements for the HAZ in HSLA-65 and DH36 steels is 30ft-lbs at -20°F and 17 ft-lbs at -4°F, respectively. The minimum charpy V-notch impact energy requirements for the HAZ in HSLA-100 steel are 35 ft-lb at -60°F and 60 ft-lbs at 0°F, for an under matching weld metal YS of between 88 < 102 ksi. Weld metal charpy V-notch impact specimens were extracted from each weld and tested in accordance with ASTM E23. For the ½-inch thick materials, the specimens were extracted from the T/2 location with the notch sampling the weld centerline. For the 1-inch thick materials, the specimens were extracted 1/16" below the surface of side #1. As required by NAVSEA Technical Specifications, the target minimum charpy V-notch impact energies for weld metals in HSLA-65 and DH36 steels are 30ft-lbs and 20ft-lbs at -20°F, respectively. The charpy V-notch impact energies required for HSLA-100 weld metals are 60 ft-lb at 0°F and 35ft-lbs at -60°F, for an under matching weld metal YS of between 88 < 102 ksi. The complete weld and HAZ impact test results are provided in **Appendix J**.

Cross-weld and all weld metal tension specimens were extracted from each of the weldments and then tested in accordance with ASTM E8. The UTS was reported from each cross-weld tensile tests, whereas UTS, YS, and percent elongation were reported from each of the all weld metal tensile tests. From each of the base metals, tensile specimens were extracted and tested to determine the strength of the unaffected base metal, and these values were reported in Table 3.12. Therefore, the joint efficiency (i.e., the demonstrated weld joint strength with respect to the original base metal strength) could be expressed. Note that 100% joint efficiency indicates that the weld joint at least meets the original strength of the unaffected base metal. The stress/strain curves for each all weld metal tensile test are provided in **Appendix K**.

Side bends were extracted from each of the welds and tested in a hydraulic bend testing apparatus. The mandrel diameter used was based on the lower minimum specified % elongation requirement between the weld and base metal. The mandrel diameters for the DH36 and HSLA-65 specimens were therefore each 1-½", and, 1-¾" for the HSLA-100. All bend specimens demonstrated good ductility with no visible discontinuities, and examples of each bend test are shown in **Figures 3.32** to **3.37**.

Figure 3.32: ½" Thick DH36 Side Bend

Figure 3.33: 1" Thick DH36 Side Bend

Figure 3.34: ½" Thick HSLA-65 Side Bend

Figure 3.35: 1” Thick HSLA-65 Side Bend

Figure 3.36: ½” Thick HSLA-100 Side Bend

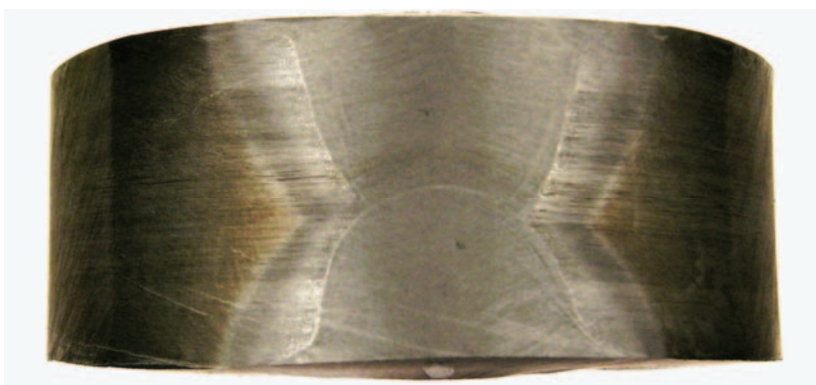


Figure 3.37: 1” Thick HSLA-100 Side Bend (66/34 EP/EN Balance)

The results of the tensile, charpy V-notch impact and side bend testing are summarized in **Tables 3.23** and **3.24**, for the ½” and 1” thick procedures, respectively. It should be noted that the cells highlighted in red are values that have marginally failed the acceptance criteria. In the case of the ½” thick HSLA-100 FL+1 and FL+3 impact values, it should be noted that this weld was completed at a heat input of 66 kJ/in, which is well below the maximum 85kJ/in heat input restriction. It is likely that the low values are a result of the HSLA-100 steel’s composition being in the lean range of the specified range, and therefore should not be a reflection on the actual welding procedure. For the four pass OSW onto a FCB, the YS was significantly lower than the other welds produced with the same electrode and flux, and is likely due to a small gas porosity located in the region of the final fracture. The gas porosity would have resulted in a reduction in cross sectional area and therefore produced the lower demonstrated YS. It should also be noted that all the weld metals produced with the developed electrode compositions comfortably met each of the minimum specified requirements.

Table 3.23: ½" Thick Procedure Qualification Test Results

Procedure	Cross Weld Tensile Test				Charpy V-notch Impacts			Side Bends
	Requirement (ksi)	Result (ksi)	Base Metal UTS (ksi)	Joint Efficiency	Requirement	Location	AVG Energy (ft-lbs)	
DH36 OSW	71	80.7	80.1	101%	20 ft-lbs @ -20F	CL	111	Acceptable
		80.5	80.1	100%	17 ft-lbs @ -4F	FL	62	
						FL+1	60	
						FL+3	106	
HSLA-65 OSW	NA	82.1	80	103%	30 ft-lbs @ -20F	CL	100	Acceptable
		81.5	80	102%		FL	59	
						FL+1	58	
						FL+3	227	
HSLA-100 1 Pass Per Side	NA	122.1	119.7	102%	60 ft-lbs @ 0F	CL	77	Acceptable
		119.9	119.7	100%		FL	78	
						FL+1	60	
						FL+3	118	
					35 ft-lbs @ -60F	CL	54	
						FL	47	
						FL+1	34	
						FL+3	32	

Table 3.24: 1" Thick Procedure Qualification Test Results

Procedure	Cross Weld Tensile Test Requirement (ksi)	Cross Weld Tensile Test Result (ksi)	Cross Weld Tensile Test Base Metal UTS (ksi)	Cross Weld Tensile Test Joint Efficiency	All Weld Metal Tensile Test Yield Strength (ksi)	All Weld Metal Tensile Test UTS (ksi)	All Weld Metal Tensile Test Elongation (%)	Charpy V-notch Impacts Requirement	Charpy V-notch Impacts Location	Charpy V-notch Impacts AVG Energy (ft-lbs)	Side Bends
DH36 OSW	71 to 95	87.4	77.8	112%	83.2	110.5	27.7	20 ft-lbs @ -20F	CL	75	Acceptable
		86.9	77.8	112%					FL	26	
					Requirement Yield Strength 58ksi, UTS 71 to 95ksi, and Elongation 20%			17 ft-lbs @ -4F	FL+1	21	
									FL+3	50	
HSLA-65 OSW	NA	81.2	78	104%	84.8	100.1	24.7	30 ft-lbs @ -20F	CL	91	Acceptable
		80.7	78	103%					FL	37	
					Requirement Yield Strength 65ksi and Elongation 20%				FL+1	44	
									FL+3	71	
HSLA-100 1 pass per side 66/34	NA	117.1	117.4	100%	94.8	116	21.8	60 ft-lbs @ 0F	CL	81	Acceptable
		118.5	117.4	101%					FL	59	
					Requirement Yield Strength 88 < 102ksi and Elongation 18%				FL+1	79	
									FL+3	173	
								35 ft-lbs @ -60F	CL	48	
									FL	37	
									FL+1	67	
									FL+3	118	
HSLA-100 1 pass per side 34/66	NA				98	119	21.3	60 ft-lbs @ 0F	CL	74	Acceptable
									FL	81	
					Requirement Yield Strength 88 < 102ksi and Elongation 18%				FL+1	Not Tested	
									FL+3		
								35 ft-lbs @ -60F	CL	42	
									FL	46	
									FL+1	64	
									FL+3	Not Tested	
HSLA-100 4 pass OSW	NA				89.8	123	20.4	60 ft-lbs @ 0F	CL	77	Acceptable
									FL	68	
					Requirement Yield Strength 88 < 102ksi and Elongation 18%				FL+1	Not Tested	
									FL+3		
								35 ft-lbs @ -60F	CL	43	
									FL	52	
									FL+1	73	
									FL+3	Not Tested	

99.6 kJ/in

90 kJ/in

Porosity Visible on Fracture Surface of Tensile Specimen

Weld metal and HAZ hardness characterizations were performed on each of the prepared microstructure specimens from each procedure. Vickers hardness measurements with a 5kg load were sampled along the weld centerline, and also at the T/2 locations for the ½" thickness, as well as the subsurface location for the 1" thickness. The intent of the hardness measurement locations was to sample the same regions that the impact and all weld metal tensile test specimens sampled. An example of the hardness locations are shown in **Figure 3.38**.

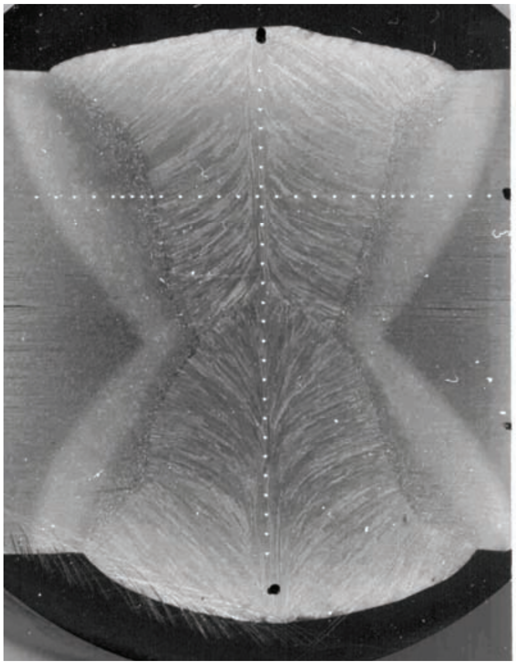


Figure 3.38: Sample Hardness Locations (1" HSLA-100 Two-sided Weld (66/34) Shown)

The complete detailed hardness results are provided in **Appendix L**, however the average values for each procedure are summarized in **Table 3.25**.

Table 3.25: Average Hardness Results

Procedure	Thickness	Average Hardness (HV5)			
		Location			
		CL	FL	HAZ	BM
DH36	1/2"	210	187	165	154
	1"	226	214	185	166
HSLA-65	1/2"	227	198	180	168
	1"	228	204	172	164
HSLA-100 (66/34)	1/2"	261	246	239	256
	1"	254	272	251	259
HSLA-100 (34/66)	1"	266	289	275	280
HSLA-100 OSW - 4 Pass	1"	286	280	252	284

3.3.5 Weld Metal Chemical Analysis

A sample was extracted from the reduced area from each fractured all weld metal tensile specimen for chemical analysis. Chemical analysis was performed on each sample in accordance with ASTM E1019, and the results are shown in **Table 3.26**. The results of the chemical analysis show an expected trend between weld metal Pcm and the weld metal UTS results in Table 3.22, in that weld UTS increases with increasing weld metal Pcm.

Table 3.26: Welding Procedure Weld Metal Chemical Analysis Results

	Composition (%)																	
	C	Mn	Si	S	P	Ni	Cr	Mo	Al	B	Cu	Zr	Nb	Ti	V	N	O	Pcm
Electrode Formulation																		
DH36	0.060	1.400	0.550	0.002	0.002	0.500	0.015	0.150	0.004	0.004	0.060	0.008	0.002	0.015	0.001			0.191
HSLA-65	0.035	1.600	0.450	0.002	0.002	1.800	0.100	0.350	0.004	0.004	0.030	0.008	0.010	0.030	0.004			0.210
HSLA-100	0.050	1.750	0.450	0.002	0.002	2.300	0.175	0.450	0.007	0.004	0.030	0.008	0.010	0.030	0.007			0.252
Weld Metal Analysis																		
DH36 / OK 10.62	0.110	1.620	0.360	0.010	0.018	0.950	0.140	0.200	0.028	0.001	0.057	0.005	0.025	0.008	0.040	0.010	0.024	0.252
HSLA-65 / MIL800-H	0.070	1.620	0.350	0.007	0.018	0.920	0.084	0.180	0.025	0.001	0.059	0.005	0.031	0.011	0.070	0.010	0.033	0.210
HSLA-100 / MIL800-H (66/34)	0.060	1.360	0.330	0.005	0.013	2.000	0.450	0.430	0.037	0.001	0.750	0.045	0.032	0.008	0.005	0.010	0.030	0.268
HSLA-100 / MIL800-H (34/66)	0.060	1.380	0.320	0.005	0.012	2.000	0.430	0.430	0.037	0.011	0.700	0.044	0.034	0.008	0.005	0.010	0.030	0.314

4 METALLOGRAPHIC ANALYSIS

Metallographic analysis of the weld metal and HAZ was focused in the area of the weld and HAZ from where the charpy V-notch specimens were extracted. In general, weld metal in this region contained "as-deposited" weld metal from the 1st side of the two sided HSLA-100 welds, except for the multi-pass OSW onto FCB configurations. Therefore for the two-sided welds, the microstructure evaluated would represent as-deposited weld metal with some changes due to thermal cycle of the weld deposited from the 2nd side. These changes are expected to be effects of aging. Typically these would be due to diffusion of interstitial elements (carbon and nitrogen) modifications to any "non-equilibrium" dislocation substructures. It is unlikely that nucleation of fine precipitates and coarsening of precipitates within the ferrite grains and at grain boundaries would occur. In the case of the multi-pass OSW's two contrasting regions, in terms of macrostructure, were analyzed; the as-deposited weld from a specimen identified as (SS3) and the re-heated region from the weld identified as SS4.

For the HAZ the coarse grain (CG) region adjacent to the fusion line (FL) was the focus.

The following weld samples were analyzed;

<u>HSLA 100 Welds</u>

- 66/34 is considered the baseline 1 pass per side welding procedure with 66% of the square wave duration being electrode positive and 34% duration electrode negative. The macro of the weld is presented in **Figure 4.1**.

- 34/66; the same as the baseline except a lower amount of heat is expected to be transferred to the plate due to the reverse balance setting at the same theoretical heat input.

- 2P/1P is a weld with two passes from the 1st side and third pass from the 2nd side.

- SS3 is a three pass OSW onto a FCB (see **Figure 4.2**).

- SS4 is a four pass OSW onto a FCB (see **Figure 4.3**).

<u>HSLA 65 Welds</u>

- 65L is a single pass OSW using Lincoln MIL800-H flux. The macro of the weld is presented in **Figure 4.4**.

- 65RG is the same as 65L with the root gap increased to 5/32 mm from the 3/32" baseline.

All the welds that were evaluated were deposited on 1-inch thick plate. The observations were made in regions marked for each of the different <u>weld geometries</u> in **Figures 4.1** through **4.4**.

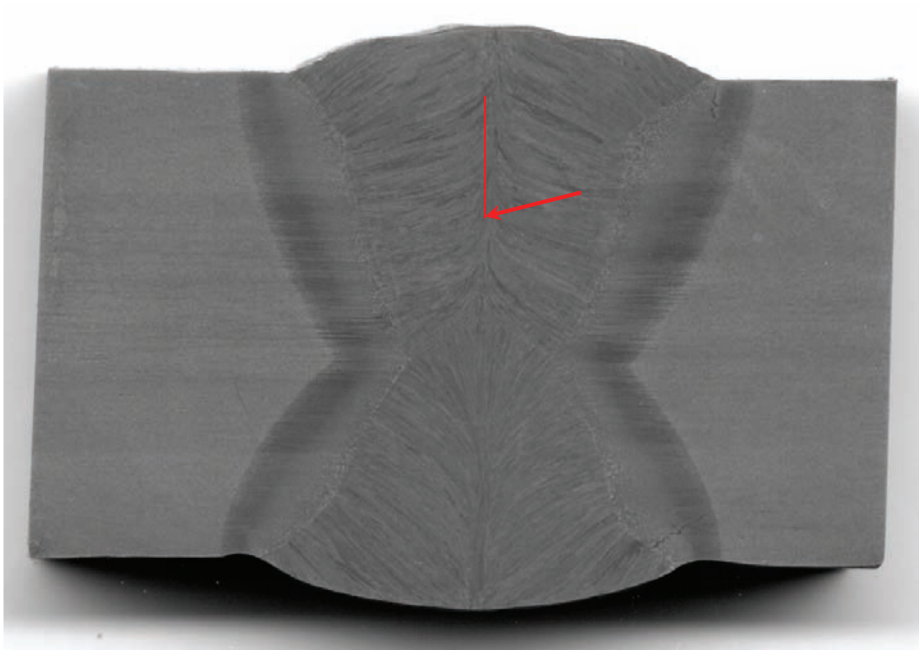


Figure 4.1: 66/34 at 2.2Xmag
(arrow marks the center on the all weld tension specimen location)

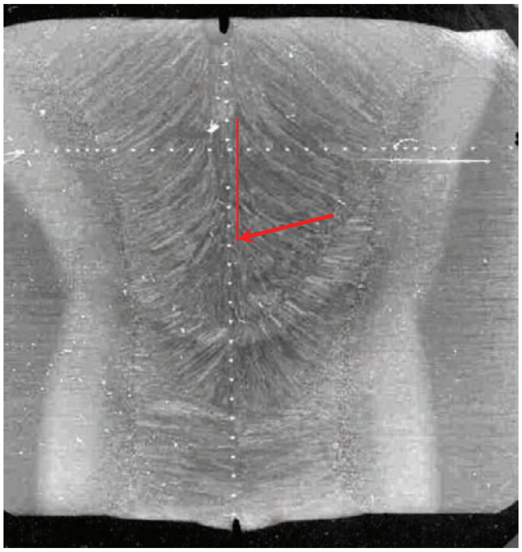


Figure 4.2: SS3 at 2.5Xmag

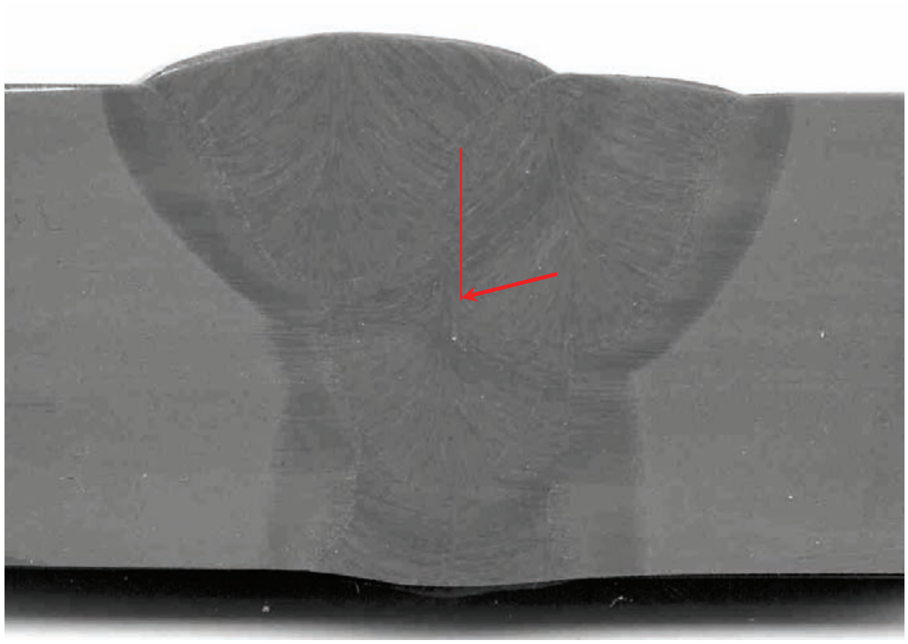


Figure 4.3: SS4 at 2.5Xmag

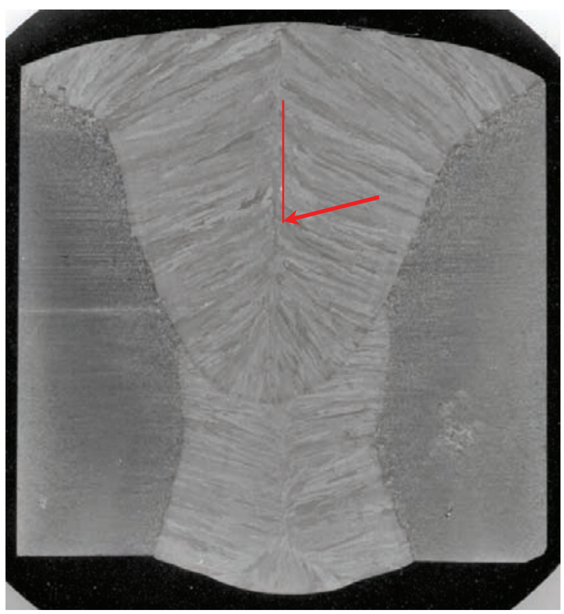


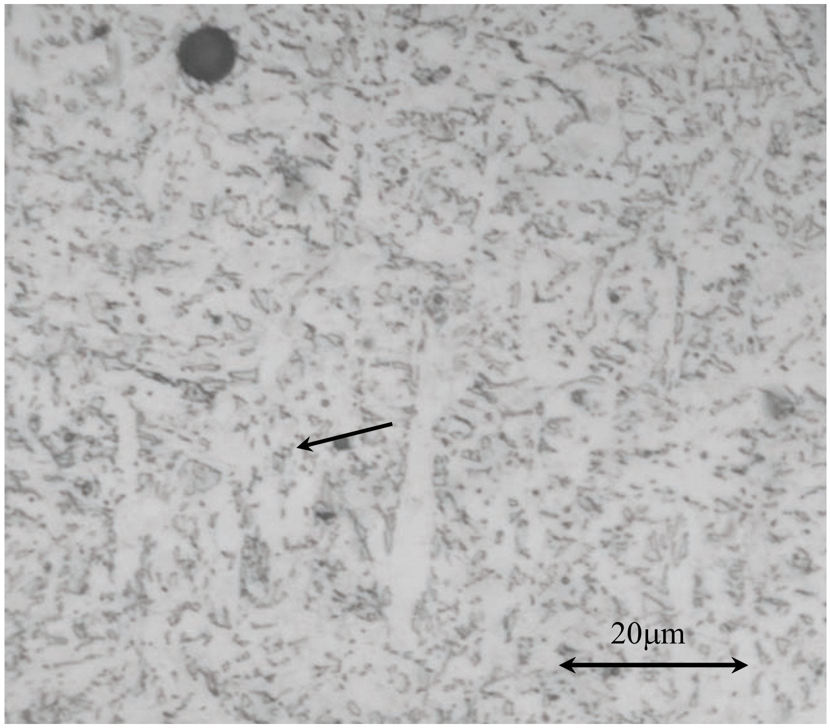
Figure 4.4: 65L at 2.5Xmag

4.1 66/34 Microstructures

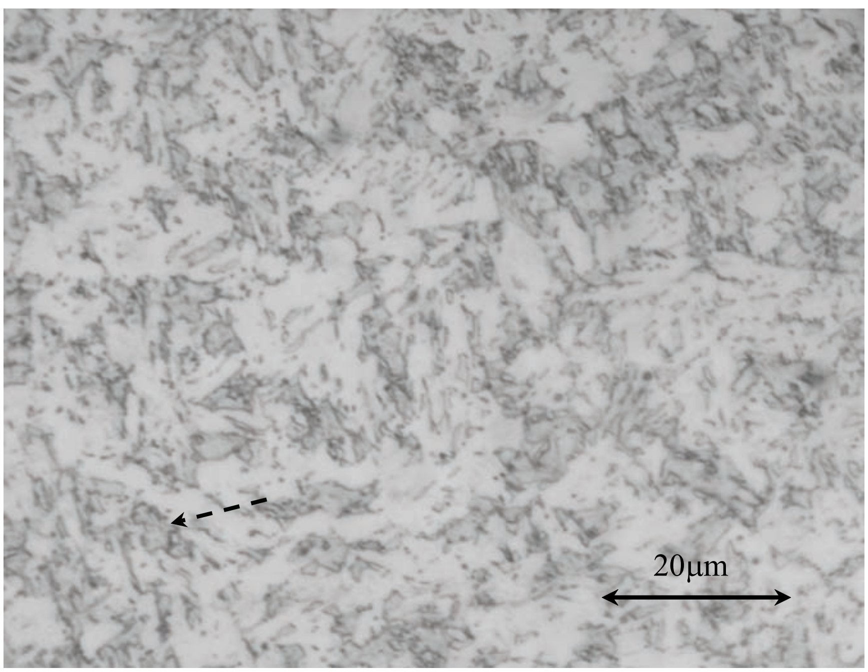
The weld metal microstructure displayed regions of dark and light etching regions on a relative basis at lower magnifications of 200X. This distinction remained up to magnifications of 1000X. **Figure 4.5** displays the microstructure of the two regions.

The most distinct difference in these two regions is the presence of a higher area fraction of the 2^{nd} phase that is displayed as the darker phase. The lighter color region is the ferrite (matrix). There are circular (spherical) inclusions of the size of 1μm distributed randomly in the ferrite matrix. An example is pointed by the arrow. On rare occasion large circular inclusions, typical of oxide inclusion are visible in the light etching region micrograph in Figure 4.5. There are many finer black “precipitates” in the ferrite matrix and these are in the order of a tenth of a micron. The latter precipitates are not clearly resolved in Figure 4.5. There are occasional regions that seem to contain what can be described as “aligned” 2^{nd} phase and a region is marked by the broken arrow.

The etching was performed using 4% picric (4g of picric acid in 100 ml methanol) having 1ml HCl. The ferrite grain boundaries (GB) were not clearly visible with this etch. However, at 400X magnification, the columnar GB’s can be visualized (see **Figure 4.6**).



weld metal (light etching region)



weld metal (darker etching region)

Figure 4.5: 66/34 at 1000X

The most distinct difference in these two regions is the presence of a higher area fraction of the 2nd phase that is displayed as the darker phase. The lighter color region is the ferrite (matrix).

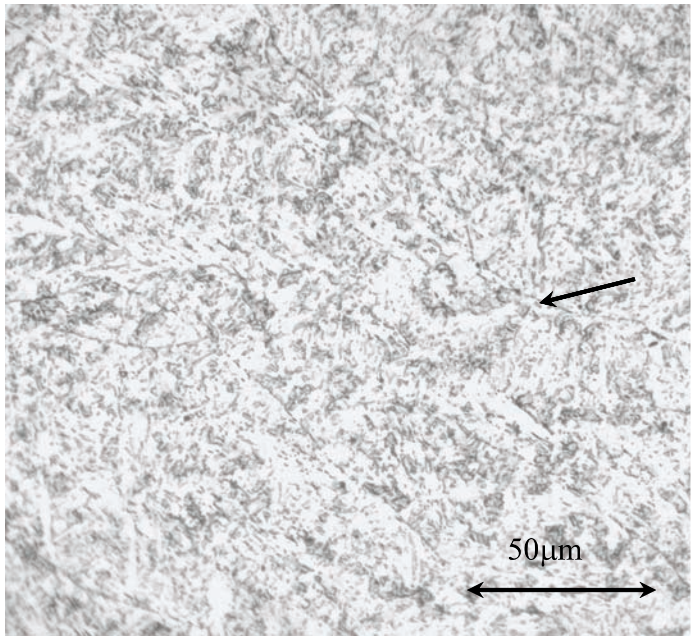
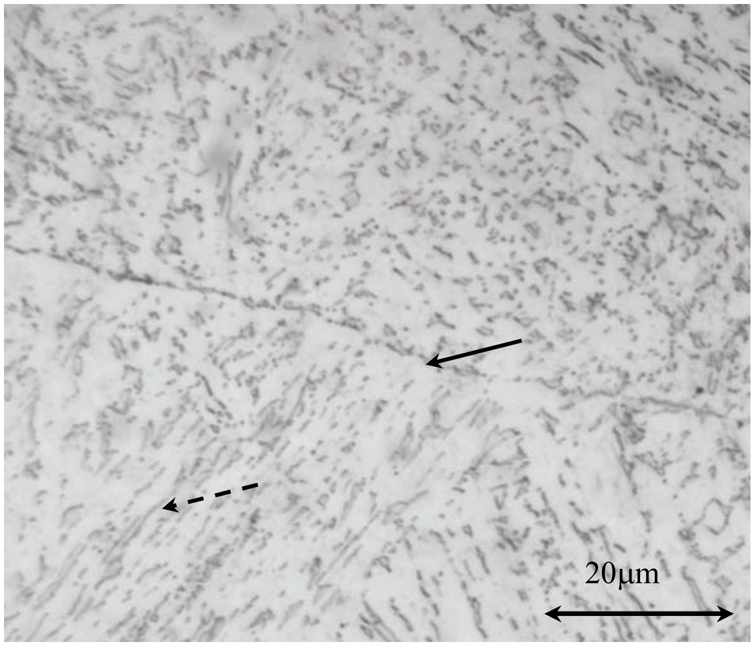
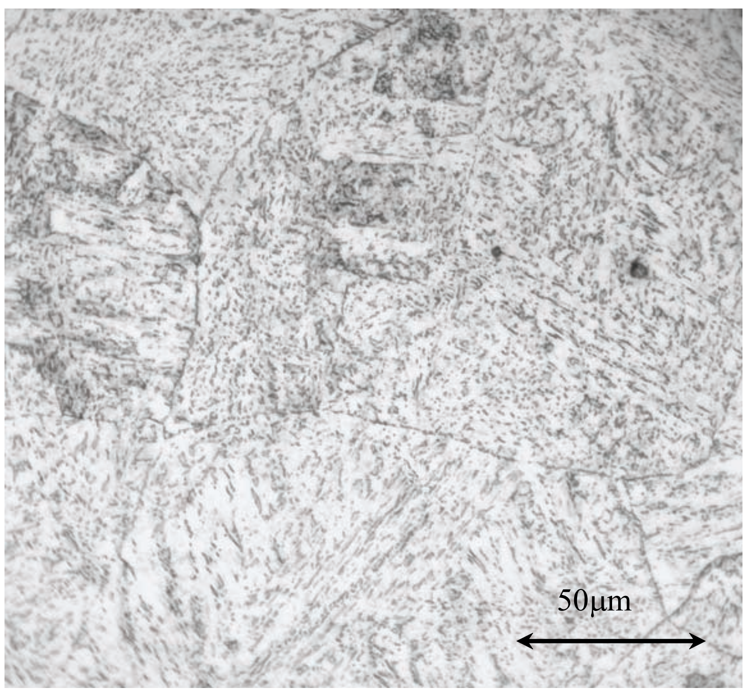


Figure 4.6: 66/34 at 400X (the GB is marked by the arrow)

The CGHAZ grain boundaries were visible and the grain size adjacent to the FL was about 100 μm. The microstructure contained aligned 2nd phase, marked by the broken arrow, fine precipitates in the grain interior (see **Figure 4.7**). This microstructure cab be categorized as ferrite with aligned 2nd phase [1,2]. This microstructure is commonly termed "bainite" [3]. The aligned 2nd phase can be carbide/martensite/retained austenite phases [1,2]. For proper identification of the aligned 2nd phase one would have to perform transmission electron microscopy (TEM)[2].



CGHAZ



CGHAZ

Figure 4.7: 66/34 HAZ close to the FL
(the arrow points to a prior austenite GB)

The sample was then carefully etched using a 2% nital solution to bring out ferrite GB's. **Figure 4.8** displays the weld metal microstructure at 1000X magnification and need to be compared with Figure 4.5. The distinction between dark etching and light etching regions were not as vivid as after the picric acid etch at high magnification, however the ferrite GB's were etched. This enabled a better characterization of the weld microstructure. For example, Figure 4.8 displays both ferrite with aligned 2nd phase and with non aligned 2nd phase [(2)]. Regions of non aligned 2nd phase are circled and regions of aligned 2nd phase are marked by arrows. An example of a region having clear distinction of aligned 2nd phase is presented in **Figure 4.9**.

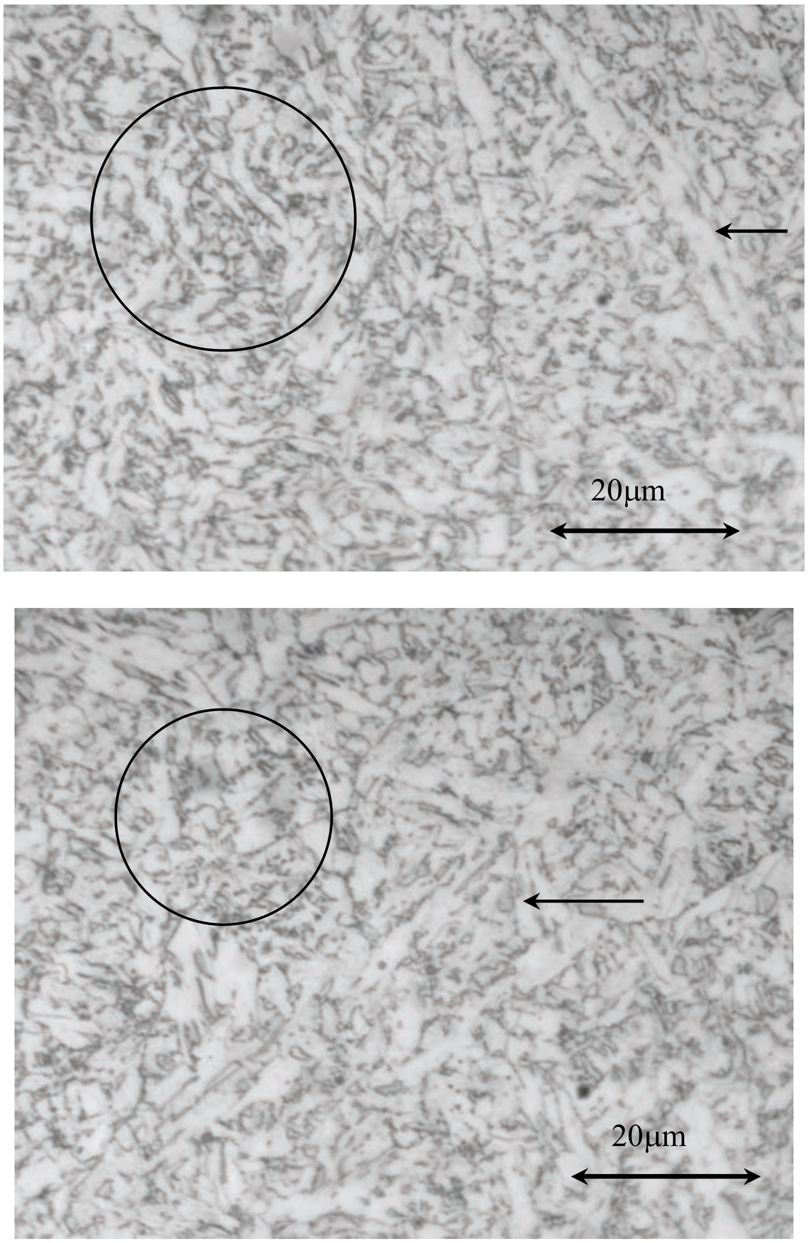


Figure 4.8: 66/34 at 1000X
(after picric acid-nital etch)

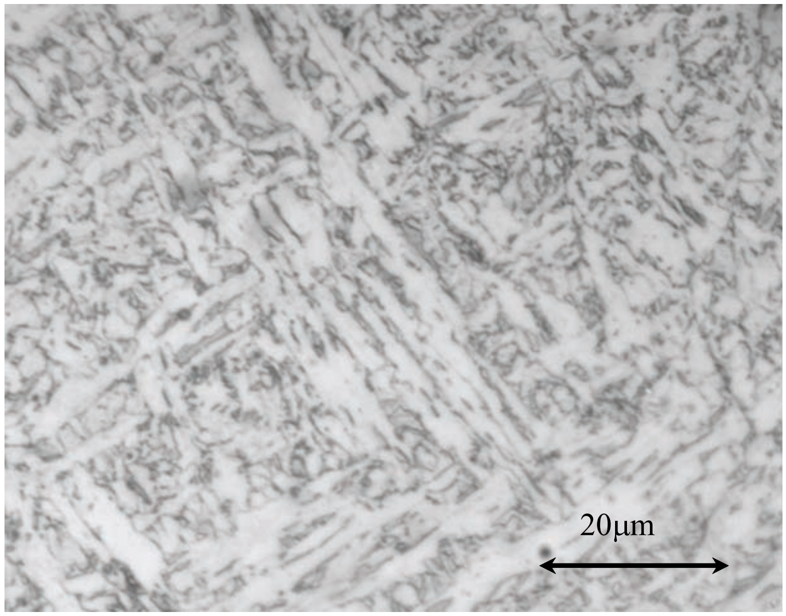
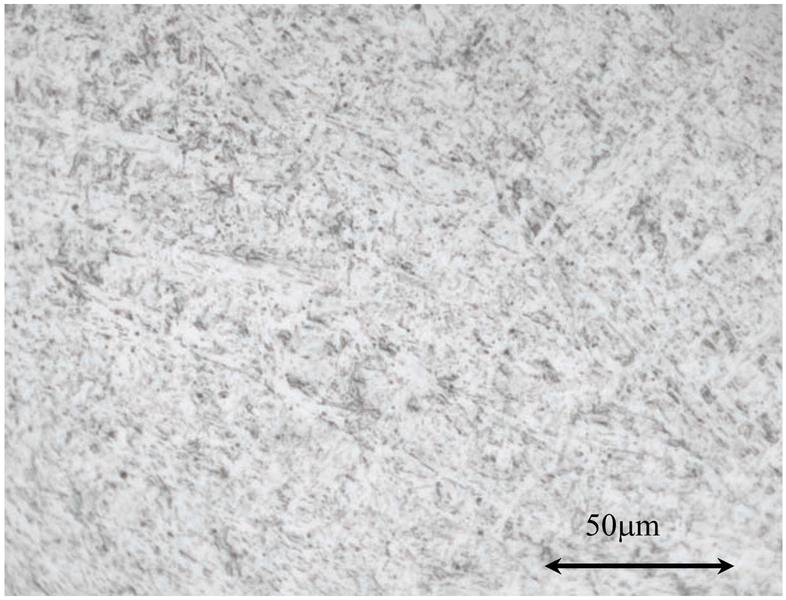


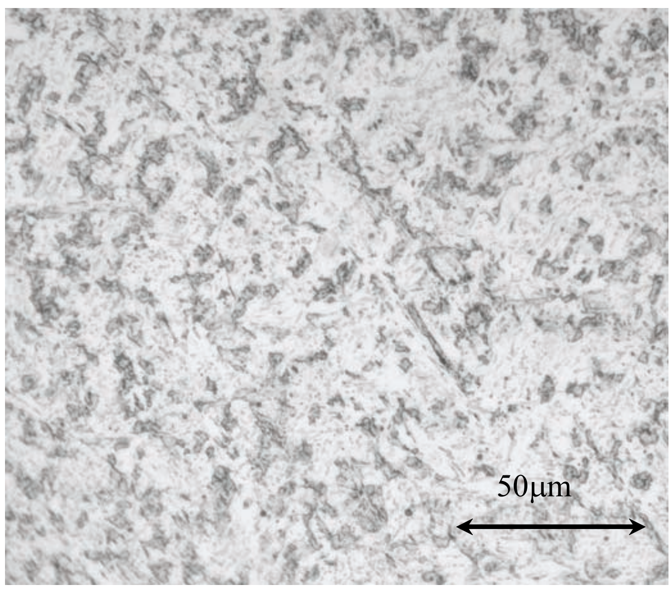
Figure 4.9: 66/34 at 1000X
(after picric acid-nital etch showing large region of aligned 2nd phase)

4.2 34/66 Microstructures

The weld metal microstructure displayed regions of dark and light etching areas on a relative basis at lower magnifications of 200X. This distinction remained up to magnifications of 1000X and in this way the observations are similar to 66/34. **Figure 4.10** displays the microstructure of the two regions at 400X. The characteristics of the weld microstructure described for weld 66/34 applies to this weld as well. In other words, circular inclusions of the size of 1μm, the non-aligned 2nd phase, some regions of aligned 2nd phase, fine black "precipitates" in the ferrite matrix and these are in the order of a tenth of a micron can be identified. The CGHAZ was also similar to that in weld 66/34 (see **Figure 4.11**). The grain size adjacent to the FL was about 100 μm.

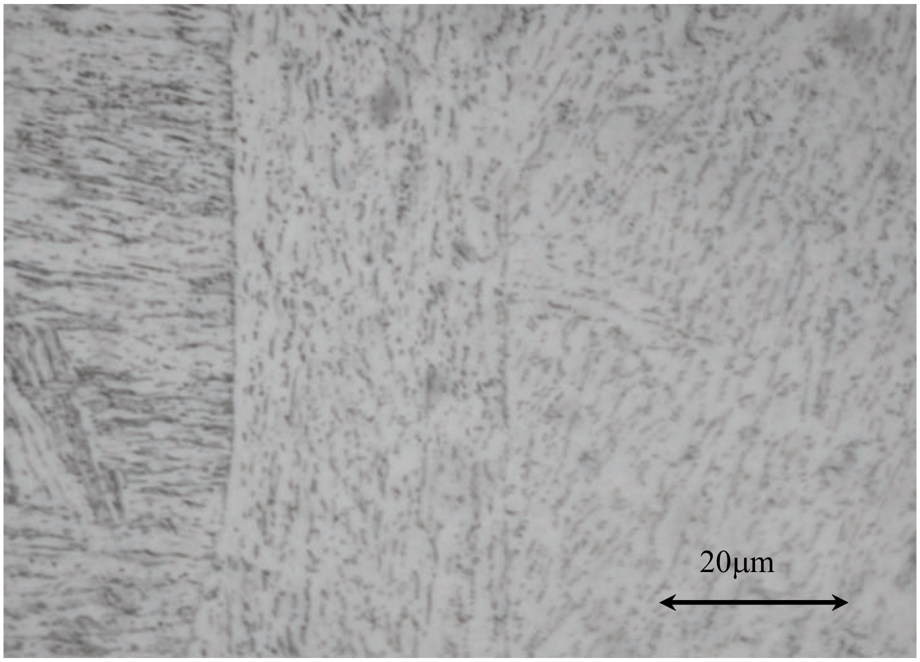


(a) Light etching

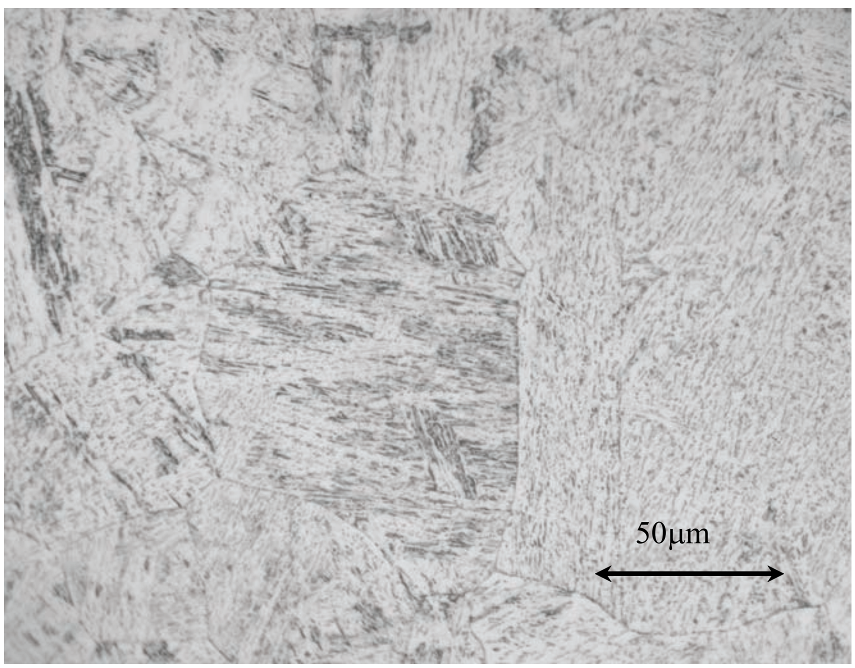


(b) Dark etching

Figure 4.10: 34/66 weld metal (picric etching)



CGHAZ



CGHAZ

Figure 4.11: CGHAZ

4.3 2P/1P Microstructures

The microstructure was first observed after the picric acid etch. The weld metal microstructure displayed regions of dark and light etching areas on a relative basis at lower magnifications of 200X. This distinction remained up to magnifications of 1000X and in this way the observations are similar to the 66/34 weld. As described above, in order to bring out the ferrite grain boundaries a light 2% nital etch was performed subsequently. At a magnification of 400X, the **Figure 4.12** displays a slight difference sufficient to contrast, the darker etching region to the right. The observation at higher magnification displays ferrite with non-aligned (circled in the micrograph) and aligned 2nd phase, marked by an arrow (see **Figure 4.13**) and in this way the similar to the baseline 66/34 weld. Circular (spherical) inclusions of the size of 1μm distributed randomly in the ferrite matrix are observed and one is marked by the broken arrow in Figure 4.13. There are many finer black "precipitates" in the ferrite matrix and these are in the order of a tenth of a micron. The latter precipitates are not clearly resolved in Figure 4.13.

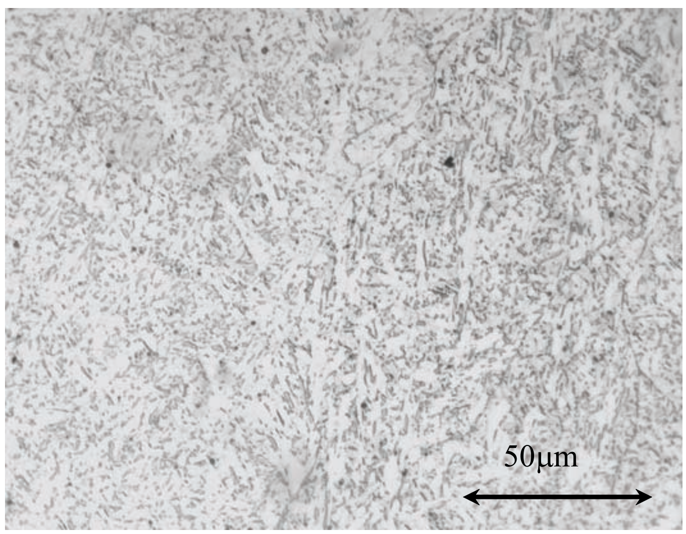
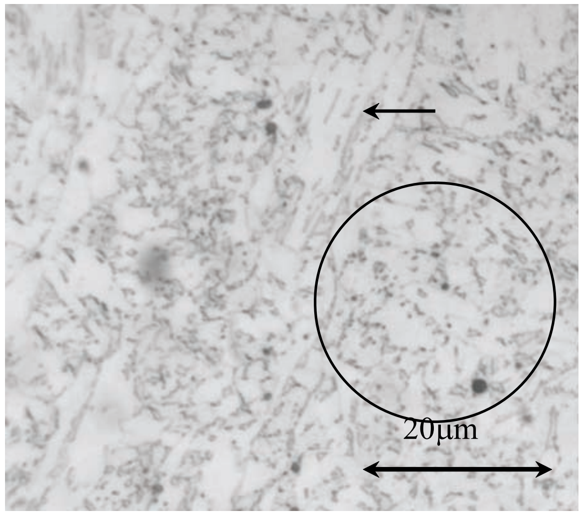


Figure 4.12: 2P/1P weld at 400X (after picric acid-nital etch)



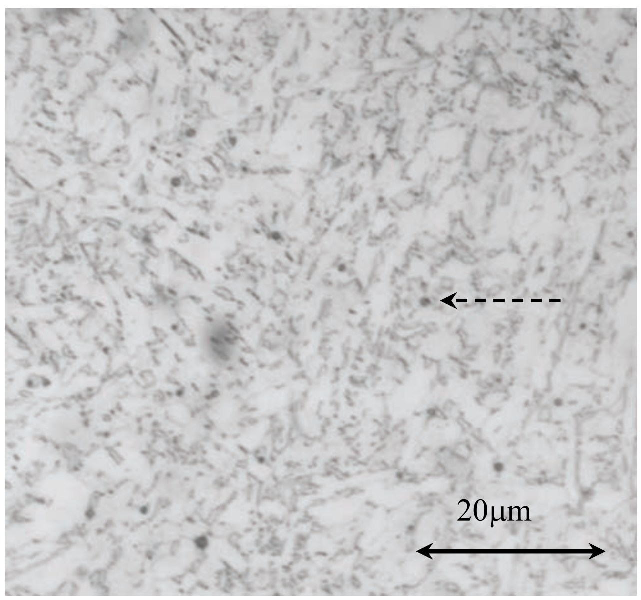


Figure 4.13: 2P/1P weld at 1000X (after picric acid-nital etch)

The CGHAZ grain boundaries were visible and the grain size adjacent to the FL was about 100 μm. The microstructure contained aligned 2^{nd} phase, fine precipitates in the grain interior (see **Figure 4.14**). The microstructure is commonly termed "bainite" and similar to the GCHAZ of other HSLA 100 welds.

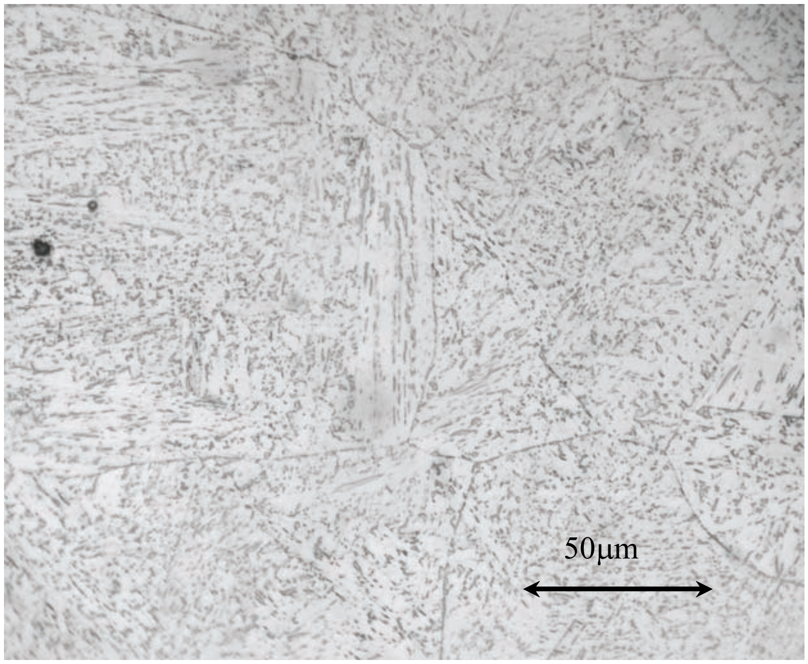


Figure 4.14: 2P/1P HAZ

4.4 SS3 Microstructures

The microstructure was first observed after the picric acid etch. Examination of the microstructure revealed similar micro-constituents as for the previous HSLA 100 welds both in terms of weld and CGHAZ adjacent to the FL. Again in order to bring out the ferrite grain boundaries a light 2% nital etch was performed subsequently. The observation at higher magnification displays ferrite with non-aligned (circled in the micrograph) and aligned 2nd phase, marked by an arrow (see **Figure 4.15**) and in this way the similar to the baseline 66/34 weld. Circular (spherical) inclusions of the size of 1μm distributed randomly in the ferrite matrix are observed and one is marked by the broken arrow in Figure 4.15. There are many finer black "precipitates" in the ferrite matrix and these are in the order of a tenth of a micron. The latter precipitates are not clearly resolved in Figure 4.15.

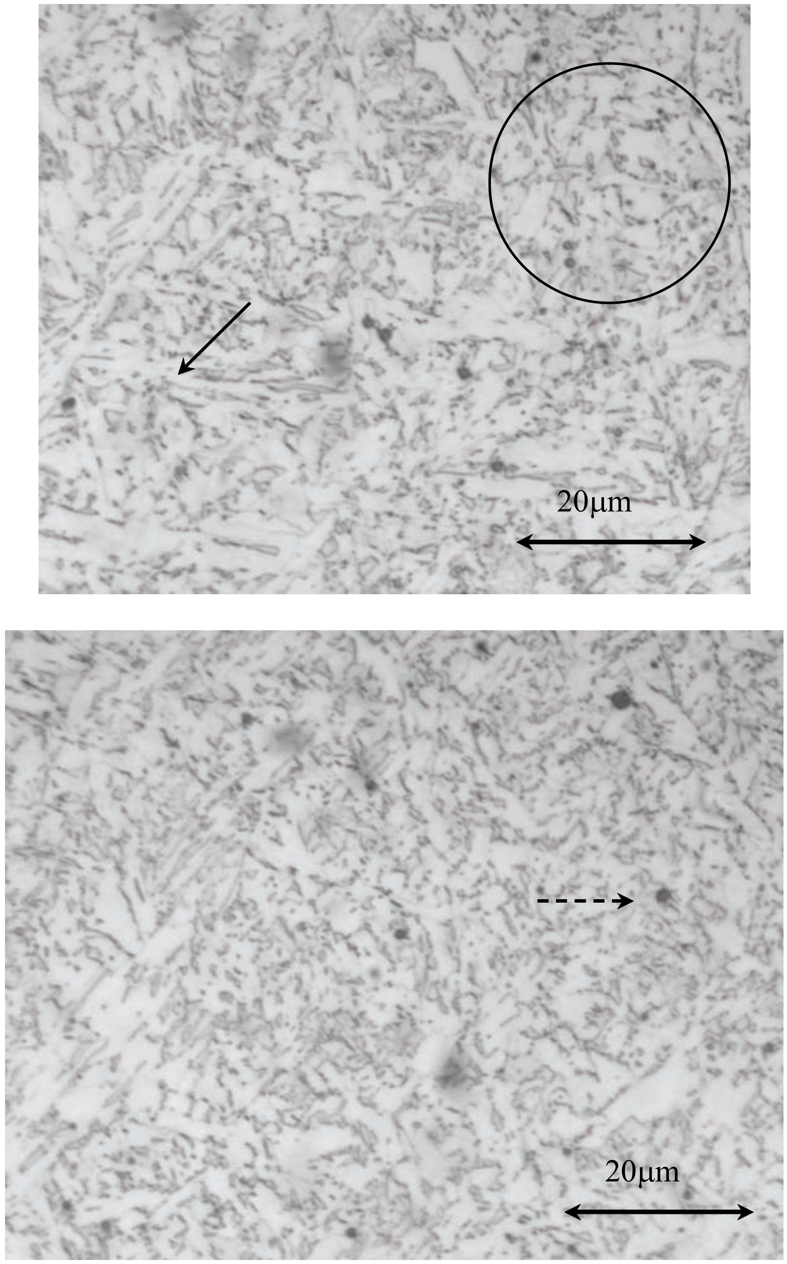


Figure 4.15: SS3 weld at 1000X (after picric acid-nital etch)

The CGHAZ grain boundaries were visible and the grain size adjacent to the FL was about 100 µm. The microstructure contained aligned 2nd phase, fine precipitates in the grain interior (see **Figure 4.16**). The microstructure is commonly termed "bainite" and similar to the GCHAZ of other HSLA 100 welds.

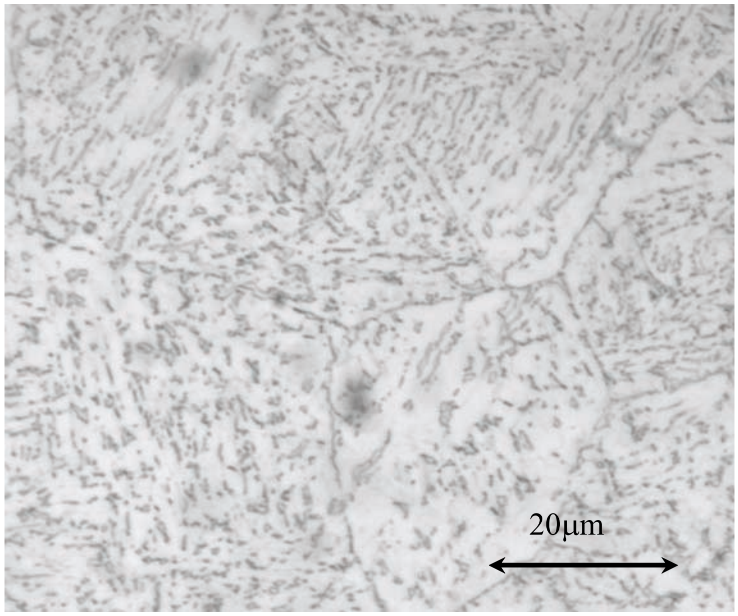
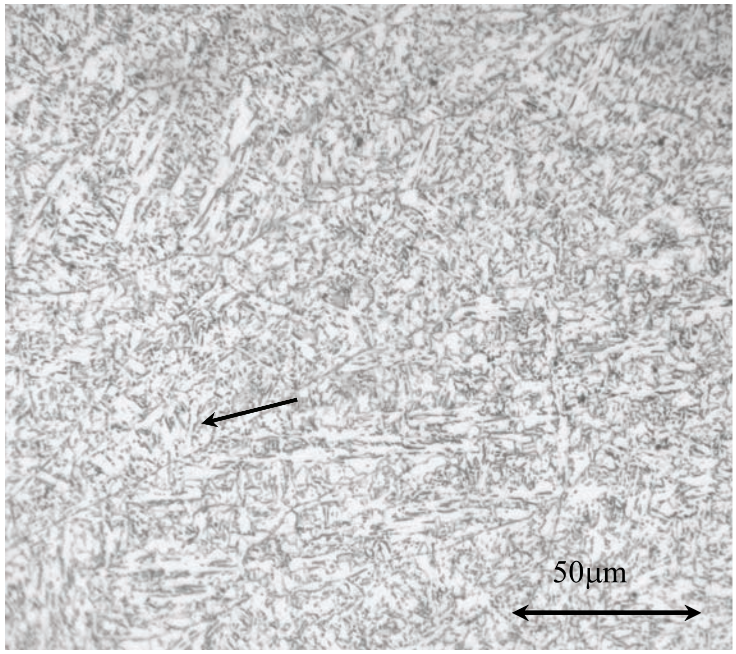


Figure 4.16: SS3 HAZ

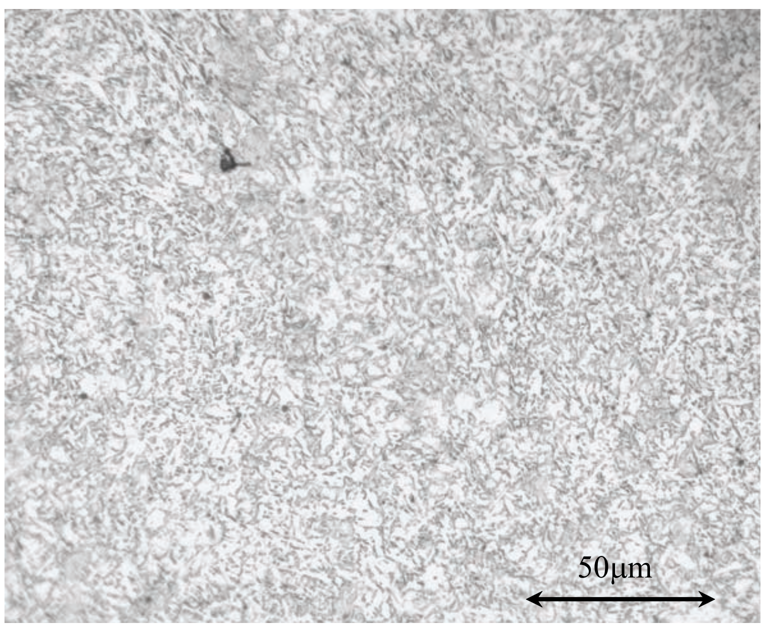
4.5 SS4 Microstructures

The weld metal microstructure displays regions in the vicinity of the location of the tension test specimen (see Figure 4.3). These include both re-heated weld metal and as-deposited weld metal. At a magnifications of 400X the microstructures in these region display features that are not similar (see **Figure 4.17**). In the as deposited region GB's can be visualized and in Figure 4.17 a GB is marked by an arrow. The metallographic specimen was etched with 2% nital. The non-aligned 2^{nd} phase does not show up as distinctly as in the metallographic specimens etched with picric acid. It was also noted that the contrast between the darker etching regions with the lighter etching regions was not retained at higher magnifications, i.e., 400X and upwards.

Examples of the as deposited microstructure at magnifications of 1000X are presented in **Figure 4.18**. Similarly the microstructures in the re-heated region are presented in **Figure 4.19**. The characteristics of the weld microstructure described for weld 66/34 applies to this weld as well. In other words, circular inclusions of the size of 1μm, the ferrite with non-aligned 2^{nd} phase and regions of ferrite with aligned 2^{nd} phase, fine black "precipitates" in the ferrite matrix and these are in the order of a tenth of a micron can be identified. The CGHAZ was also similar to that in weld 66/34. The grain size adjacent to the FL was about 100 μm.

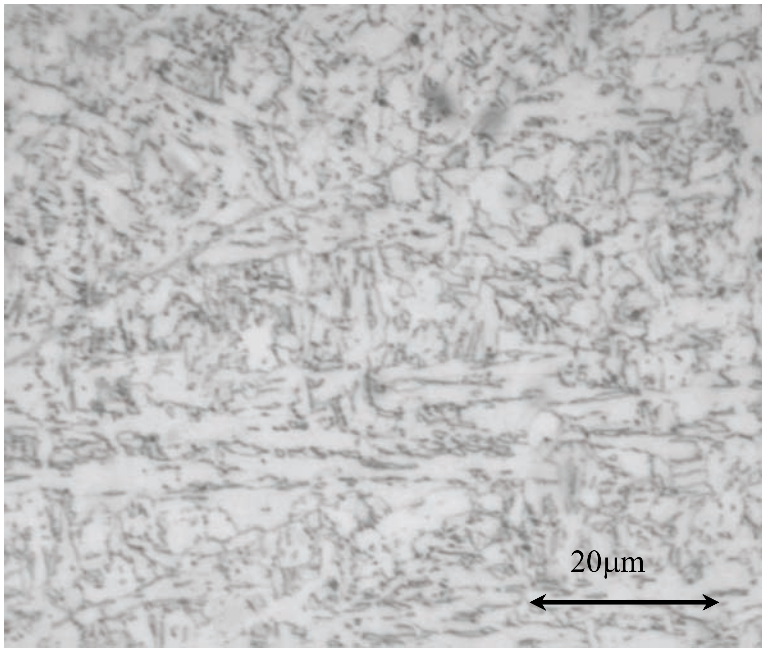


as deposited weld

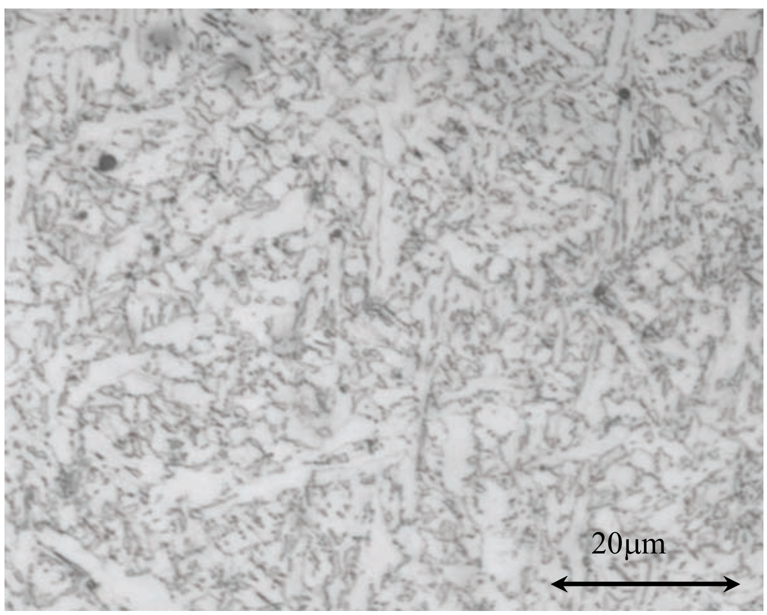


re-heated weld

Figure 4.17: SS4 Weld
(microstructures representing the location of the tension test specimen)

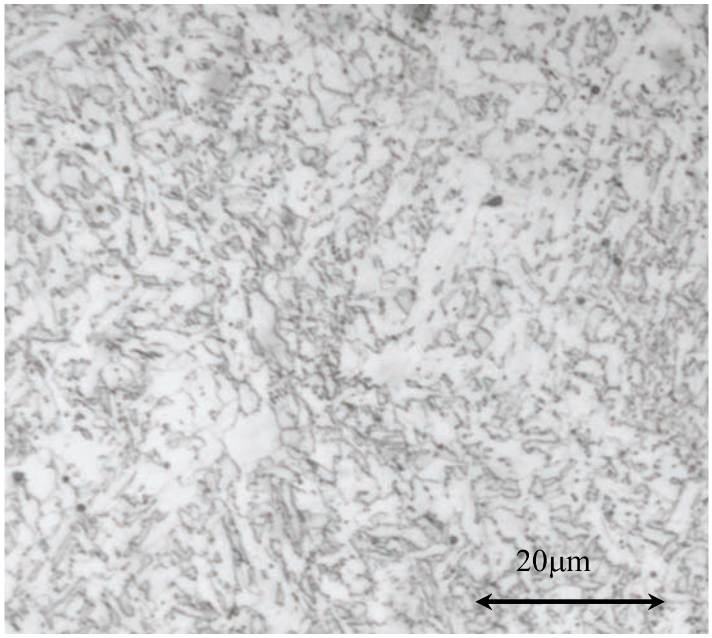


as deposited weld

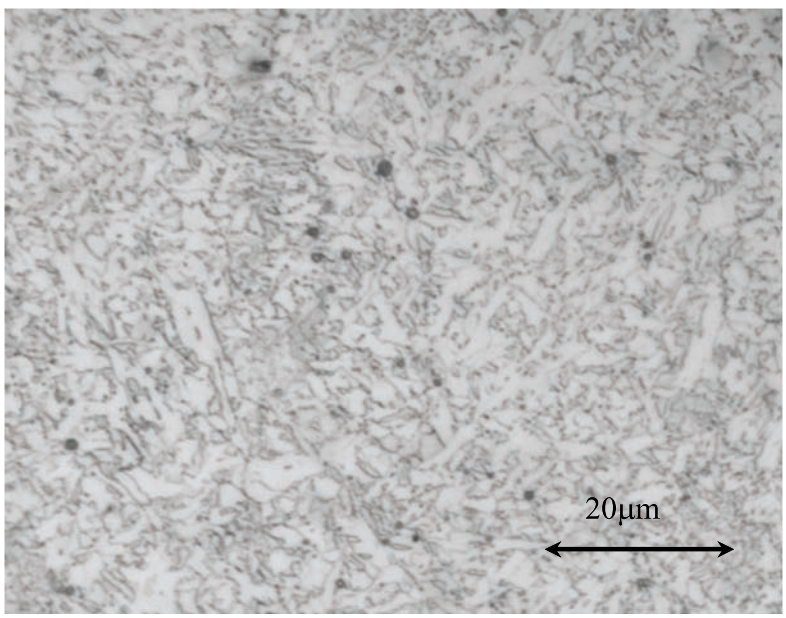


as deposited weld

Figure 4.18: SS4 Weld
(microstructures in as deposited regions)



reheated weld

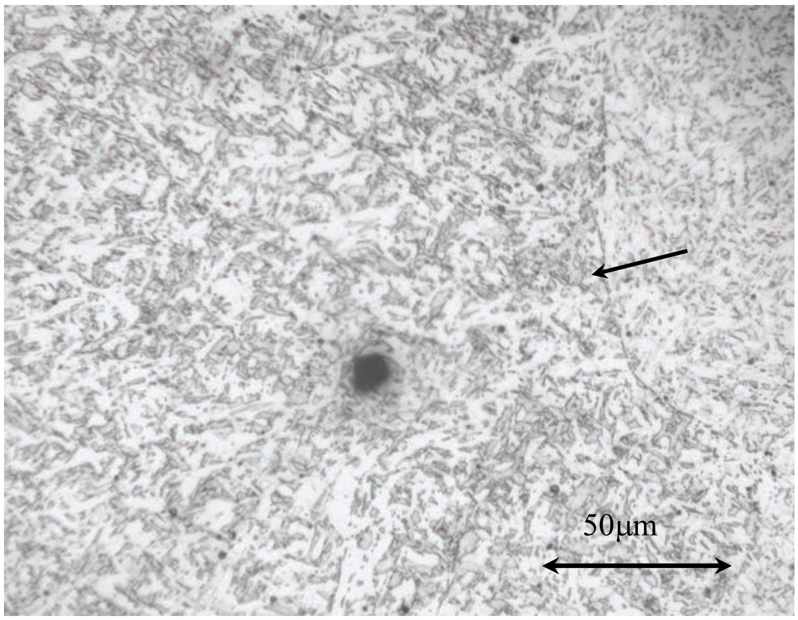


reheated weld

Figure 4.19: SS4 Weld
(microstructures in re-heated regions)

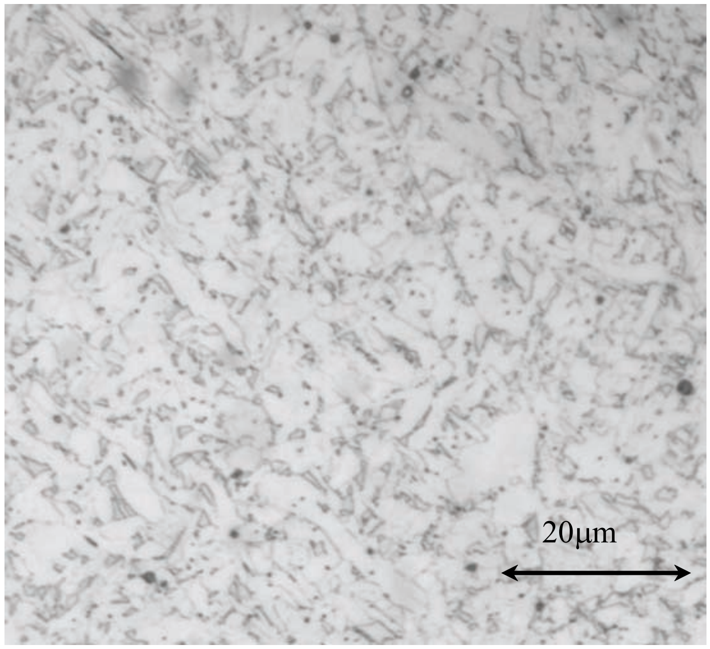
4.6 65L Microstructures

Noting that the picric acid etch was used for this metallographic specimen, the weld metal microstructure displays light and dark etching regions and in this way the appearance of two regions was similar to the HSLA 100 weld metal microstructure (see **Figure 4.20**). The higher magnification (1000X) micrographs are presented in **Figure 4.21**. The constituents present in the HSLA 100 weld were apparent in this microstructure as well. The ferrite with aligned 2nd phase was sparse.

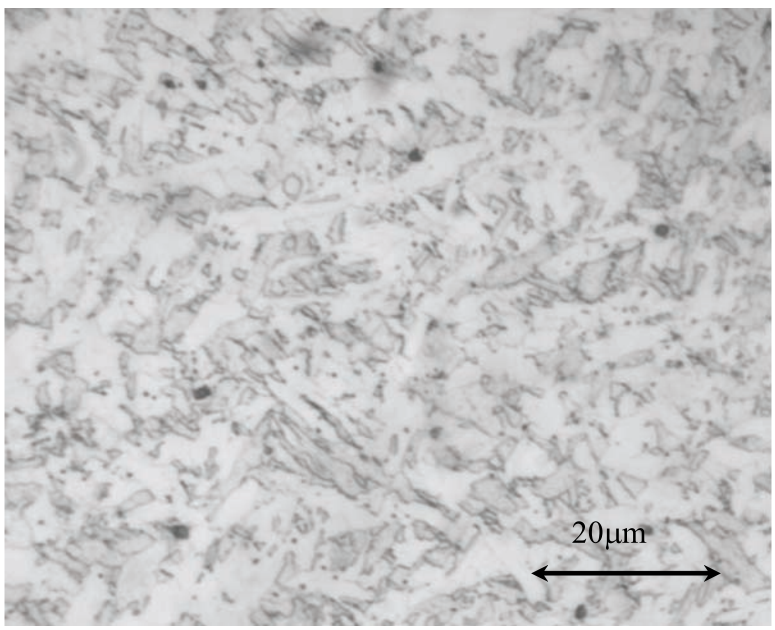


as deposited weld

Figure 4.20: Weld 65L at 400X
(GB is marked by the arrow)



as deposited weld – lighter etching



as deposited weld – darker etching

Figure 4.21: Weld 65L at 1000X.

The 2% nital etching was used to outline the ferrite GB's. **Figure 4.22** shows the weld metal after this etching and **Figure 4.23** displayed the micro constituents and the ferrite grain morphology (at 1000X). Although the micro constituents observed in HSLA 100 welds are apparent in micrographs presented in Figure 4.23, the ferrite grain morphology is different. Region displaying indications of what can be described as acicular ferrite can be observed.[1,2] Examples of these regions are circled in Figure 4.23.

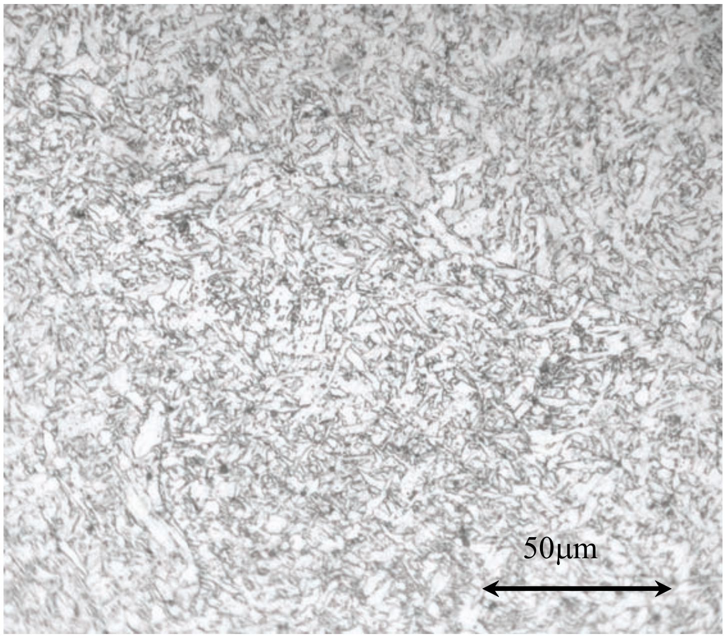
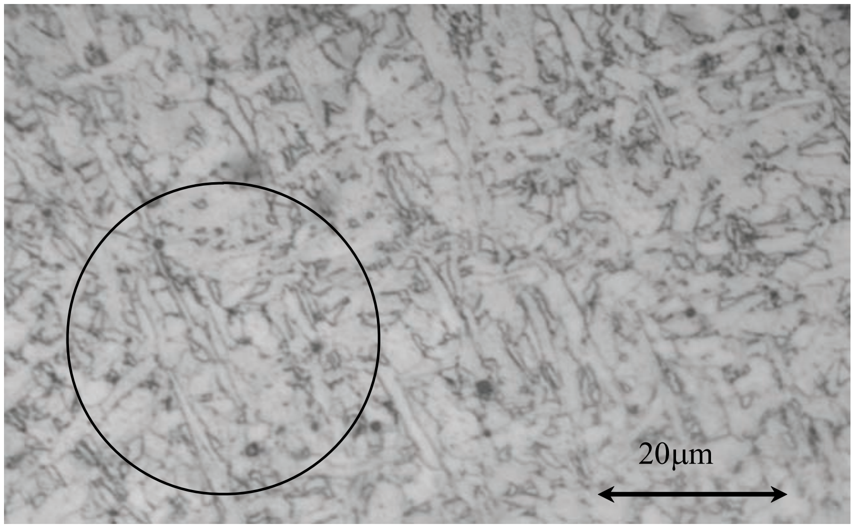


Figure 4.22: Weld 65L at 400X
(after etching in picric acid followed by 2% nital)



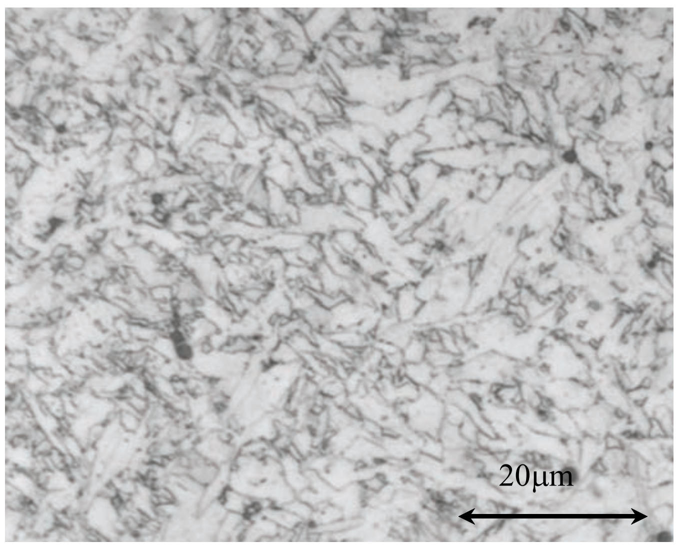
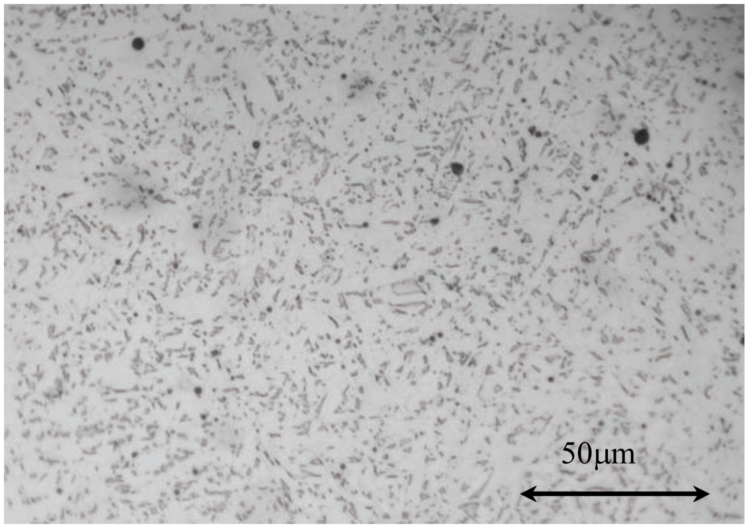


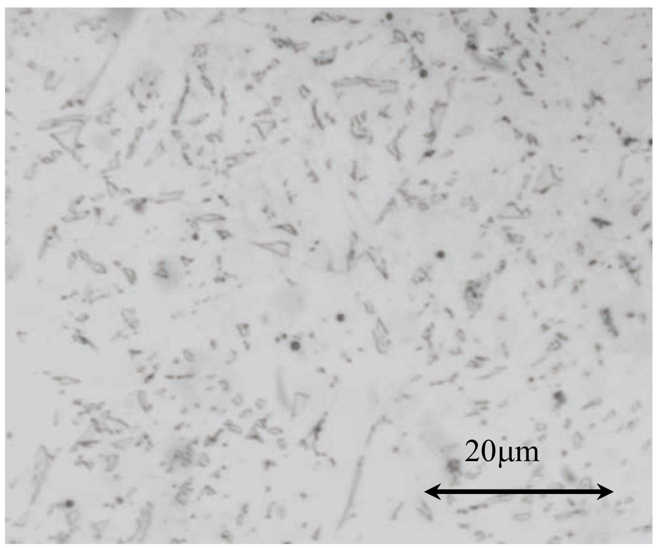
Figure 4.23: Weld 65L at 1000X
(after etching in picric acid followed by 2% nital)

4.7 65RG 3.5 Microstructures

This specimen was first etched with picric and followed with 2% nital. After the picric acid etching the 2nd phase and precipitates were delineated (see **Figure 4.24**). After nital etching the ferrite GB's were delineated (see **Figure 4.25**). Acicular ferrite (marked by the circle) is evident in this microstructure as well.

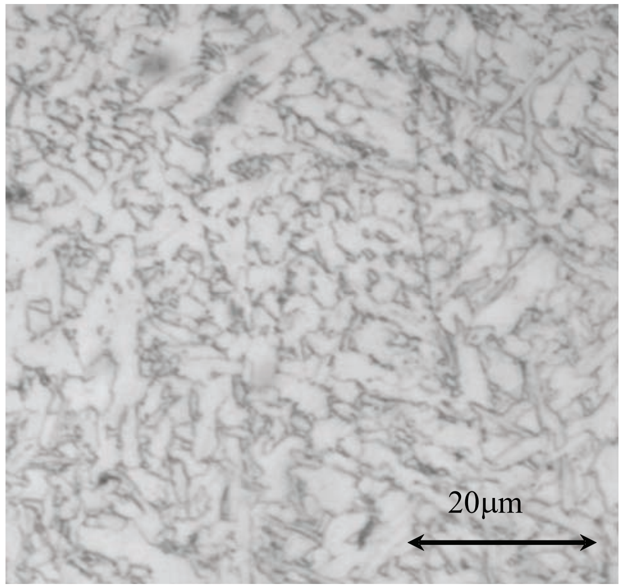


400X



1000X

Figure 4.24: Weld 65RG 3.5
(after picric acid etch)



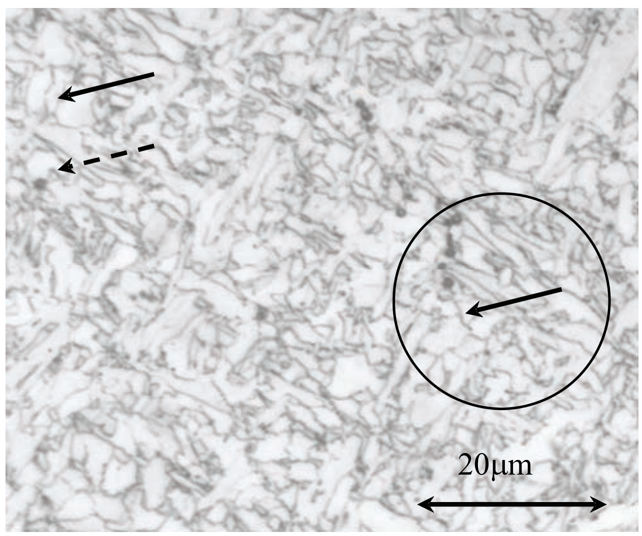


Figure 4.25: Weld 65RG 3.5
(after picric acid + 2% nital etch - Ferrite GB's are marked by the arrows and the broken arrow points to 1µm circular inclusion)

4.8 Metallographic Analysis Summary

The HSLA 100 welds displayed microstructures that can be characterized as; ferrite with aligned 2nd phase and ferrite with non aligned 2nd phase. Other features noted were circular inclusions of the size of 1μm, fine black "precipitates" in the ferrite matrix and these are in the order of a tenth of a micron were identified.

The CGHAZ grain size adjacent to the FL was about 100 μm for the HSLA 100 welds. The microstructure contained aligned 2nd phase, fine precipitates in the grain interior. The microstructure is commonly termed "bainite" and similar to the GCHAZ of other HSLA 100 welds.

The aligned 2nd phase can be carbide/martensite/retained austenite phases. For proper identification of the aligned 2nd phase one would have to perform transmission electron microscopy (TEM). For proper identification of the "light etching" non-aligned 2nd phase again TEM is the best examination procedure.

The constituents present in the HSLA 65 weld indicated that the ferrite with aligned 2nd phase was sparse. Although the micro constituents observed in HSLA 100 welds were apparent the ferrite grain morphology is different. Region displaying indications of what can be described as acicular ferrite were observed. The presence of acicular ferrite in the HSLA 65 weld metal indicates that the cooling conditions and hardenability during the transformation of the austenite promotes its formation as dictated by the applicable continuous cooling (CCT) diagram. Two factors that would assist such a scenario would be the demonstrated lower Ni, Cr and Mo contents of the as deposited weld metal and the possibility of an "effective" slower cooling rate of the HSLA 65 welds compared to those for the HSLA 100. From the HSLA-65 electrode formulation to the deposited weld metal, the Ni content was lowered from 2.00 wt% to 0.92 wt%, the Cr content was lowered from 0.45 wt% to 0.08 wt% and the Mo content was lowered from 0.43 wt% to 0.18 wt%. The lower alloy content of the HSLA 65 weld metal could lead to lower volume/area fraction of 2nd phase.

The weld metal microstructure differences in the HSLA 100 and HSLA 65 welds resulted in notable changes to the toughness (absorbed energy and % shear area). The % shear determined for weld metal centerline (CL) specimens from the HSLA 65 welds were above 85% at a test temperature of -20°F (-29°C). For the HSLA 100 weld CL specimens the % shear ranged from 55 to 70% at a test temperature of 0°F (-18°C). These observations indicate that while at a test temperature of -20°F the HSLA-65 weld metal demonstrates "upper shelf" behavior while the HSLA 100 weld metal is in the fracture transition range at 0°F. It is known that acicular ferrite in the weld metal microstructure improves the charpy V-notch toughness and the observations in the current work support this as demonstrated in these results.

In the case of the CGHAZ of the HSLA 100 welds the charpy V-notch impact toughness at the test temperature of 0°F (-18°C) was in the transition range. This would be expected from the large prior austenite grain size (100 μm) and the aligned 2nd phase.

5 PRODUCTIVITY ENHANCEMENT ANALYSIS

To demonstrate the enhancements that can be achieved using the VBAC and metal cored electrode technologies when applied to panel line welding, a comparison has been made of the "*Total Arc Time per Foot of Completed Weld Joint*" between the benchmark procedures and those developed under this investigation. The "total" arc time per foot of completed joint is the sum of the arc times per individual passes to fill the joint, as follows:

Total Arc Time per Foot of Completed Joint =

$$\text{Pass \#1} \ \frac{\text{12 in (ft)}}{\text{Travel Speed (in/min)}} + \text{Pass \#2} \ \frac{\text{12 in (ft)}}{\text{Travel Speed (in/min)}} + \text{Pass \# 3} \ \frac{\text{12 in (ft)}}{\text{Travel Speed (in/min)}}$$

The results are shown in **Table 5.1**.

Table 5.1: Comparison of Arc Time per Foot of Completed Weld Joint

	Procedure	Thickness (in)	Side	Pass (#)	Travel Speed (ipm)	Total Arc Time per ft of Joint (min)	Productivity Improvement Over Benchmarks (%)
Benchmarks	DH36 - Series AC	0.5	1	1	12	1.00	
		1	1	1	12	4.40	
				2 to 5	14		
	HSLA-65 - Tandem Arc	0.5	1	1	27.5	0.44	
		1	1	1	23.5	1.30	
				2	15.5		
	HSLA-100 - Single Arc	0.5	1	1	14	1.70	
			2	2	14		
		1	1	1 to 4	14	6.80	
			2	5 to 8	14		
VBAC Procedures	DH36 - Tandem OSW	0.5	1	1	30	0.40	250%
		1	1	1	20.5	0.59	746%
	HSLA-65 - Tandem OSW	0.5	1	1	30	0.40	10%
		1	1	1	20.5	0.59	245%
	HSLA-100 - Tandem 64/36 (EP/EN) - 2 passes	0.5	1	1	45	0.53	321%
			2	2	45		
		1	1	1	38	0.58	1172%
			2	2	45		
	HSLA-100 - Tandem 34/66 (EP/EN) - 2 Passes	1	1	1	38	0.58	1172%
			2	2	45		
	HSLA-100 - Tandem 64/36 (EP/EN) OSW - 4 Passes	1	1	1	35	1.18	576%
				2	38		
				3 to 4	45		

The results of the "total arc times" demonstrate that enhancements of over 1172% can be achieved using the VBAC and metal cored electrode technologies. These enhancements do not include those that can be achieved by the elimination of interpass operations (such as chipping, grinding, cleaning, realignment of electrodes for subsequent passes, etc.) in the benchmark multi-pass welding procedures.

These enhancements can be attributed to the higher joint filling rates of the VBAC and metal cored electrode procedures as well as the reduced weld volume requirements compared to current practice. The measured weld metal deposition rates achieved in this investigation are summarized below:

- DH36 and HSLA-65 Procedures
  - 75 lbs/hr (112.5 kJ/in) – (½" Thickness)
  - 112 lbs/hr (214.1 kJ/in) – (1" Thickness)

- HSLA-100 Steel Procedures
  - 81 lbs/hr (66 kJ/in) – (½" thickness)
  - One pass per side (66/34) = 104 lbs/hr 1st pass (99.6 kJ/in), and, 89 lbs / hr 2nd pass (75 kJ/in) - (1" Thickness)
  - One pass per side (34/66) = 112 lbs/hr for 1st (90kJ/in) and 2nd (83 kJ/in) - (1" Thickness)
  - Multi-pass OSW = 81 lbs/hr for each of the 4 passes (70 to 83.9 kJ/in) - (1" Thickness)

In comparison, a typical deposition rate for a single 5/32" diameter solid wire electrode welded at a current of 900 amps on DCEP will provide a deposition rate of approximately 25 lbs/hr. The deposition rates achieved in this investigation surpass this value by as much as 450%.

6 COST BENEFIT ANALYSIS

To demonstrate the cost savings (electrode and labor) that can be achieved in per foot of completed weld joint when using VBAC and metal cored electrodes compared to the benchmark procedures, a series of cost calculations were made based on the following:

- The calculated weld deposit weight per foot of joint for the benchmark procedures is based on the expected weld volume and a weight density of .284lbs / in^3.
- Calculated arc time is based on the number of passes and travel speeds per pass of the benchmark procedures.
- The actual weld weight per foot of the VBAC procedures using metal cored electrodes.
- The actual arc time based on the number of passes and travel speeds per pass of the VBAC procedures using metal cored electrodes.
- A cost of $1.75 per pound for each of the Lincoln L61 solid wire and DH36 metal cored electrodes, assuming that the solid wire and metal cored electrodes are the same price per pound for this grade.
- A cost of $3.50 per pound for a MIL100S-1 solid wire electrode.
- A cost of $3.10 per pound for the HSLA-65 and HSLA-100 metal cored electrodes, based on the assumption that the alloyed metal cored products cost 30% less than an equivalent alloyed solid wire.
- A labor cost of $55/hr.

The cost of electrode per foot was based on either the calculated or actual weight of weld metal per foot of completed joint multiplied by the cost per pound of electrode, as follows:

Weight of Weld Deposit (lbs/ft) x Cost of Electrode ($/lb) = $/ft

The labor cost per foot was based on the arc time per foot of completed joint multiplied by the labor rate, as follows:

Arc Time (minutes/ft) x Labor Rate (($/hr)/60) = $/ft

The above information and calculations were used to determine the cost savings that can be achieved by switching to the VBAC and metal cored electrode technologies using the procedures developed under this investigation. These costs savings, expressed in percent of cost reduction per foot of completed joint are provided in **Table 6.1**. These calculations demonstrate that the combination of labor and electrode costs per foot of completed weld joint can be reduced by as much as 64% compared to current practice that uses solid wire electrodes and conventional welding equipment.

Table 6.1: Potential Cost Reductions for Electrode and Labor per Foot of Completed Weld Joint

	Procedure	Thickness (in)	Side	Pass (#)	Weld Weight per Foot (lbs)	Electrode Cost ($/lb)	Electrode Cost per Foot ($)	Travel Speed (ipm)	Total Arc Time per ft (min)	Labor Cost ($/hr)	Labor Cost per Foot ($)	Total Electrode and Labor Cost per Foot ($)	Potential Cost Reduction
Benchmarks	DH36 - Series AC	0.5	1	1	0.43	1.75	0.75	12	1.00	55	0.92	1.67	
		1	1	1	1.6	1.75	2.80	12	4.40	55	4.03	6.83	
				2 to 5				14					
	HSLA-65 - Tandem Arc	0.5	1	1	0.62	3.5	2.17	27.5	0.44	55	0.40	2.57	
		1	1	1	1.6	3.5	5.60	23.5	1.30	55	1.19	6.79	
				2				15.5					
	HSLA-100 - Single Arc	0.5	1	1	0.43	3.5	1.51	14	1.70	55	1.56	3.06	
			2	2				14					
		1	1	1 to 4	0.95	3.5	3.33	14	6.80	55	6.23	9.56	
			2	5 to 8				14					
VBAC Procedures	DH36 - Tandem	0.5	1	1	0.5	1.75	0.875	30	0.40	55	0.37	1.24	-26%
		1	1	1	1.09	1.75	1.9075	20.5	0.59	55	0.54	2.45	-64%
	HSLA-65 - Tandem	0.5	1	1	0.5	3.1	1.55	30	0.40	55	0.37	1.92	-26%
		1	1	1	1.09	3.1	3.379	20.5	0.59	55	0.54	3.92	-42%
	HSLA-100 - Tandem 64/36 (EP/EN)	0.5	1	1	0.72	3.1	2.232	45	0.53	55	0.49	2.72	-11%
			2	2				45					
		1	1	1	0.94	3.1	2.914	38	0.58	55	0.53	3.45	-64%
			2	2				45					
	HSLA-100 - Tandem 34/66 (EP/EN)	1	1	1	1.09	3.1	3.379	38	0.58	55	0.53	3.91	-59%
			2	2				45					
	HSLA-100 - Tandem OSW - 4 Pass	1	1	1	1.59	3.1	4.929	35	1.18	55	1.08	6.01	-37%
				2				38					
				3 to 4				45					

7 CONCLUSIONS

Based on the results of the procedure qualification testing and the productivity and cost benefit analyses, it can be concluded that:

- Highly productive VBAC tandem procedures have been developed for single pass OSW of ½” and 1” thick DH36 and HSLA-65 steels.

    - All procedures demonstrated a minimum of 100% joint efficiency and met all weld metal and HAZ requirements.
    - Productivity improvements (arc time per foot of completed joint) as high as 750% were demonstrated over benchmark procedures for current panel line welding practice.
    - Weld metal deposition rates as high as 112 lbs / hr were achieved.
    - The calculated cost per foot of completed joint (electrode and labor costs) demonstrated reductions as much as 64% compared to benchmark procedures that use solid wire electrodes.

- Highly productive VBAC tandem procedures have been developed for two sided welding (1 pass per side) with no back gouging of ½” and 1” thick HSLA-100 steels.

    - All procedures demonstrated a minimum of 100% joint efficiency and met all weld metal requirements, even for heat inputs as high as 99.6 kJ/in.
    - HAZ impact properties for the ½” thickness marginally failed the HAZ FL+1 and FL+3 requirements of 35ft-lbs @ -60F, despite the welding heat input (66kJ/in) being well below the 85kJ/in restriction.
    - Productivity improvements (arc time per foot of completed joint) as high as 1172% were demonstrated over benchmark procedures for current panel line welding practice.
    - Weld metal deposition rates as high as 112 lbs / hr were achieved. Switching from 66/34 (EP/EN) to 34/66 (EP/EN) balance setting demonstrated a 15% improvement in deposition rate for the same welding conditions.
    - The calculated cost per foot of completed joint (electrode and labor costs) demonstrated reductions as much as 64% compared to benchmark two sided procedures that use solid wire electrodes.
    - Further cost reductions can be demonstrated by considering the elimination of interpass welding operations such as back gouging, chipping and cleaning slag, realignment of electrodes, etc.

- Highly productive VBAC tandem procedures have been developed for multi-pass OSW of 1” thick HSLA-100 steel onto a FCB.

    - All procedures demonstrated a minimum of 100% joint efficiency and met all weld metal and HAZ requirements.

- Productivity improvements (arc time per foot of completed joint) as high as 576% were demonstrated over benchmark procedures for current panel line welding practice.
- Weld metal deposition rates as high as 81 lbs / hr were achieved.
- The calculated cost per foot of completed joint (electrode and labor costs) demonstrated reductions as much as 37% compared to two sided benchmark procedures that use solid wire electrodes.
- Further cost reductions can be demonstrated by considering the elimination of interpass welding operations such as back gouging, chipping and cleaning slag, realignment of electrodes, etc,.

A metric of this investigation was demonstrate that the mechanical properties (weld zone integrity) could be improved by using VBAC and metal cored electrodes, compared to current practice. The tests that were carried out previously by the project sponsors used different base metal chemistries and different testing parameters, and therefore would not be a valid comparison to the test results demonstrated in this investigation. A summary has been provided on the test results qualified using VBAC and metal cored electrodes, however it can not be determined if the results are better or worse than those achieved using current practice. Although, it can be however all we can stated that the properties achieved met the applicable acceptance criteria while demonstrating significant productivity gains.

Another metric of this investigation was to compare defect incidence rates between the VBAC and metal cored electrode procedures and those of existing practices. Although a zero defect incidence rate was demonstrated in this investigation procedure qualification, it cannot be determined if this is any better than what is achieved in production, as the baseline data was not readily available from the shipyards. However, it can be stated that the procedures developed in this investigation met the applicable requirements and the welds contained zero defects or flaws.

8 RECOMMENDATIONS

Based on the results of this investigation, it is recommended to:

- Evaluate a range of HSLA-100 compositions (lean and rich) for 1” thickness to determine the significance of heat input on CG-HAZ impact properties.
- Acquire thermal histories from the weld zone to determine the significance of electrode spacing on overall weld cooling rate. This information could be used to modify the standard heat input calculation.
- Evaluate 2” thick HSLA-100
  - Compare productivity of tandem VBAC to other practices, and determine if higher heat inputs could be adopted for 2 inch thickness due to the greater heat sink capacity.
  - Possible lower preheat and interpass temperatures.
  - Further enhancements to weld metal and HAZ properties.
- Perform qualification of procedures for Aircraft Carrier approval (Explosion Bulge and Dynamic Tear Testing).
- Provide production trials to further validate the technologies.

9 TECHNOLOGY TRANSFER

In support of the technology transfer initiative of the NSRP, the results of this investigation were presented to the NSRP SP-7 Welding Technology Panel in Provo, Utah, on April 5, 2006. A copy of this presentation is provided in this report as **Appendix M**.

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APPENDIX A

HIGH STRENGTH ELECTRODE LITERATURE REVIEW

The literature that was reviewed during this task included references that dealt with welding of higher strength steels. These steels included the quenched and tempered (QT) grades, HY-80, HY-100, and HY-120, as well as the high-strength, low-alloy (HSLA) steels with yield strengths of 80 ksi (550 MPa) and higher.

QT Steels

Vassilaros [1] describes the approaches that have been used to produce HY-130 weld metals. The HY-130 steels are weldable, quenched and tempered (QT) martensitic steels, and attaining high strength and toughness in the weld metal requires using low heat inputs during welding to produce martensite, which is tempered during subsequent passes. The welds are prone to hydrogen-induced cracking, requiring the used of preheat, but this acts against producing martensitic weld metal by reducing cooling rates. Pickering [2] had shown that the strength of bainitic steels could be controlled by chemistry alone without stringent control on preheat, but this approach had not been demonstrated for weld metals, leading to this project.

Equations used by Vassilaros [1] in selecting weld chemistry target chemistries are shown below. The chemistries were based on strengths predicted between 100 and 145 ksi using equation (1) from Garcia [3].

$$YieldStrength = 25\left[10.2 + 68.1(C+N) + 1623B + 46.3(Ti+Nb) + 4.8Mo + 2.6Cr + 0.3Ni\right] + 116\sqrt{grainsize(wt\%)} \quad [MPa] \qquad (1)$$

The ultimate tensile strengths were predicted using an equation from Heuschkel [4].

$$UTS = 43 + 200N + 128C + 73V + 19.5Mo + 17Mn + 15Si + 13.5Cr + 4.3Ni \quad [MPa] \qquad (2)$$

The resultant strengths were lower than had been expected using these equations. Vassilaros suggests that the low yield strengths could be attributed to the fact that the Garcia equation had been developed for plate that had received significant thermo-mechanical treatments. The low UTS was attributed to Heuschkel having examined microstructures that obtained significant strengthening from carbon, whereas all of the steels examined here had low carbon contents. The author discusses some of the metallurgical changes that have been suggested to changes in strength with these steels. Single pass welds usually have higher strengths than multi-pass welds as additional passes temper the weld bead, dissolving finely distributed carbides and forming larger carbides which do not increase strength. A small increase in yield and ultimate strengths observed with these chemistries was suggested to have been due to secondary hardening associated with the strong carbide formers: chromium, molybdenum, and niobium. Vassilaros proposes that fine carbonitrides had been precipitated and that they contribute to strengthening by a dislocation pinning mechanism; furthermore, these precipitates are stable and resistant to Oswald ripening. There was no study of microstructures to examine the metallurgical changes responsible for the observed results.

With HY-100 steels, Clark [5] describes the microstructural development in welds and the transformations to the various phases that are observed. Acicular ferrite is assumed to nucleate on inclusions due to one of the following theories proposed by Fox et al [6]:

1. Nucleation of ferrite on a substrate;
2. Epitaxial growth on a suitably oriented inclusion facet, i.e. lattice matching;
3. Strain energy effects due to differences in thermal expansion between the inclusion and the matrix; and

4. Lower hardenability in the region near an inclusion due to the diffusion field during its formation.

The types of inclusions that are most likely to promote AF are not proposed, but rather the author suggests that further analysis is needed on inclusions for subsequent use in predicting inclusion chemistry using thermodynamics by others such as Babu [7].

HSLA Steels

The strength and toughness of high heat input welds is determined by the microstructure, which is a function of chemistry and cooling rate. The highest strengths and toughness are obtained with fine-grained microstructures, and these form at cooling rates that are intermediate between those that produce either martensite or grain boundary ferrite.

The microstructure of the weld is determined primarily by the chemical composition of the welding consumables, but the composition of the baseplate is also important as dilution from the baseplate also contributes to the weld chemistry. In addition to the core wire of the consumable and the baseplate, fluxes and/or shielding that function mainly to protect the weld from oxidation are very important in determining the final weld microstructure and toughness. Their contribution is a result of the volume fraction and size distribution of inclusions within the weld. A large volume fraction of inclusions lowers the resistance to ductile fracture, but a low inclusion volume fraction reduces the toughness because the resultant microstructures are often found to contain large amounts of grain boundary and lath ferrite, both of which have poor toughness. The optimum toughness is obtained with a fine distribution of small inclusions as they are able to nucleate fine-grained acicular ferrite.

Continuous cooling transformation (CCT) diagrams have been developed in many of the studies to understand the nature of the transformation characteristics of the weld, i.e. the transformation of austenite (γ) to grain boundary ferrite, acicular ferrite, bainite, and/or martensite. The CCT diagram in Figure A1 shows the influence of alloying, inclusion formers, and cooling rate on the prediction of weld microstructures. The exact position of the region that promotes acicular ferrite is generally between the ferrite and bainite regions, but many authors suggest that acicular ferrite is a form of bainite because its transformation temperature is in the same region as bainite. Notwithstanding the exact position of the acicular ferrite transformation, CCT diagrams can be used to predict the roles of alloying and cooling characteristics on the resultant microstructure.

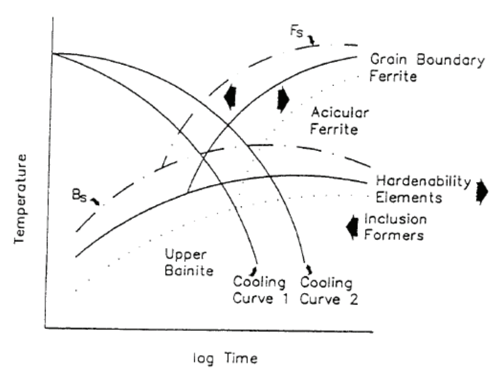

Figure A1: CCT diagram showing general transformation characteristics for HSLA weld metal showing the influences of alloying elements, inclusion formers, and cooling rate, after Liu [8]

Eakes [9] gives a good summary of the development of microstructures following weld deposition, and gives information on the role of different alloying elements in promoting the various microstructures. The example in Figure A2 shows how the austenite grain size influences the development of acicular ferrite, and describes it as a competition between grain boundary nucleation of bainite and intragranular nucleation of acicular ferrite. Inclusion composition and distribution is described and related to their roles on grain boundaries and within grains.

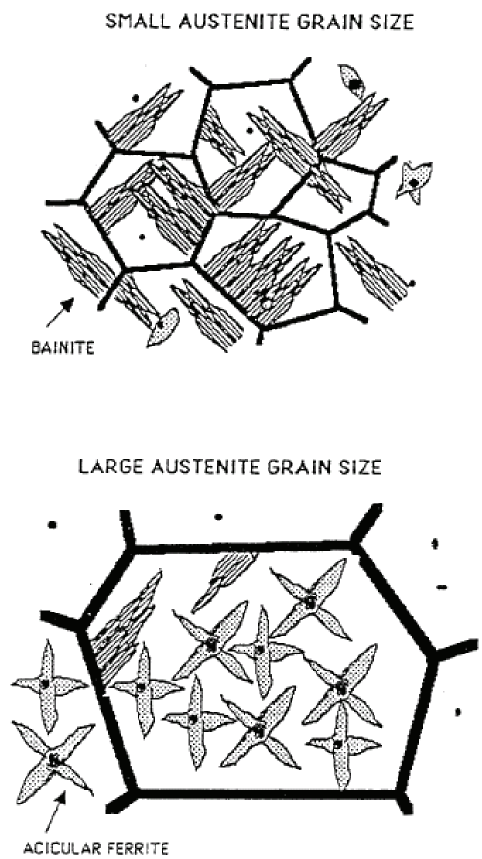

Figure A2: Schematic showing the influence of prior austenite grain size on whether the final transformation products are bainite or acicular ferrite [10]

Eakes [9] found that the volume fraction of inclusions is smaller for multi-pass GMAW welds compared to single pass GMAW. This was attributed to the larger inclusions floating out of the weld upon remelting and the formation of smaller inclusions within this region.

The percentage of acicular ferrite in GMAW deposits did not show a strong correlation with either weld metal oxygen or inclusion content. Eakes suggests that the average inclusion size was too large and that the time to cool through the 800 to 500C range was too short for optimizing AF in the weld. The average inclusion sizes ranged from 0.667 to 0.897 microns, and the time to cool $t_{800-500}$ was 6 to 8 s. He includes observations from Brothers (1994) in which AF formation was maximized with oxygen contents from 250-300 ppm, an average inclusion size of 0.3 to 0.5 microns, and $t_{800-500}$ between 5 and 30 s.

The SAW deposits had higher percentages of AF and were near optimal conditions for AF formation according to Brothers, $t_{800-500}$ of 16 s and optimal inclusion chemistry and size. The AF fraction was plotted against chemistry and inclusions and dome correlations were found, i.e., AF increased with Ti and Al, and decreased with Mn. Upon review of SAW inclusion details, and assuming that AF formation is a two step process, i.e., nucleation as a function of chemistry and growth as a function of inclusion volume fraction, the following acicular ferrite index (AFI) was developed:

$$Acicular\ Ferrite\ Index = \frac{Al + Ti + Zr}{Mn + Si} * Volume\ Fraction\ of\ Inclusions \qquad (\ )$$

Strong correlations between AF volume fraction and AFI (R^2 = 0.8913) and Basicity Index and AFI (R^2 = 0.8761) were observed, and were considered to be significant as they tie together inclusions, AF, and BI for SAW welds. Eakes notes that oxygen is not specifically included in this index, but that it is indirectly included in the volume fraction of inclusions.

A similar correlation with GMAW was not successful, and Eakes suggests that the usefulness of the AFI lies towards the high side of the curve shown in Figure A3.

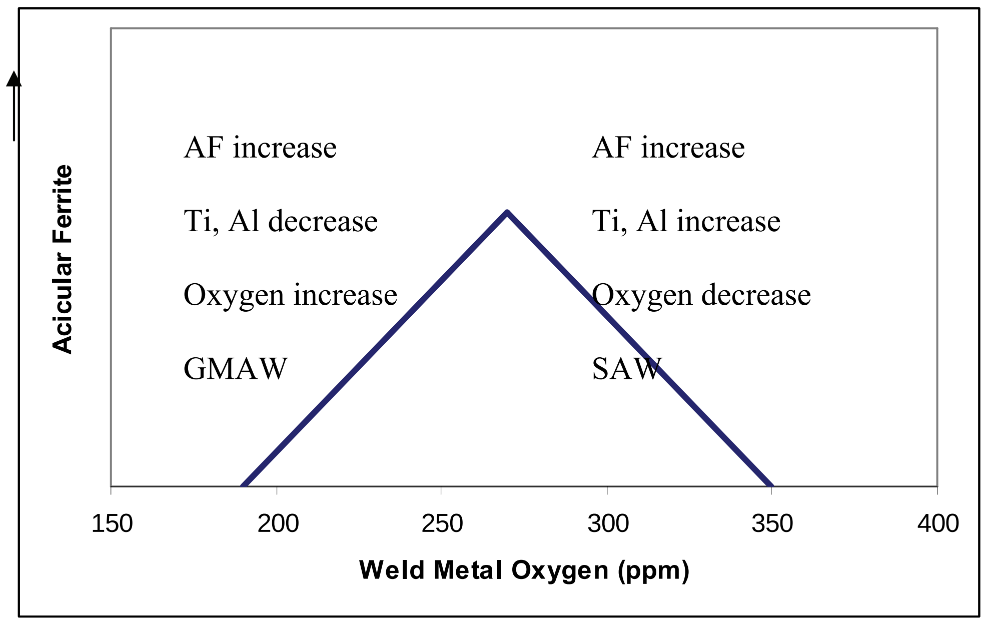

Figure A3: Schematic Diagram of Acicular Ferrite vs. Weld Metal Oxygen [9]

Fairchild et al [11] aimed to develop X120 consumables and their goal on metallurgical design was to aim for a microstructure that would be predominantly a martensitic/bainitic (M/B) structure with some acicular ferrite (AF). The AF was expected to reduce the austenite grain size and thereby improve strength and toughness. The positive and negative aspects of weld metal inclusion volume fraction and size distribution were considered, leading to a specification of weld metal oxygen contents between 200 and 300 ppm. Inclusions can promote desirable microstructures, i.e. AF, but can also initiate cleavage failures, particularly within M/B laths.

PGMAW was chosen as it was expected to provide consistent welds, low hydrogen contents, and low defect rates. The low heat input of this process was also expected to be an advantage as M/B structures would be achievable at lower alloy contents. It was noted that shipbuilding requirements would call for microstructures that could be achievable over a wider range of heat inputs than would be studied in this project.

Fairchild et al [11] described their approach that strength was intended to be obtained using elements other than carbon, as C adversely affects toughness and cracking resistance. The alloy design was as follows:

- Ni was added to promote toughness;
- Cr was limited for cleavage and cracking resistance, although some wires tested its strengthening potential;
- B was intended to act as an interstitial strengthener and to promote bainite formation;
- V was added for precipitation strengthening and temper resistance;
- Si was added for tempering resistance; and
- Ti and Zr were added for their effects on inclusions. Zr's high affinity for O was considered to be the best option for limiting inclusion size in low heat input welds.

All of the weld microstructures were mixtures of a soft AF phase and a hard constituent, the latter being mostly lath martensite (LM) and or degenerate upper bainite (DUB). The authors refer to this microstructure as AFIM – acicular ferrite interspersed in martensite. The schematic of the microstructures (See Figure A4) shows that the main differences were due to hardenability were attributed to the transformation temperatures and the driving forces for either grain thickening or lengthening.

No AFIM was observed with P_{cm}>0.31.

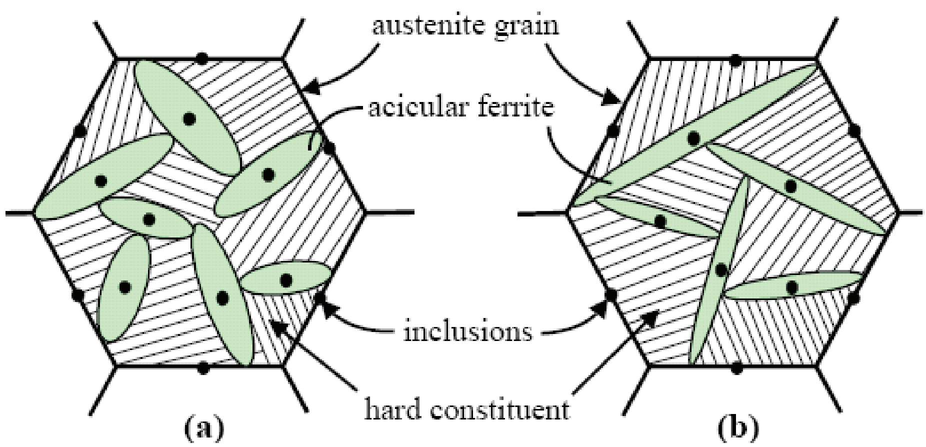

Figure A4: Schematic of the acicular ferrite interspersed in martensite (AFIM) microstructure, (a) lower P_{cm} morphology, (b) higher P_{cm} morphology [11]

The authors note that Zr additions improved toughness, and TEM found that this was due to Zr being able to nucleate a fine distribution of inclusions which later nucleate AF.

It was found that reducing the CO_2 in the shielding gas from 15% resulted in fewer inclusions and improved toughness. (The results suggest that oxygen should be below 300 ppm, and preferably between 200-260 ppm.) This reduction in CO_2, however, made the weld pool more difficult to control, but adding He to the shielding gas improved operating characteristics.

Olson and Frost [12] examined the use of Zr-Al additions as opposed to Ti-B additions to welds to promote the formation of acicular ferrite. Zr was used as it is chemically similar to Ti but has oxides with very different mismatch compared to ferrite. Al was used to replace B to compare the results. This project was undertaken to test the theory that low ferrite – lattice mismatch was needed to promote the formation of acicular ferrite. The results showed that mismatch was not important, but rather that the inclusion number and size distribution were controlling factors for promoting acicular ferrite. It was also found that Al behaved similar to B in small quantities. The authors suggest that it is necessary to study inclusion evolution to establish ways to formulate high performance welding consumables.

A study of the sequence of evolution of inclusions used the free energies of formation of oxides and segregation of elements in the weld pool during solidification to predict the location (weld pool or interdendritic) and the order of inclusion formation. In Al-killed steels with Ti, aluminum oxides will be the first to precipitate during the initial stages of solidification. Ti_2O_3 and Ti_3O_4 inclusions form near the end of solidification, as do manganese and silicon oxides. The observed bimodal distribution of inclusions could be explained with reference to the temperatures of oxide formation and interdendritic microsegregation. The larger inclusions results from primary deoxidation due to Al, and the smaller inclusions are found in the interdendritic regions and form at lower temperatures. The project results suggest that optimum microstructures could be attained through proper alloy additions, and specifically shielding gas oxygen content.

Small shifts in shielding gas content and microstructural examinations were used to show how oxygen affects the various forms of weld metal ferrite. One of the outcomes was a determination of the relationship between the weld metal oxygen content and the oxygen or CO_2 content of the shielding gas. A modified alloying index, P_{cmo}, was developed that included oxygen content.

Mahony [13] investigated the mechanisms of the nucleation of acicular ferrite, describing the roles of prior austenite grain size, inclusion types, and the numbers of inclusions in terms of promoting acicular ferrite. The competition process between bainite and acicular ferrite is described and related to the results observed in past research. He used five C-Mn steel weldments with varying amounts of Al and Ti to promote different acicular ferrite contents, and details of the inclusions and microstructures were examined using SEM and TEM to determine if the chemistry or crystallographic orientation of the inclusions, or both, were important in determining the nucleation and growth of acicular ferrite.

The average prior austenite grain size in the welds studied was similar and did not appear to influence the amount of acicular ferrite. The inclusion size distributions tended to be skewed to higher values with a mean of 23 microns, and the volume fraction of acicular ferrite increases with decreasing mean inclusion diameter.

The results have shown that Ti-rich inclusions are the strongest acicular ferrite formers and accelerate the growth. The authors suggest that mechanism by which inclusions nucleate acicular ferrite appears to be through chemical reaction and epitaxial growth. The regions around the initial Ti-rich oxides (TiO_2 and Ti_2O_3) produces a lean area immediately surrounding the now TiO dominant inclusion creating an inclusion/matrix interface (chemistry) and good lattice matching (epitaxial) for the nucleation of acicular ferrite.

Blackburn et al [14] completed a series of GMAW welds at 2.4 kJ/mm on HSLA-100 steel using an argon/oxygen mixed shielding gas, with oxygen of 2, 5, and 10%, to alter the weld inclusion characteristics. The welds were subsequently subjected to as many as three thermal cycles to 1100°C using a Gleeble machine to refine the prior austenite grain size. The weld Charpy impact toughness is discussed in relation to grain size and inclusions.

The resultant weld oxygen levels were 220, 260, and 470 ppm, and as a consequence of the oxygen levels there was some de-alloying of C and Mn. This in turn affected the 50% transformation temperatures and weld strengths through reduced hardenability. The as-deposited austenite grain width of 250-475 microns were reduced to about 25 microns with thermal cycling, with the second and third cycles only causing further refinement of about 5 microns.

The results indicate that reducing the austenite grain size results in improving toughness, except that inclusion volume fraction and count limited the upper shelf toughness, and thereby limited the overall toughness improvement that could be achieved. The authors also suggest that the lower toughness in the weld could be attributed to the as-deposited columnar structure (which could not be altered using the Gleeble thermal cycles).

Thewlis [15] examined single pass, SAW deposits in high strength low alloy steel plates that would be suitable for X100 linepipe weld seams. The materials used three experimental plates and four commercially available welding wires. A wide range of alloying was for the welds and the resulting compositions were compared against mechanical properties, microstructures, and some dilatometry to identify transformation characteristics.

All welds were bead-in-groove with either a three-wire (2.7 kJ/mm) or five-wire (4.3 kJ/mm) SAW procedure; DC lead and AC on remaining arcs.

The optimum strength and toughness was obtained for Mo-B-Ti alloyed welds that had P_{cm} valued between 0.218 and 0.250, with a resultant microstructure was almost completely acicular ferrite (>97%). The dilatometry studies showed that the maximum rate of transformation occurred between 515 and 570°C, which indicate (from the continuous cooling transformation diagram) that the acicular ferrite consists of Widmanstätten ferrite and/or bainite. The ferrite nucleated intragranularly on both large and small inclusions, and the fine distribution of inclusions meant that the ferrite did not grow large before impinging on adjacent ferrite, resulting in the fine acicular ferrite grain size.

Higher alloyed welds containing 2-3% Mn and 1.5% Si transformed at lower temperatures, giving higher strengths, but lower toughness. The microstructures were mainly large ferrite plates that grew from larger inclusions and the regions between the ferrite plates were mainly martensite-austenite (M-A), a low toughness microstructure

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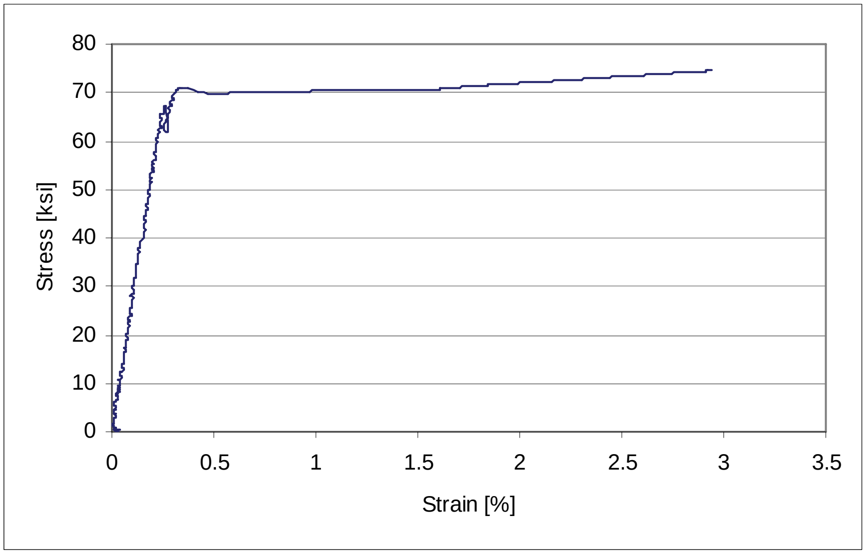
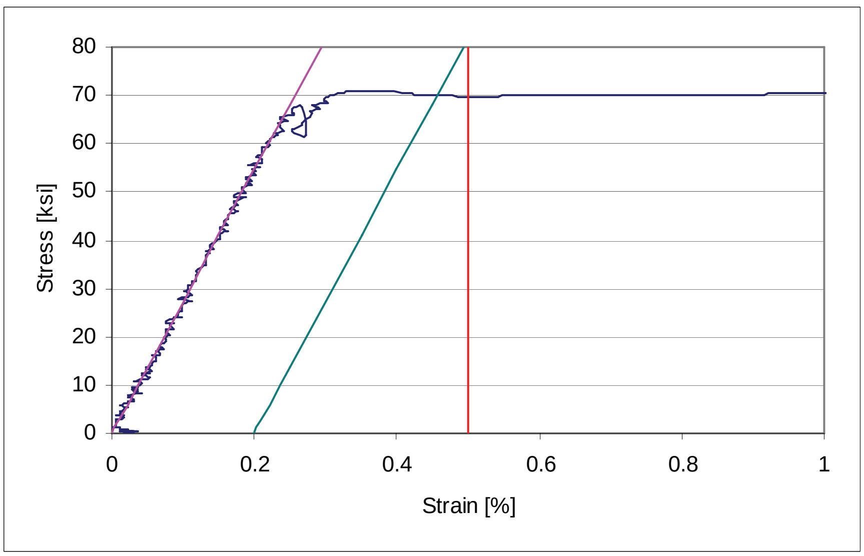
APPENDIX B

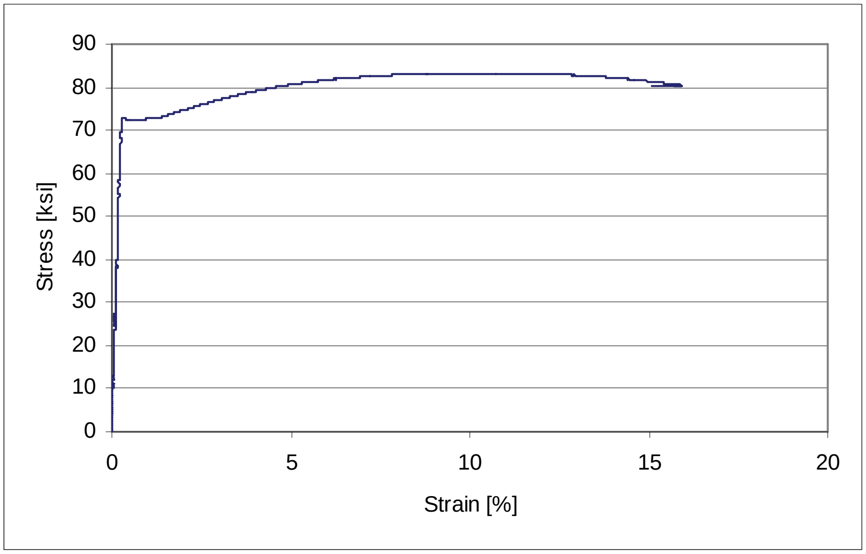
STRESS STRAIN CURVES – FIRST ROUND OF ELECTRODE FORMULATIONS

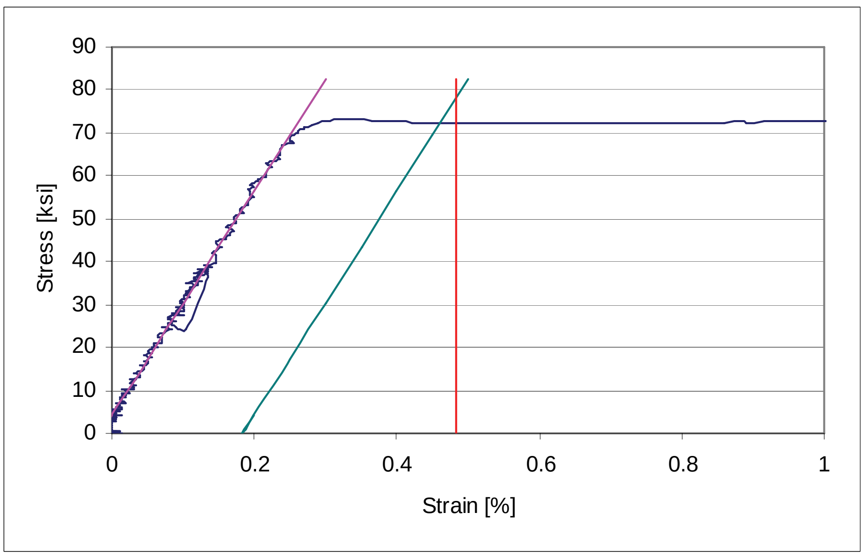
DH36-1


Stress [ksi]
Strain [%]
80
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
3.5

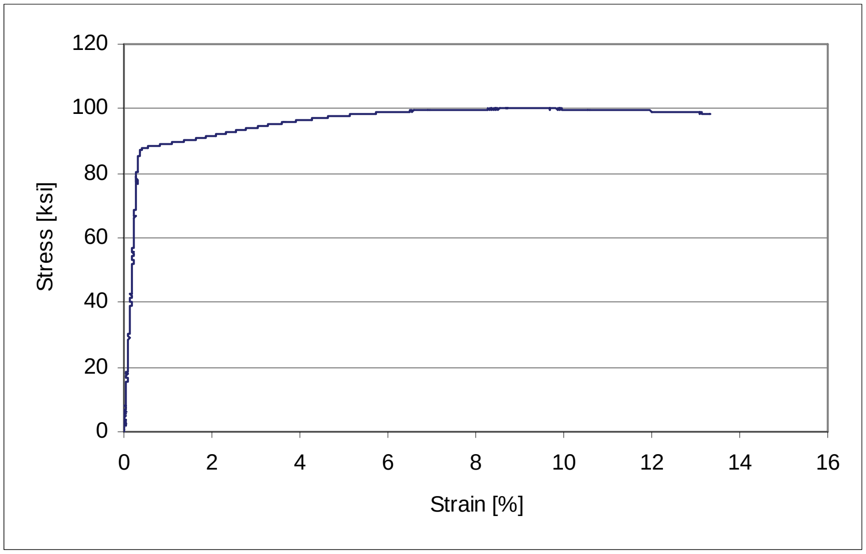

Stress [ksi]
Strain [%]
80
70
60
50
40
30
20
10
0
0
0.2
0.4
0.6
0.8
1

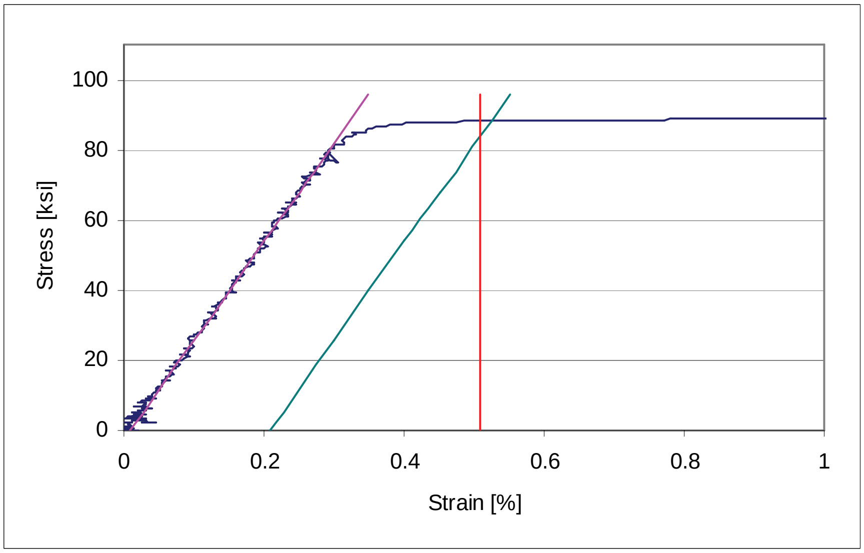
HSLA-65-1


90
80
70
60
50
40
30
20
10
0
Stress [ksi]
0
5
10
15
20
Strain [%]


90
80
70
60
50
40
30
20
10
0
Stress [ksi]
0
0.2
0.4
0.6
0.8
1
Strain [%]

HSLA-100-1

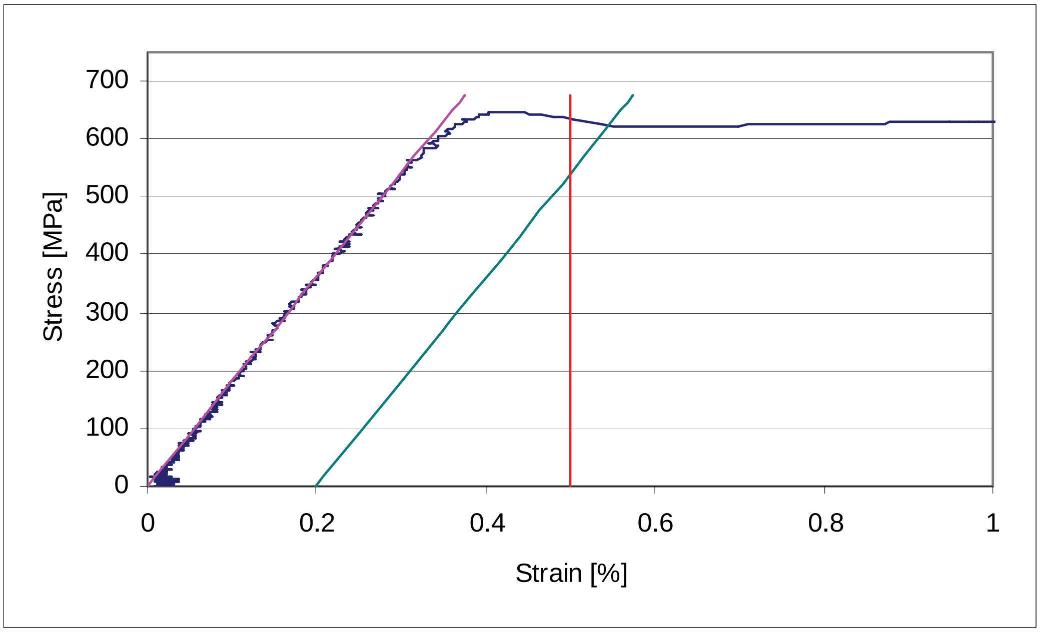

120
100
80
60
40
20
0
Stress [ksi]
0
2
4
6
8
10
12
14
16
Strain [%]


100
80
60
40
20
0
Stress [ksi]
0
0.2
0.4
0.6
0.8
1
Strain [%]

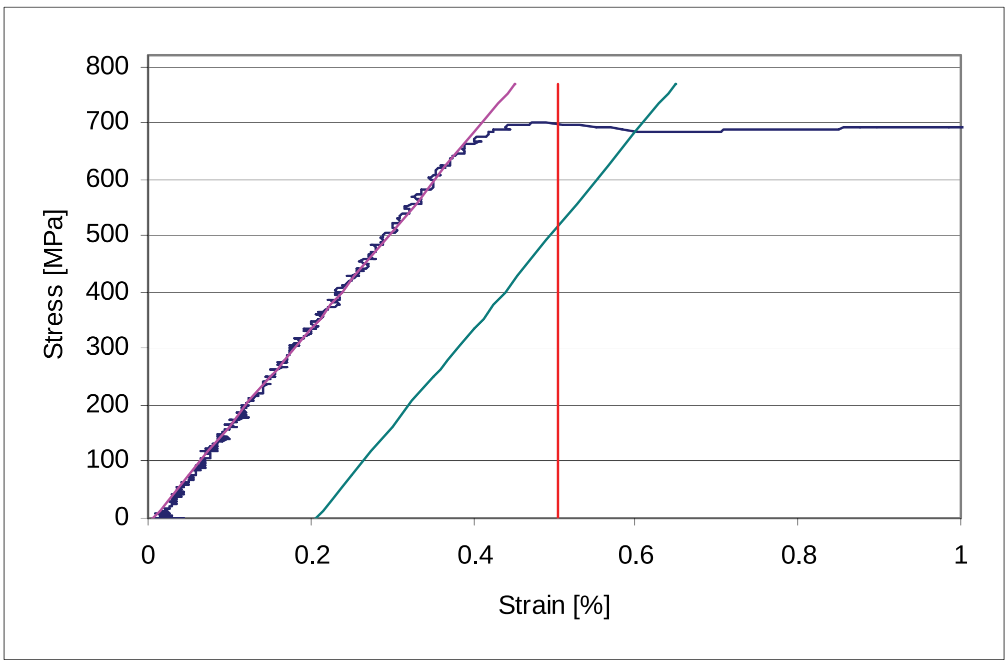
APPENDIX C

STRESS/STRAIN CURVES – SECOND ROUND OF ELECTRODE FORMULATIONS

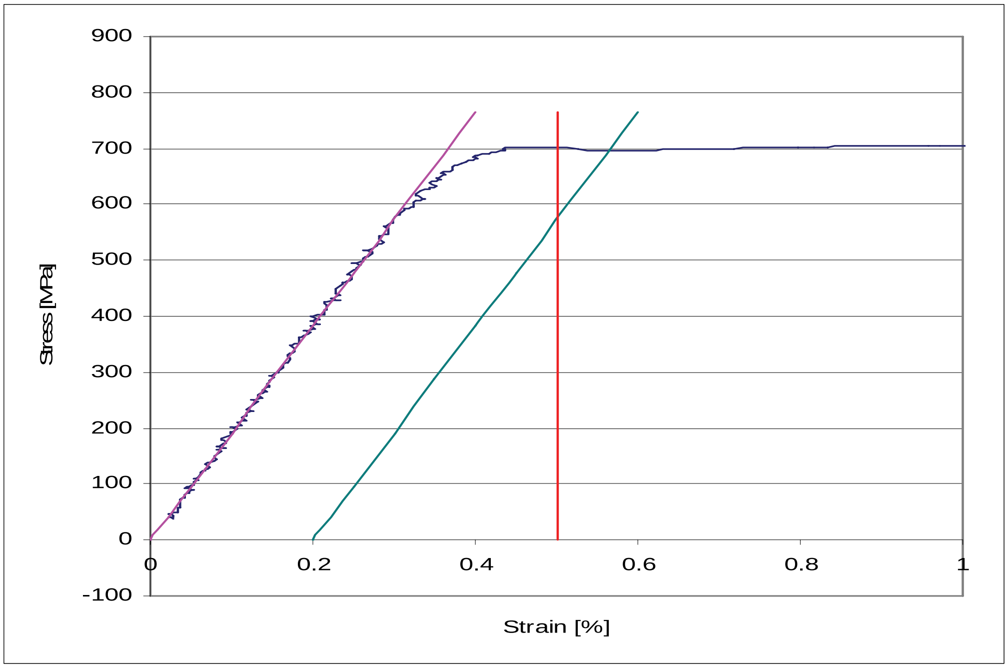
DH36-2



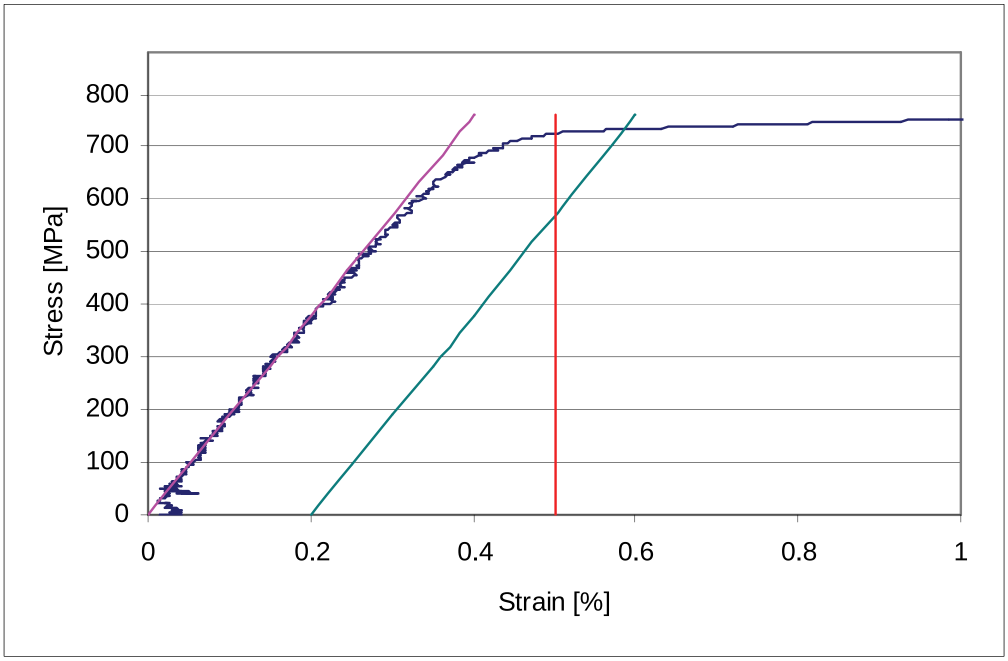
HSLA-65-2, ESAB OK10.62



HSLA-65-2, LINCOLN MIL800-H



HSLA-100-3



APPENDIX D

½” DH36 ONE-SIDED WELDING PROCEDURE DATA SHEET

BMT Fleet Technology Limited

WELDING PROCEDURE DATA SHEET

WPS No.: ______________________

WPDS No.: SAWDH36T.5E

Welding Process: SAW **Electrode Type:** Metal Cored **Flux:** ESAB 10.62

Filler Metal Identification: NISP-1-006

Material Specification: DH36

Preheat Temperature (°F): Ambient

Interpass Temperature (°F): N/A

Preheat Method: N/A

Position of Welding: Flat

Travel Direction Lead Wire: 15°Drag **Travel Direction Trail Wire:** 5°Push

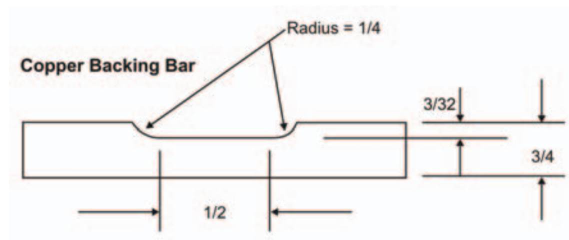
Current: CV **Polarity:** 66% DCEP 34%DCEN

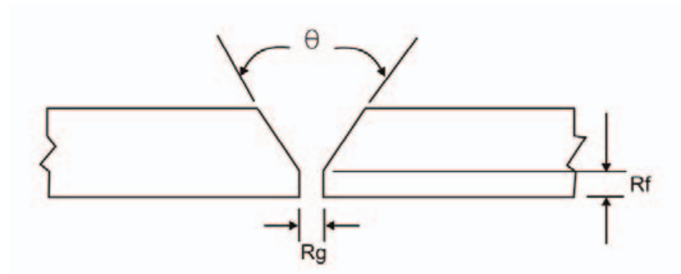
Manual, Semi-Auto, Auto,Machine: Machine

Single or Multiple Arc: Multiple (Tandem Arc)

Single or Multipass: Single

Cleaning Method: Grind to remove scale and paint 2" in all directions of joint





Θ=30° Included Angle **Rg = 3/32** **Rf = 1/8**

Material Thickness	Tandem Process	Weld Sequence			Electrode Size	Wire Feed Speed	Flux Depth	Amps	Volts	CTWD	Travel Speed	Electrode Spacing
in.	Wire	Side	Layer	Pass	in.	ipm	in.	A	V	in.	ipm	in.
1/2	Lead	1	1	1	1/8	200	1	800	37.5	3/4	30	5 1/4
	Trail	1	1	1	5/32	100	1 3/4	700	37.5	1 3/4		

Procedure Qualification Record No.:

Date:

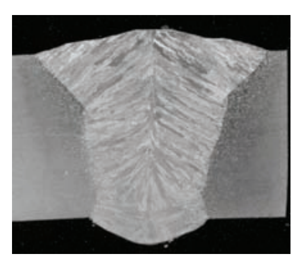
FTL:

Procedure Notes:

Fill groove in copper backing bar flush with flux. Copper backing bar shall fit tight to back of plate.

Flux shall be baked and held in a holding oven at temperatures within manufacturer's specified range.

MACRO:



APPENDIX E

½" HSLA-65 ONE-SIDED WELDING PROCEDURE DATA SHEETS

BMT Fleet Technology Limited

WELDING PROCEDURE DATA SHEET

WPS No.:

WPDS No.: SAWHSLA65T.5L

Welding Process: SAW **Electrode Type:** Metal Cored **Flux:** Lincoln MIL 800-H

Filler Metal Identification: NISP-1-005

Material Specification: HSLA 65

Preheat Temperature (°F): Ambient

Interpass Temperature (°F): N/A

Preheat Method: N/A

Position of Welding: Flat

Travel Direction Lead Wire: 15°Drag **Travel Direction Trail Wire:** 5°Push

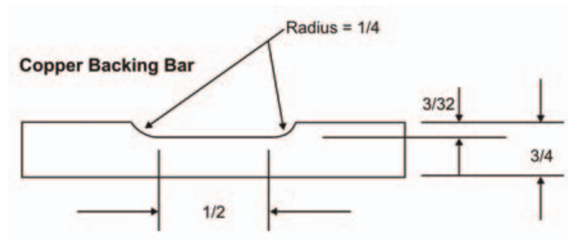
Current: CV **Polarity:** 66% DCEP 34%DCEN

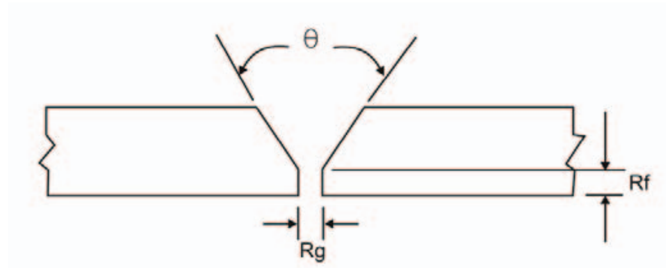
Manual, Semi-Auto, Auto,Machine: Machine

Single or Multiple Arc: Multiple (Tandem Arc)

Single or Multipass: Single

Cleaning Method: Grind to remove scale and paint 2” in all directions of joint





ϴ=30° Included Angle **Rg = 3/32** **Rf = 1/8**

Material Thickness	Tandem Process	Weld Sequence			Electrode Size	Wire Feed Speed	Flux Depth	Amps	Volts	CTWD	Travel Speed	Electrode Spacing
in.	Wire	Side	Layer	Pass	in.	ipm	in.	A	V	in.	ipm	in.
1/2	Lead	1	1	1	1/8	200	1	780	37.5	3/4	30	5 1/4
	Trail	1	1	1	5/32	100	1 3/4	670	37.5	1 3/4		

Procedure Qualification Record No.:

Date:

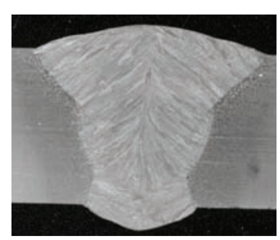
FTL:

Procedure Notes:

Fill groove in copper backing bar flush with flux. Copper backing bar shall fit tight to back of plate.

Flux shall be baked and held in a holding oven at temperatures within manufacturer’s specified range.

MACRO:



BMT Fleet Technology Limited

WELDING PROCEDURE DATA SHEET

WPS No.:

WPDS No.: SAWHSLA65T.5E

Welding Process: SAW **Electrode Type:** Metal Cored **Flux:** ESAB 10.62

Filler Metal Identification: NISP-1-005

Material Specification: HSLA 65

Preheat Temperature (°F): Ambient

Interpass Temperature (°F): N/A

Preheat Method: N/A

Position of Welding: Flat

Travel Direction Lead Wire: 15°Drag **Travel Direction Trail Wire:** 5°Push

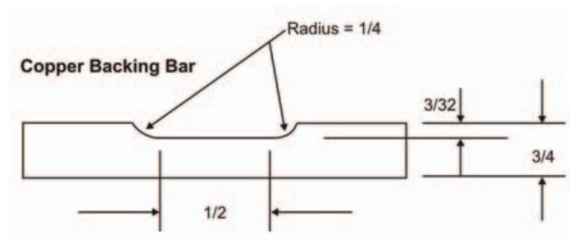
Current: CV **Polarity:** 66% DCEP 34%DCEN

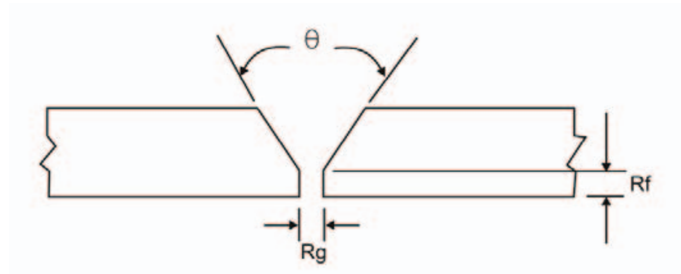
Manual, Semi-Auto, Auto, Machine: Machine

Single or Multiple Arc: Multiple (Tandem Arc)

Single or Multipass: Single

Cleaning Method: Grind to remove scale and paint 2" in all directions of joint





Θ=30° Included Angle Rg = 3/32 Rf = 1/8

Material Thickness	Tandem Process	Weld Sequence			Electrode Size	Wire Feed Speed	Flux Depth	Amps	Volts	CTWD	Travel Speed	Electrode Spacing
in.	Wire	Side	Layer	Pass	in.	ipm	in.	A	V	in.	ipm	in.
1/2	Lead	1	1	1	1/8	200	1	820	39.5	3/4	30	5 1/4
	Trail	1	1	1	5/32	100	1 3/4	650	37.5	1 3/4		

Procedure Qualification Record No.:

Date:

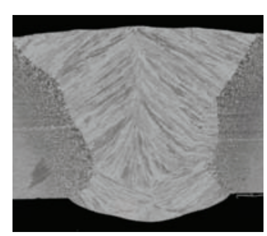
FTL:

Procedure Notes:

Fill groove in copper backing bar flush with flux. Copper backing bar shall fit tight to back of plate.

Flux shall be baked and held in a holding oven at temperatures within manufacturer's specified range.

MACRO:



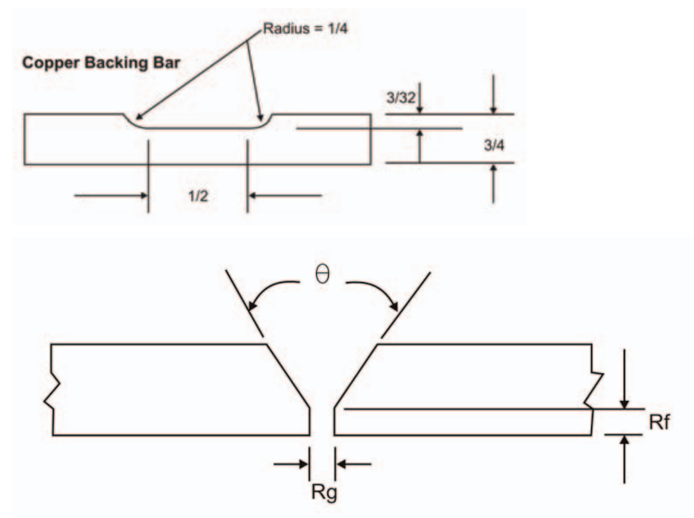
APPENDIX F

1" DH36 AND HSLA-65 ONE-SIDED WELDING PROCEDURE DATA SHEETS

BMT Fleet Technology Limited	WELDING PROCEDURE DATA SHEET	WPS No.: ____ WPDS No.: SAWDH36T1E

Welding Process: SAW **Electrode Type:** Metal Cored **Flux:** ESAB 10.62

Filler Metal Identification:	NISP-1-006
Material Specification:	DH36
Preheat Temperature (°F):	Ambient
Interpass Temperature (°F):	N/A
Preheat Method:	N/A
Position of Welding:	Flat
Travel Direction Lead Wire: 15°Drag	**Travel Direction Trail Wire:** 0°Angle
Current: CV	**Polarity:** 66% DCEP 34%DCEN
Manual, Semi-Auto, Auto,Machine:	Machine
Single or Multiple Arc:	Multiple (Tandem Arc)
Single or Multipass:	Single
Cleaning Method:	Grind to remove scale and paint 2" in all directions of joint



Θ = 30° Included Angle Rg = 3/32 Rf = 3/16

Material Thickness	Tandem Process	Weld Sequence			Electrode Size	Wire Feed Speed	Flux Depth	Amps	Volts	CTWD	Travel Speed	Electrode Spacing
in.	Wire	Side	Layer	Pass	in.	ipm	In.	A	V	in.	ipm	in.
1	Lead	1	1	1	5/32	225	3/4	1150	32.5	1/2	20.5	4
	Trail	1	1	1	5/32	175	1 3/4	980	36.5	1 3/4		

Procedure Qualification Record No.:

Date:

FTL:

Procedure Notes:

Fill groove in copper backing bar flush with flux. Copper backing bar shall fit tight to back of plate.

Flux shall be baked and held in a holding oven at temperatures within manufacturer's specified range.

MACRO:

BMT Fleet Technology Limited

WELDING PROCEDURE DATA SHEET

WPS No.:

WPDS No.: SAWHSLA65T1E

Welding Process: SAW **Electrode Type:** Metal Cored **Flux:** ESAB 10.62

Filler Metal Identification: NISP-1-005

Material Specification: HSLA 65

Preheat Temperature (°F): Ambient

Interpass Temperature (°F): N/A

Preheat Method: N/A

Position of Welding: Flat

Travel Direction Lead Wire: 15°Drag **Travel Direction Trail Wire:** 0°Angle

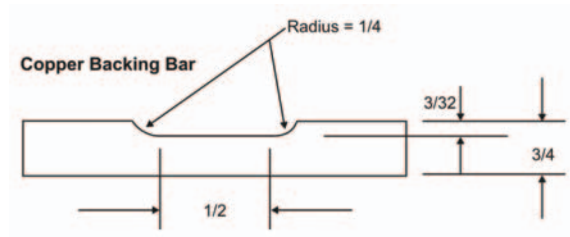
Current: CV **Polarity:** 66% DCEP 34%DCEN

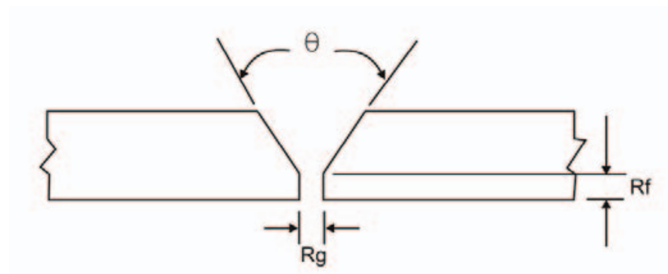
Manual, Semi-Auto, Auto, Machine: Machine

Single or Multiple Arc: Multiple (Tandem Arc)

Single or Multipass: Single

Cleaning Method: Grind to remove scale and paint 2" in all directions of joint





Θ=30° Included Angle Rg = 3/32 Rf = 3/16

Material Thickness	Tandem Process	Weld Sequence			Electrode Size	Wire Feed Speed	Flux Depth	Amps	Volts	CTWD	Travel Speed	Electrode Spacing
in.	Wire	Side	Layer	Pass	in.	ipm	in.	A	V	in.	ipm	in.
1	Lead	1	1	1	5/32	225	3/4	1100	32.5	1/2	20.5	4
	Trail	1	1	1	5/32	175	1 3/4	950	36.5	1 3/4		

Procedure Qualification Record No.:

Date:

FTL:

Procedure Notes:

Fill groove in copper backing bar flush with flux. Copper backing bar shall fit tight to back of plate.

Flux shall be baked and held in a holding oven at temperatures within manufacturer's specified range.

MACRO:

BMT Fleet Technology Limited

WELDING PROCEDURE DATA SHEET

WPS No.: ____________________

WPDS No.: SAWHSLA65T1L

Welding Process: SAW **Electrode Type:** Metal Cored **Flux:** Lincoln MIL 800-H

Filler Metal Identification: NISP-1-005

Material Specification: HSLA 65

Preheat Temperature (°F): Ambient

Interpass Temperature (°F): N/A

Preheat Method: N/A

Position of Welding: Flat

Travel Direction Lead Wire: 15°Drag **Travel Direction Trail Wire:** 0°Angle

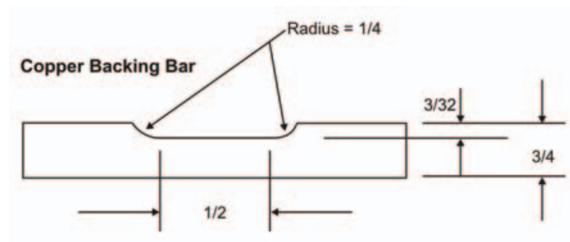
Current: CV **Polarity:** 66% DCEP 34%DCEN

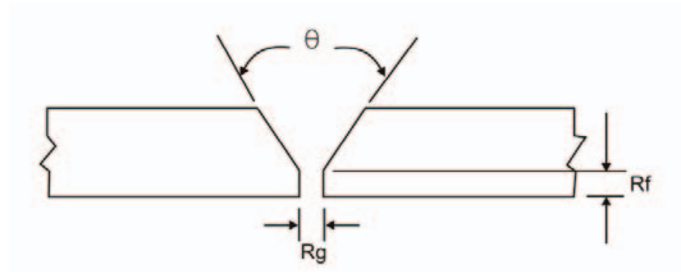
Manual, Semi-Auto, Auto, Machine: Machine

Single or Multiple Arc: Multiple (Tandem Arc)

Single or Multipass: Single

Cleaning Method: Grind to remove scale and paint 2" in all directions of joint





Θ=30° Included Angle **Rg = 3/32** **Rf = 3/16**

Material Thickness	Tandem Process	Weld Sequence			Electrode Size	Wire Feed Speed	Flux Depth	Amps	Volts	CTWD	Travel Speed	Electrode Spacing
in.	Wire	Side	Layer	Pass	in.	ipm	in.	A	V	In.	ipm	in.
1	Lead	1	1	1	5/32	225	3/4	1180	32.5	1/2	20.5	4
	Trail	1	1	1	5/32	175	1 3/4	950	36.5	1 3/4		

Procedure Qualification Record No.:

Date:

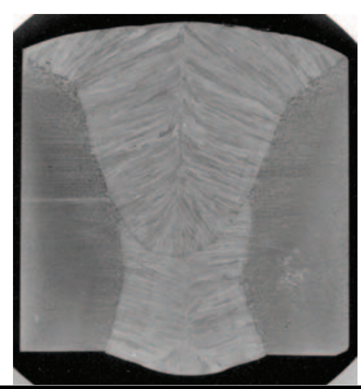
FTL:

Procedure Notes:

Fill groove in copper backing bar flush with flux. Copper backing bar shall fit tight to back of plate.

Flux shall be baked and held in a holding oven at temperatures within manufacturer's specified range.

MACRO:



APPENDIX G

1" HSLA-100 TWO-SIDED NO BACK GOUGE WELDING PROCEDURE DATA SHEETS

BMT Fleet Technology Limited

WELDING PROCEDURE DATA SHEET

WPS No.: ____________________

WPDS No.: SAWHSLA100T1-2PEP

Welding Process: SAW **Electrode Type:** Metal Cored **Flux:** Lincoln MIL 800-H

Filler Metal Identification: Lead: NISP-1-004 Trail: NISP-1-005

Material Specification: HSLA 100

Preheat Temperature (°F): Ambient

Interpass Temperature (°F): 300°

Preheat Method: Oxy-Fuel

Position of Welding: Flat

Travel Direction Lead Wire: 0°Angle **Travel Direction Trail Wire:** 15°Push

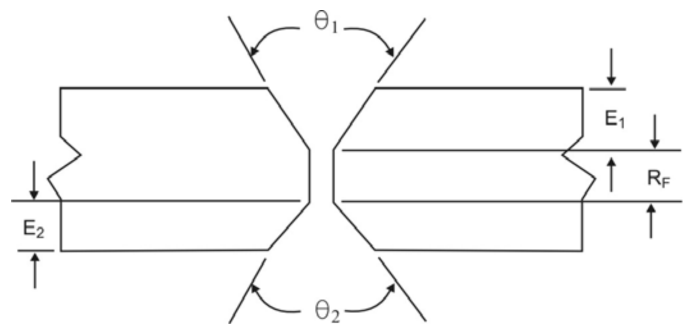
Current: CV **Polarity:** 66% DCEP 34%DCEN

Manual, Semi-Auto, Auto, Machine: Machine

Single or Multiple Arc: Multiple (Tandem Arc)

Single or Multipass: Multipass

Cleaning Method: Grind to remove scale and paint 2" in all directions of joint



Θ_1=70° Included Angle, Θ_2=90° Included Angle, Rg = 0, Rf = 5/16, E_1=7/16, E_2=1/4

Material Thickness	Tandem Process	Weld Sequence			Electrode Size	Wire Feed Speed	Flux Depth	Amps	Volts	CTWD	Travel Speed	Electrode Spacing
in.	Wire	Side	Layer	Pass	in.	ipm	In.	A	V	in.	ipm	in.
1	Lead	1	1	1	5/32	175	1 1/2	1000	32.5	1 1/4	38	3/4
	Trail	1	1	1	5/32	195	1 3/4	850	36.0	1 1/2		
	Lead	2	1	1	5/32	160	1 1/2	960	32.5	1 1/4	45	
	Trail	2	1	1	5/32	160	1 3/4	730	35	1 1/2		

Procedure Qualification Record No.:

Date:

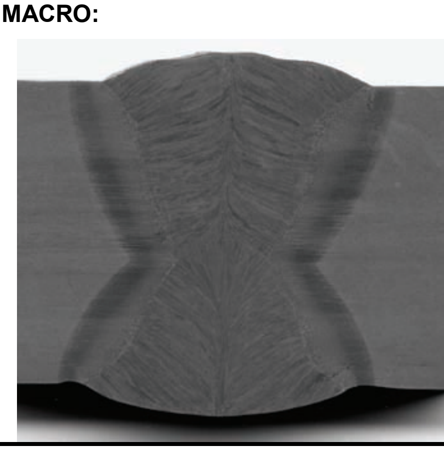
FTL:

Procedure Notes:

Flux shall be baked and held in a holding oven at temperatures within manufacturer's specified range.

No back gouging required before welding of 2^{nd} pass.

MACRO:



BMT Fleet Technology Limited

WELDING PROCEDURE DATA SHEET

WPS No.: ______________________

WPDS No.: SAWHSLA100T1-2PEN

Welding Process: SAW **Electrode Type:** Metal Cored **Flux:** Lincoln MIL 800-H

Filler Metal Identification: Lead: NISP-1-004 Trail: NISP-1-005

Material Specification: HSLA 100

Preheat Temperature (°F): Ambient

Interpass Temperature (°F): 300°

Preheat Method: Oxy-Fuel

Position of Welding: Flat

Travel Direction Lead Wire: 0°Angle **Travel Direction Trail Wire:** 15°Push

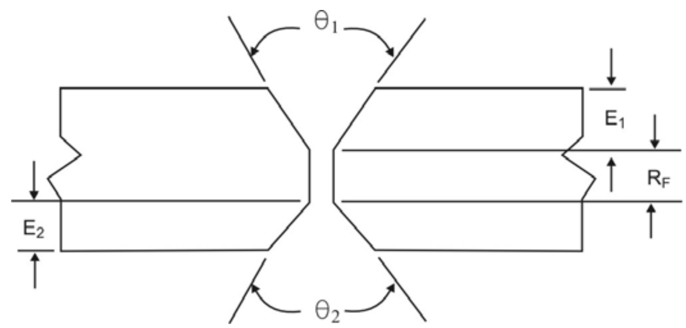
Current: CV **Polarity:** 34% DCEP 66%DCEN

Manual, Semi-Auto, Auto, Machine: Machine

Single or Multiple Arc: Multiple (Tandem Arc)

Single or Multipass: Multipass

Cleaning Method: Grind to remove scale and paint 2" in all directions of joint



Θ_1=70° Included Angle, Θ_2=90° Included Angle, Rg = 0, Rf = 5/16, E_1=7/16, E_2=1/4

Material Thickness	Tandem Process	Weld Sequence			Electrode Size	Wire Feed Speed	Flux Depth	Amps	Volts	CTWD	Travel Speed	Electrode Spacing
in.	Wire	Side	Layer	Pass	in.	ipm	In.	A	V	in.	ipm	in.
1	Lead	1	1	1	5/32	200	1 1/2	1000	32.5	1 1/4	38	3/4
	Trail	1	1	1	5/32	200	1 3/4	680	36.0	1 1/2		
	Lead	2	1	1	5/32	200	1 1/2	1050	32.5	1 1/4	45	
	Trail	2	1	1	5/32	200	1 3/4	800	36	1 1/2		

Procedure Qualification Record No.:

Date:

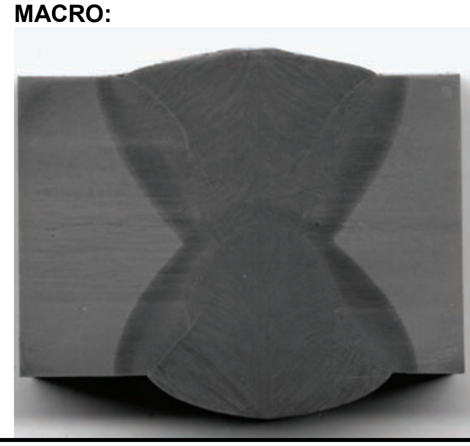
FTL:

Procedure Notes:

Flux shall be baked and held in a holding oven at temperatures within manufacturer's specified range.

No back gouging required before welding of 2nd pass.

MACRO:



APPENDIX H

1” HSLA-100 ONE-SIDED MULTIPASS WELDING PROCEDURE DATA SHEET

WELDING PROCEDURE DATA SHEET

BMT Fleet Technology Limited

WPS No.: ____________________

WPDS No.: SAWHSLA100T1-OSW-4P

Welding Process: SAW **Electrode Type:** Metal Cored **Flux:** Lincoln MIL 800-H

Filler Metal Identification: Lead Wire: NISP-1-004 Trail Wire: NISP-1-005

Material Specification: HSLA 100

Preheat Temperature (°C): Ambient

Interpass Temperature (°C): 125° Max

Preheat Method: Oxy-Fuel

Position of Welding: Flat

Travel Direction Lead Wire: 15°Drag **Travel Direction Trail Wire:** 0°Angle

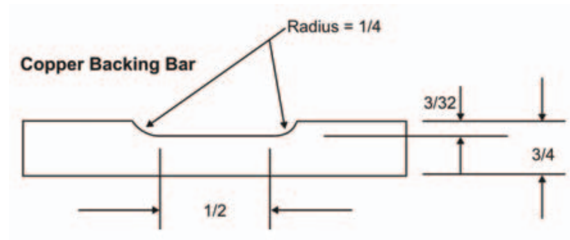
Current: CV **Polarity:** 66% DCEP 34%DCEN

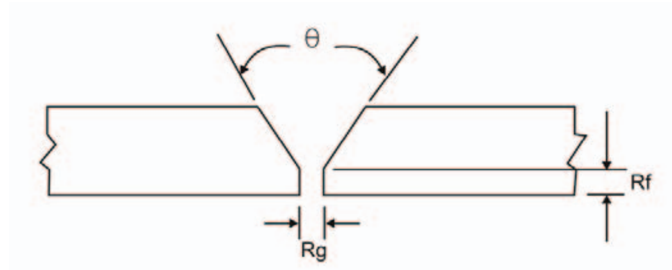
Manual, Semi-Auto, Auto, Machine: Machine

Single or Multiple Arc: Multiple (Tandem Arc)

Single or Multipass: Multipass

Cleaning Method: Grind to remove scale and paint 2" in all directions of joint





Θ=45° Included Angle **Rg = 1/8** **Rf = 5/32**

Material Thickness	Tandem Process	Weld Sequence			Electrode Size	Wire Feed Speed	Flux Depth	Amps	Volts	CTWD	Travel Speed	Electrode Spacing
In.	Wire	Side	Layer	Pass	in's	ipm	in.	A	V	in.	ipm	in.
1	Lead	1	1	1	5/32	145	1 1/2	800	33.0	1 1/4	35	3/4
	Trail	1	1	1	5/32	145	1 1/2	660	34.0	1 1/4		
2	Lead	1	2	1	5/32	145	1 1/2	860	33.0	1 1/4	40	3/4
	Trail	1	2	1	5/32	145	1 1/2	680	34.0	1 1/4		
3	Lead	1	3	1	5/32	145	1 1/2	900	32.5	1 1/4	45	3/4
	Trail	1	3	1	5/32	145	1 1/2	680	35.0	1 1/4		
4	Lead	1	3	2	5/32	145	1 1/2	920	32.5	1 1/4	45	3/4
	Trail	1	3	2	5/32	145	1 1/2	700	35.0	1 1/4		

Procedure Qualification Record No.:

Date:

FTL:

Procedure Notes:

Fill groove in copper backing bar flush with flux. Copper backing bar shall fit tight to back of plate.

Flux shall be baked and held in a holding oven at temperatures within manufacturer's specified range.

MACRO:

APPENDIX I

½" HSLA-100 TWO-SIDED NO BACK GOUGE WELDING PROCEDURE DATA SHEETS

BMT Fleet Technology Limited

WELDING PROCEDURE DATA SHEET

WPS No.: ____________

WPDS No.: SAWHSLA100T.5L

Welding Process: SAW **Electrode Type:** Metal Cored **Flux:** Lincoln MIL 800-H

Filler Metal Identification: NISP-1-004

Material Specification: HSLA 100

Preheat Temperature (°F): Ambient

Interpass Temperature (°F): 150

Preheat Method: N/A

Position of Welding: Flat

Travel Direction Lead Wire: 0°Angle **Travel Direction Trail Wire:** 18.6°Push

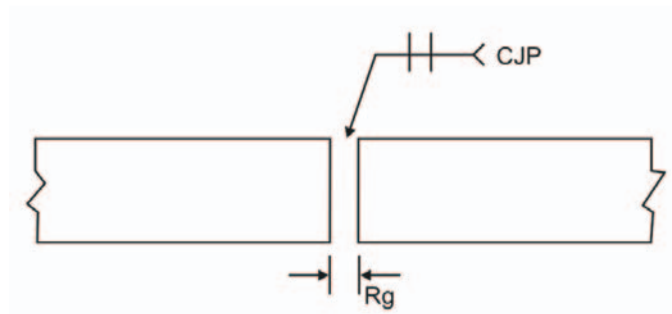
Current: **CV+C** **Polarity:** 66% DCEP 34%DCEN

Manual, Semi-Auto, Auto,Machine: Machine

Single or Multiple Arc: Multiple (Tandem Arc)

Single or Multipass: Multipass

Cleaning Method: Grind to remove scale and paint 2" in all directions of joint



Weld first side of joint, flip plate and weld side 2.

Rg = 0

Material Thickness	Tandem Process	Weld Sequence			Electrode Size	Wire Feed Speed	Flux Depth	Amps	Volts	CTWD	Travel Speed	Electrode Spacing
in.	Wire	Side	Layer	Pass	in.	ipm	in.	A	V	in.	ipm	in.
1/2	Lead	1	1	1	5/32	150	1.5	950	30.0	1	45	3/4
	Trail	1	1	1	5/32	100	1.5	600	35.0	1		
	Lead	2	1	1	5/32	150	1.5	950	30.0	1	45	3/4
	Trail	2	1	1	5/32	100	1.5	600	35.0	1		

Procedure Qualification Record No.:

Date:

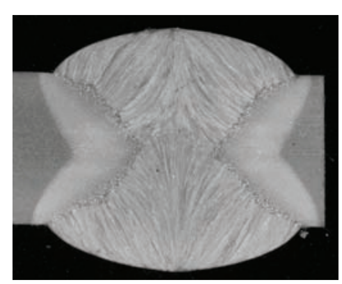
FTL:

Procedure Notes:

Flux shall be baked and held in a holding oven at temperatures within manufacturer's specified range.

Back gouging is not required before welding side 2 of joint.

MACRO:



APPENDIX J

CHARPY V-NOTCH IMPACT TEST RESULTS

CONTRACT NO.:	**5854**
TECH:	**Darren Begg/Kent Leclair**
SPECIMEN SIZE:	**10mm x 10mm**
DATE:	**March 14, 2006**
IDENTIFICATION:	**DH36 (1 pass OSW)**
PLATE THICKNESS:	**1/2”**

SPECIMEN No.	TEMP.	FT. LBS	LAT. EXP	%SHEAR
CL-1	-20°F	92	.074	85
CL-2	-20°F	108	.076	85
CL-3	-20°F	115	.080	85
CL-4	-20°F	118	.080	90
CL-5	-20°F	120	.075	90
FL-1	-4°F	43	.032	30
FL-2	-4°F	98	.068	50
FL-3	-4°F	22	.021	20
FL-4	-4°F	102	.078	50
FL-5	-4°F	46	.036	40
FL1-1	-4°F	34	.024	20
FL1-2	-4°F	112	.082	50
FL1-3	-4°F	67	.052	40
FL1-4	-4°F	56	.045	30
FL1-5	-4°F	29	.025	20
FL3-1	-4°F	102	.074	50
FL3-2	-4°F	107	.080	60
FL3-3	-4°F	116	.075	60
FL3-4	-4°F	80	.066	50
FL3-5	-4°F	124	.080	90

CONTRACT NO.:	**5854**
TECH:	**Darren Begg/Kent Leclair**
SPECIMEN SIZE:	**10mm x 10mm**
DATE:	**March 14, 2006**
IDENTIFICATION:	**HSLA 65 (1 pass OSW)**
PLATE THICKNESS:	**1/2”**

SPECIMEN No.	TEMP.	FT. LBS	LAT. EXP	%SHEAR
CL-1	-20°F	113	.074	90
CL-2	-20°F	92	.068	85
CL-3	-20°F	110	.075	90
CL-4	-20°F	89	.062	85
CL-5	-20°F	95	.065	85
FL-1	-20°F	61	.050	40
FL-2	-20°F	57	.043	50
FL-3	-20°F	28	.023	30
FL-4	-20°F	58	.043	40
FL-5	-20°F	90	.065	50
FL1-1	-20°F	155	.088	85
FL1-2	-20°F	38	.033	40
FL1-3	-20°F	39	.032	40
FL1-4	-20°F	32	.027	40
FL1-5	-20°F	28	.025	40
FL3-1	-20°F	134	.093	90
FL3-2	-20°F	267	.086	95
FL3-3	-20°F	294	.086	95
FL3-4	-20°F	267	.084	95
FL3-5	-20°F	175	.094	90

CONTRACT NO.:	**5854**
TECH:	**Darren Begg/Kent Leclair**
SPECIMEN SIZE:	**10mm x 10mm**
DATE:	**March 14, 2006**
IDENTIFICATION:	**DH36 (1 pass OSW)**
PLATE THICKNESS:	**1"**

SPECIMEN No.	TEMP.	FT. LBS	LAT. EXP	%SHEAR
CL-1	-20°F	75	.058	90
CL-2	-20°F	68	.054	85
CL-3	-20°F	82	.063	90
CL-4	-20°F	74	.051	90
CL-5	-20°F	78	.057	95
FL-1	-4°F	28	.031	40
FL-2	-4°F	26	.031	40
FL-3	-4°F	28	.030	40
FL-4	-4°F	25	.024	40
FL-5	-4°F	25	.026	40
FL1-1	-4°F	23	.027	40
FL1-2	-4°F	23	.021	30
FL1-3	-4°F	24	.023	30
FL1-4	-4°F	20	.018	30
FL1-5	-4°F	17	.012	10
FL3-1	-4°F	51	.042	50
FL3-2	-4°F	45	.031	40
FL3-3	-4°F	48	.040	40
FL3-4	-4°F	53	.042	50
FL3-5	-4°F	52	.043	50

CONTRACT NO.:	**5854**
TECH:	**Darren Begg/Kent Leclair**
SPECIMEN SIZE:	**10mm x 10mm**
DATE:	**March 14, 2006**
IDENTIFICATION:	**HSLA 65L (1 pass OSW)**
PLATE THICKNESS:	**1”**

SPECIMEN No.	TEMP.	FT. LBS	LAT. EXP	%SHEAR
CL-1	-20°F	94	.065	85
CL-2	-20°F	88	.066	85
CL-3	-20°F	84	.062	85
CL-4	-20°F	95	.070	90
CL-5	-20°F	95	.072	90
FL-1	-20°F	34	.026	20
FL-2	-20°F	29	.019	20
FL-3	-20°F	32	.023	20
FL-4	-20°F	35	.036	20
FL-5	-20°F	55	.047	30
FL1-1	-20°F	32	.031	20
FL1-2	-20°F	78	.067	50
FL1-3	-20°F	29	.025	20
FL1-4	-20°F	38	.032	20
FL1-5	-20°F	45	.039	30
FL3-1	-20°F	67	.060	40
FL3-2	-20°F	38	.026	20
FL3-3	-20°F	46	.038	40
FL3-4	-20°F	115	.088	60
FL3-5	-20°F	88	.074	50

CONTRACT NO.:	**5854**
TECH:	**Darren Begg/Kent Leclair**
SPECIMEN SIZE:	**10mm x 10mm**
DATE:	**March 14, 2006**
IDENTIFICATION:	**HSLA 100 (66/34, 1 pass per side)**
PLATE THICKNESS:	**1”**

SPECIMEN No.	TEMP.	FT. LBS	LAT. EXP	%SHEAR
CL-1	0°F	77	.052	70
CL-2	0°F	79	.052	70
CL-3	0°F	85	.054	70
CL-4	0°F	85	.056	70
CL-5	0°F	80	.055	70
FL-1	0°F	58	.041	40
FL-2	0°F	78	.056	50
FL-3	0°F	28	.021	10
FL-4	0°F	60	.050	40
FL-5	0°F	72	.048	45
FL1-1	0°F	68	.044	30
FL1-2	0°F	77	.047	30
FL1-3	0°F	112	.066	50
FL1-4	0°F	66	.042	25
FL1-5	0°F	70	.044	25
FL3-1	0°F	173	.086	100
FL3-2	0°F	170	.088	100
FL3-3	0°F	168	.090	100
FL3-4	0°F	185	.091	100
FL3-5	0°F	171	.089	100

CONTRACT NO.:	**5854**
TECH:	**Darren Begg/Kent Leclair**
SPECIMEN SIZE:	**10mm x 10mm**
DATE:	**March 14, 2006**
IDENTIFICATION:	**HSLA 100 (66/34, 1 pass per side)**
PLATE THICKNESS:	**1”**

SPECIMEN No.	TEMP.	FT. LBS	LAT. EXP	%SHEAR
CL-1	-60°F	50	.034	40
CL-2	-60°F	52	.034	40
CL-3	-60°F	42	.027	30
CL-4	-60°F	48	.034	30
CL-5	-60°F	50	.034	40
FL-1	-60°F	20	.015	20
FL-2	-60°F	25	.017	20
FL-3	-60°F	33	.022	20
FL-4	-60°F	52	.039	30
FL-5	-60°F	55	.039	40
FL1-1	-60°F	46	.032	30
FL1-2	-60°F	44	.031	30
FL1-3	-60°F	100	.063	50
FL1-4	-60°F	100	.068	50
FL1-5	-60°F	45	.032	30
FL3-1	-60°F	125	.080	70
FL3-2	-60°F	120	.077	70
FL3-3	-60°F	117	.077	65
FL3-4	-60°F	108	.073	60
FL3-5	-60°F	118	.078	60

CONTRACT NO.:	**5854**
TECH:	**Darren Begg/Kent Leclair**
SPECIMEN SIZE:	**10mm x 10mm**
DATE:	**March 14, 2006**
IDENTIFICATION:	**HSLA 100 (34/66, 1 Pass Per Side)**
PLATE THICKNESS:	**1"**

SPECIMEN No.	TEMP.	FT. LBS	LAT. EXP	%SHEAR
CL-1	0°F	75	.050	60
CL-2	0°F	78	.051	70
CL-3	0°F	65	.043	55
CL-4	0°F	72	.045	60
CL-5	0°F	78	.053	70
FL-1	0°F	75	.050	60
FL-2	0°F	88	.056	80
FL-3	0°F	75	.050	60
FL-4	0°F	74	.046	60
FL-5	0°F	94	.060	80

CONTRACT NO.:	**5854**
TECH:	**Darren Begg/Kent Leclair**
SPECIMEN SIZE:	**10mm x 10mm**
DATE:	**March 14, 2006**
IDENTIFICATION:	**HSLA 100 (34/66 – 1 Pass Per Side)**
PLATE THICKNESS:	**1”**

SPECIMEN No.	TEMP.	FT. LBS	LAT. EXP	%SHEAR
CL-1	-60°F	38	.024	20
CL-2	-60°F	46	.028	30
CL-3	-60°F	48	.030	30
CL-4	-60°F	47	.028	30
CL-5	-60°F	32	.015	10
FL-1	-60°F	55	.030	30
FL-2	-60°F	20	.014	10
FL-3	-60°F	57	.033	30
FL-4	-60°F	44	.027	20
FL-5	-60°F	54	.032	30
FL1-1	-60°F	86	.049	50
FL1-2	-60°F	48	.032	40
FL1-3	-60°F	115	.074	70
FL1-4	-60°F	32	.022	10
FL1-5	-60°F	38	.024	20

CONTRACT NO.:	**5854**
TECH:	**Darren Begg/Kent Leclair**
SPECIMEN SIZE:	**10mm x 10mm**
DATE:	**March 14, 2006**
IDENTIFICATION:	**HSLA 100 (OSW, 4 pass)**
PLATE THICKNESS:	**1”**

SPECIMEN No.	TEMP.	FT. LBS	LAT. EXP	%SHEAR
CL-1	0°F	85	.057	70
CL-2	0°F	77	.051	65
CL-3	0°F	78	.051	70
CL-4	0°F	75	.051	70
CL-5	0°F	68	.046	60
FL-1	0°F	75	.045	60
FL-2	0°F	60	.038	50
FL-3	0°F	57	.036	50
FL-4	0°F	74	.047	60
FL-5	0°F	72	.047	60

CONTRACT NO.:	**5854**
TECH:	**Darren Begg/Kent Leclair**
SPECIMEN SIZE:	**10mm x 10mm**
DATE:	**March 14, 2006**
IDENTIFICATION:	**HSLA 100 (OSW, 4 passes)**
PLATE THICKNESS:	**1”**

SPECIMEN No.	TEMP.	FT. LBS	LAT. EXP	%SHEAR
CL-1	-60°F	58	.037	50
CL-2	-60°F	27	.014	20
CL-3	-60°F	37	.021	30
CL-4	-60°F	48	.030	40
CL-5	-60°F	47	.028	40
FL-1	-60°F	42	.029	40
FL-2	-60°F	53	.036	40
FL-3	-60°F	45	.029	40
FL-4	-60°F	44	.030	40
FL-5	-60°F	75	.046	50
FL1-1	-60°F	85	.048	60
FL1-2	-60°F	68	.042	60
FL1-3	-60°F	70	.036	50
FL1-4	-60°F	85	.054	60
FL1-5	-60°F	57	.038	60

CONTRACT NO.:	**5854**
TECH:	**Darren Begg/Kent Leclair**
SPECIMEN SIZE:	**10mm x 10mm**
DATE:	**March 14, 2006**
IDENTIFICATION:	**HSLA 100 (1 pass per side)**
PLATE THICKNESS:	**1/2”**

SPECIMEN No.	TEMP.	FT. LBS	LAT. EXP	%SHEAR
CL-1	0°F	76	.052	70
CL-2	0°F	82	.057	90
CL-3	0°F	72	.050	85
CL-4	0°F	78	.050	85
CL-5	0°F	76	.051	85
FL-1	0°F	76	.046	80
FL-2	0°F	76	.050	80
FL-3	0°F	80	.053	80
FL-4	0°F	82	.052	80
FL-5	0°F	74	.051	80
FL1-1	0°F	65	.037	60
FL1-2	0°F	66	.047	60
FL1-3	0°F	55	.036	60
FL1-4	0°F	57	.039	60
FL1-5	0°F	55	.039	60
FL3-1	0°F	140	.087	90
FL3-2	0°F	117	.076	90
FL3-3	0°F	134	.081	90
FL3-4	0°F	118	.077	90
FL3-5	0°F	80	.060	90

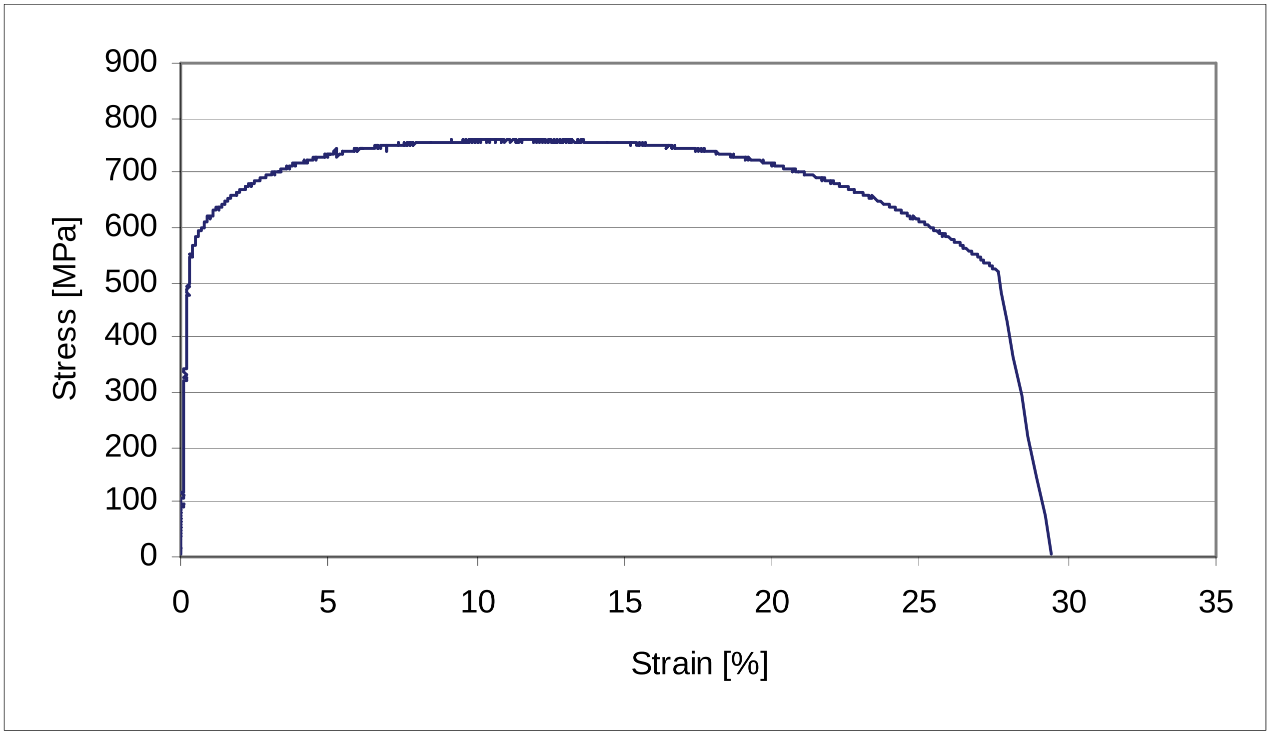
CONTRACT NO.:	**5854**
TECH:	**Darren Begg/Kent Leclair**
SPECIMEN SIZE:	**10mm x 10mm**
DATE:	**March 14, 2006**
IDENTIFICATION:	**HSLA 100 (1 pass per side)**
PLATE THICKNESS:	**1/2"**

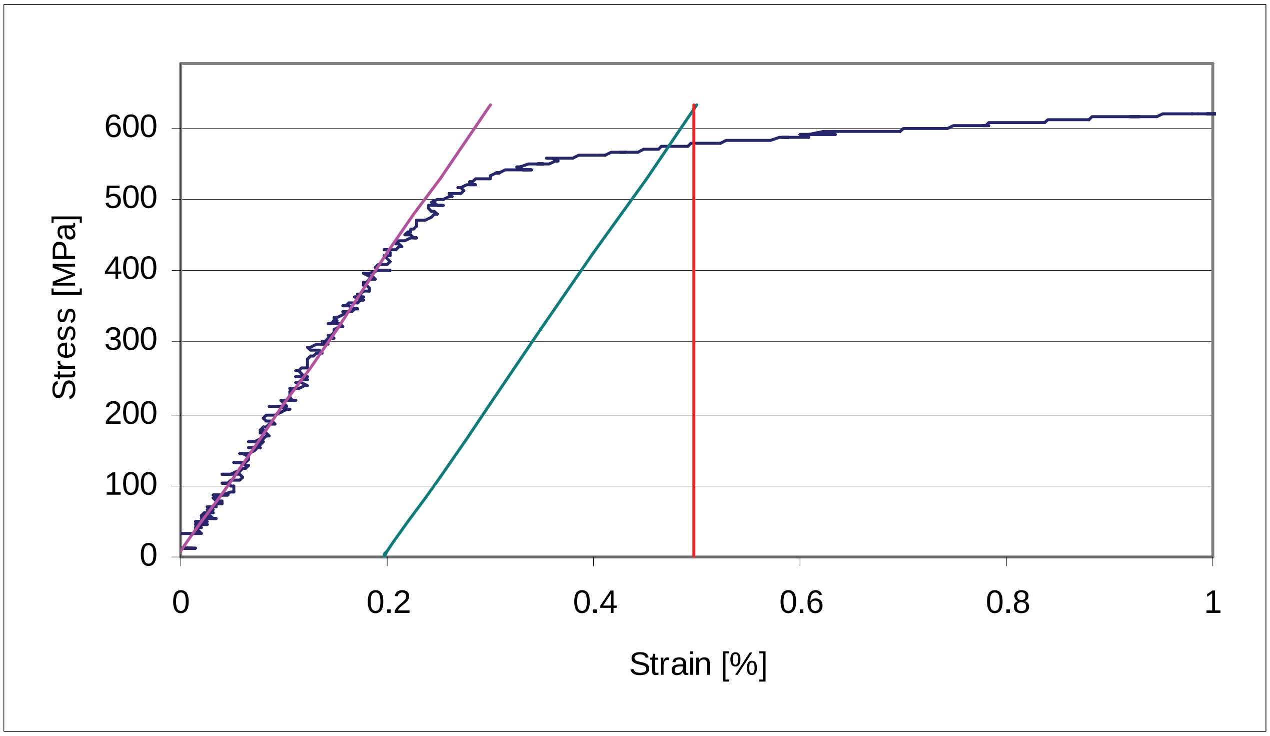
SPECIMEN No.	TEMP.	FT. LBS	LAT. EXP	%SHEAR
CL-1	-60°F	49	.035	50
CL-2	-60°F	53	.037	50
CL-3	-60°F	60	.046	55
CL-4	-60°F	52	.038	50
CL-5	-60°F	55	.036	50
FL-1	-60°F	44	.033	70
FL-2	-60°F	45	.035	70
FL-3	-60°F	41	.032	70
FL-4	-60°F	42	.035	70
FL-5	-60°F	62	.041	70
FL1-1	-60°F	34	.027	50
FL1-2	-60°F	34	.028	50
FL1-3	-60°F	27	.019	40
FL1-4	-60°F	35	.025	40
FL1-5	-60°F	40	.028	40
FL3-1	-60°F	28	.025	10
FL3-2	-60°F	22	.025	20
FL3-3	-60°F	29	.026	20
FL3-4	-60°F	42	.035	30
FL3-5	-60°F	38	.035	30

APPENDIX K

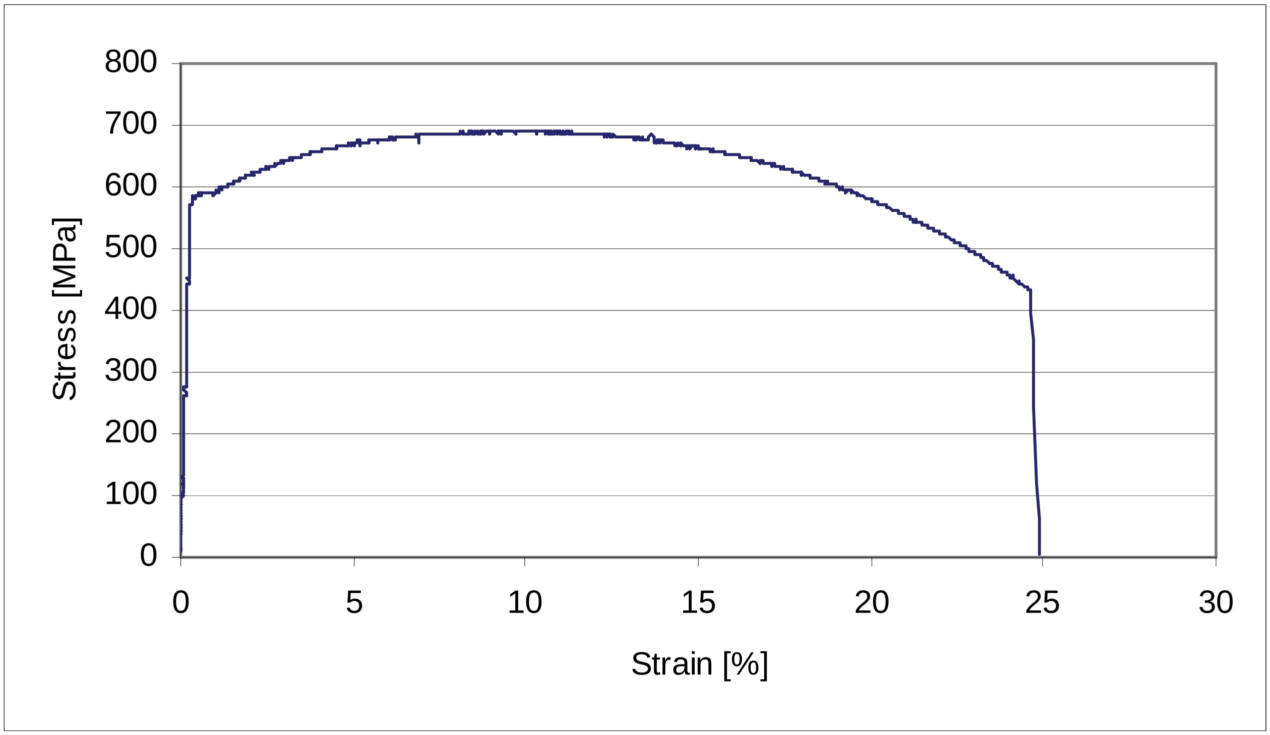
STRESS/STRAIN CURVES FOR ALL WELD METAL TENSILE TESTS FROM PROCEDURE QUALIFICATION TEST WELDS

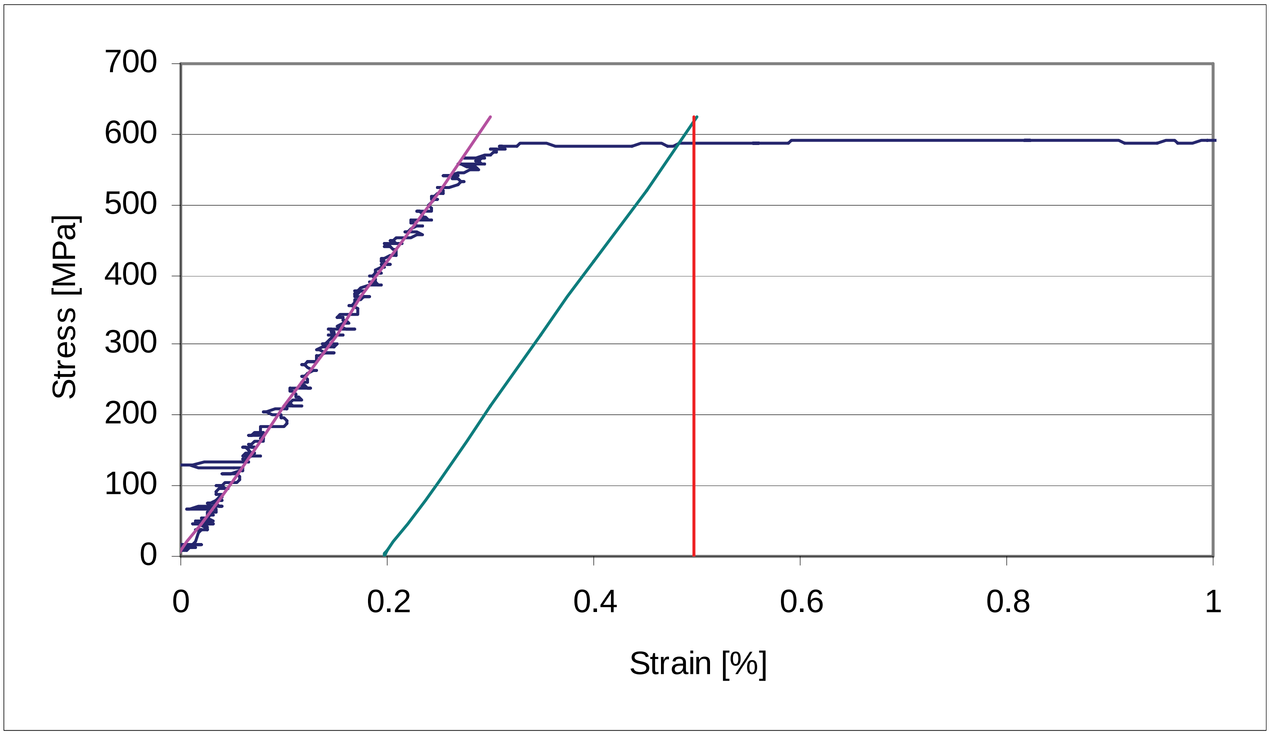
1" DH36 SINGLE PASS OSW



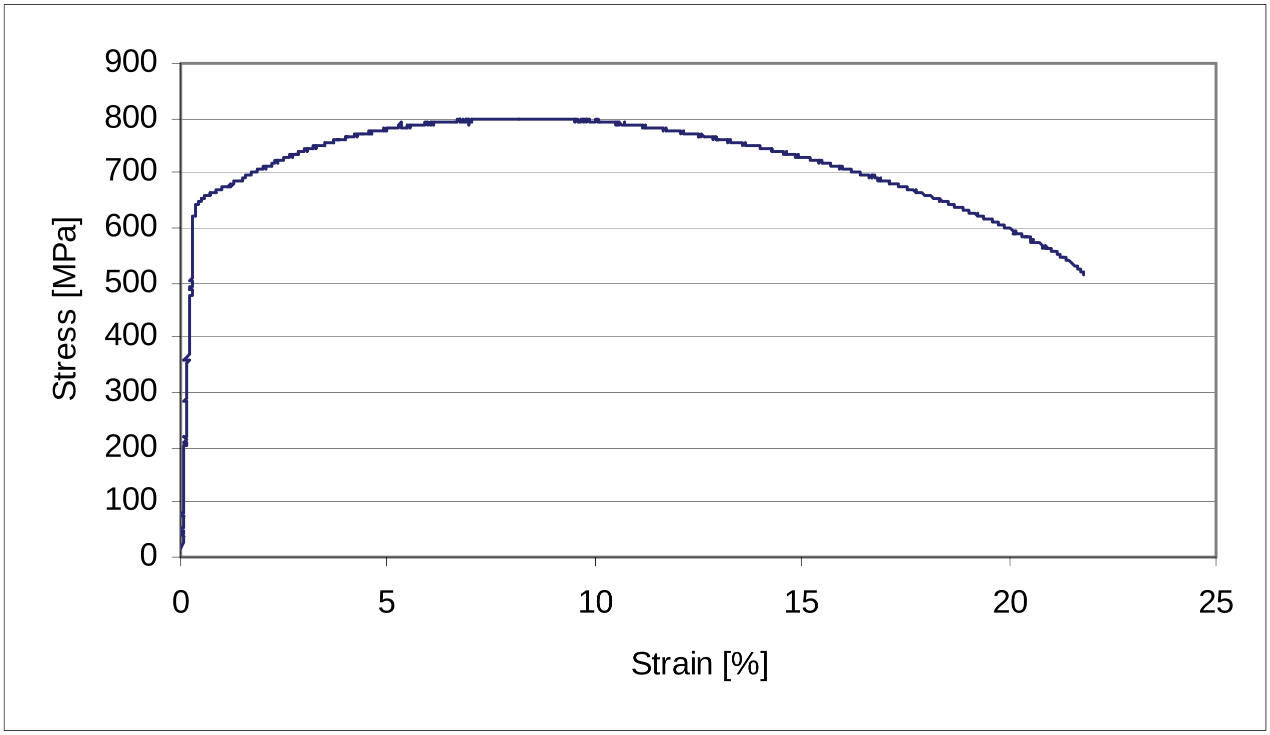


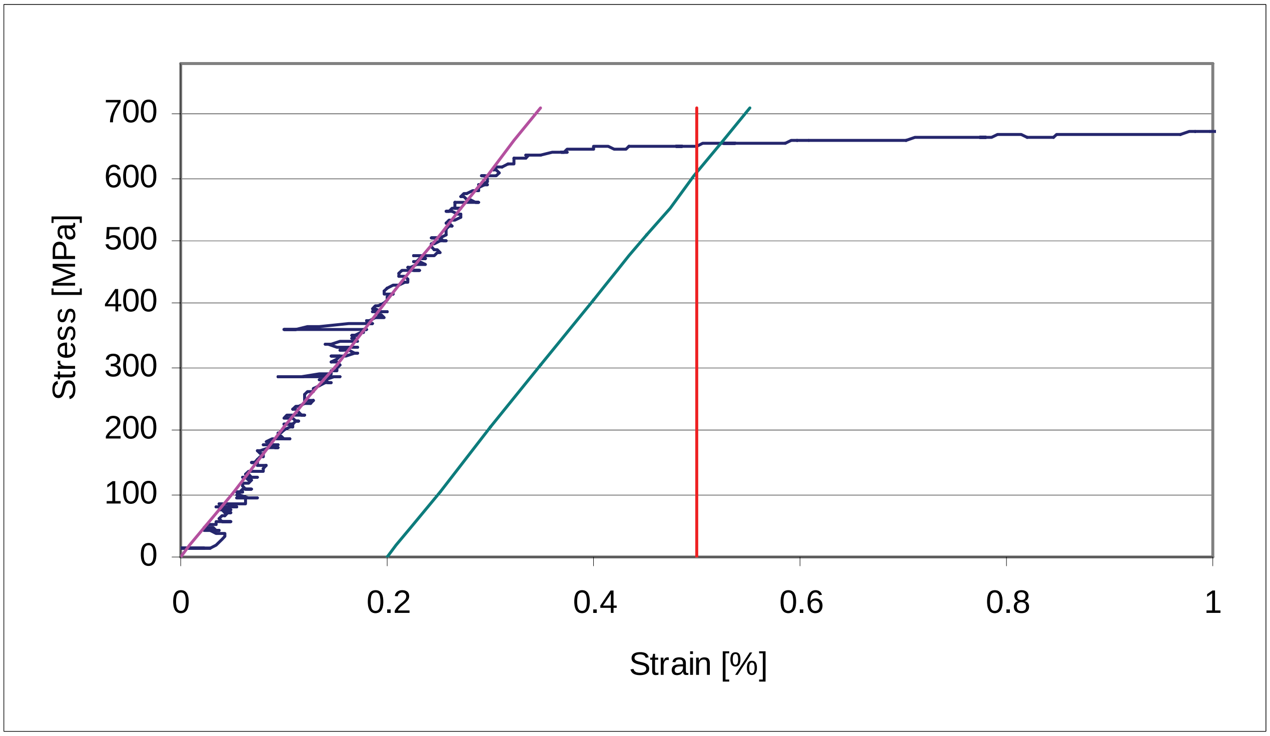
1" HSLA-65 SINGLE PASS OSW


Stress [MPa]
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
Strain [%]

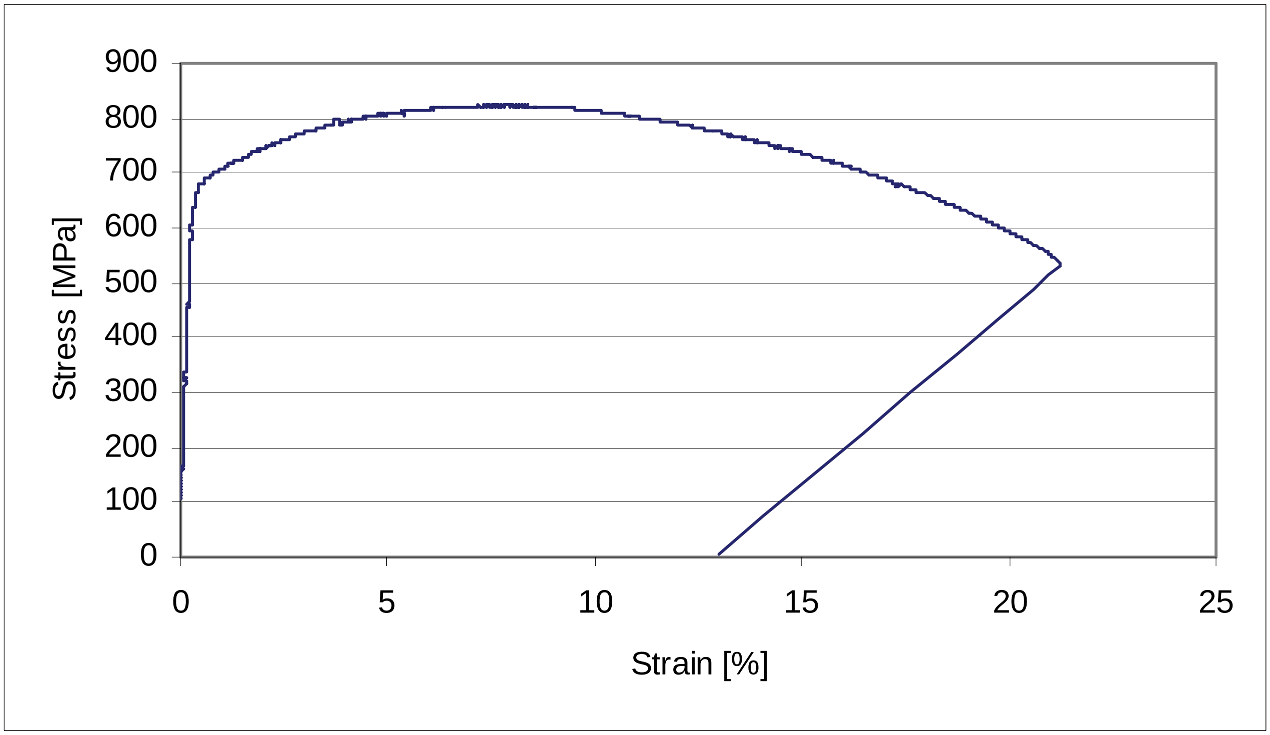

Stress [MPa]
700
600
500
400
300
200
100
0
0
0.2
0.4
0.6
0.8
1
Strain [%]

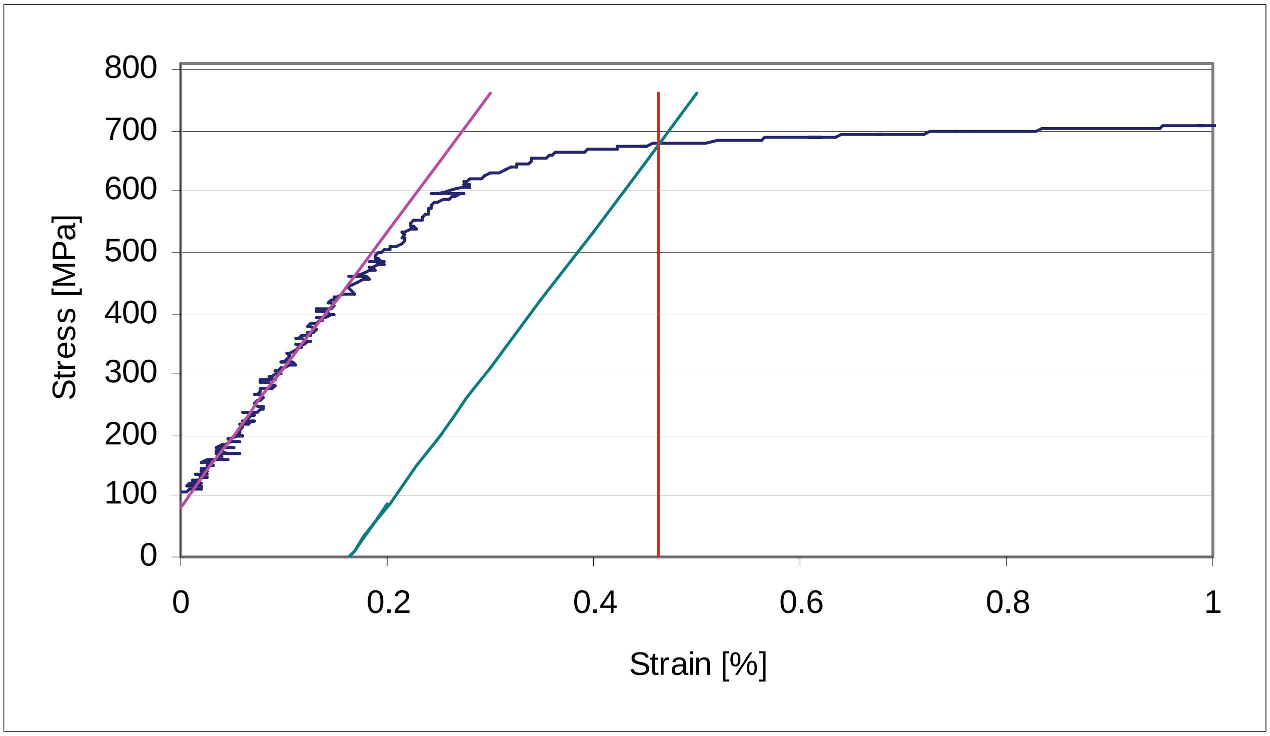
1" HSLA-100 ONE PASS PER SIDE (66/34)



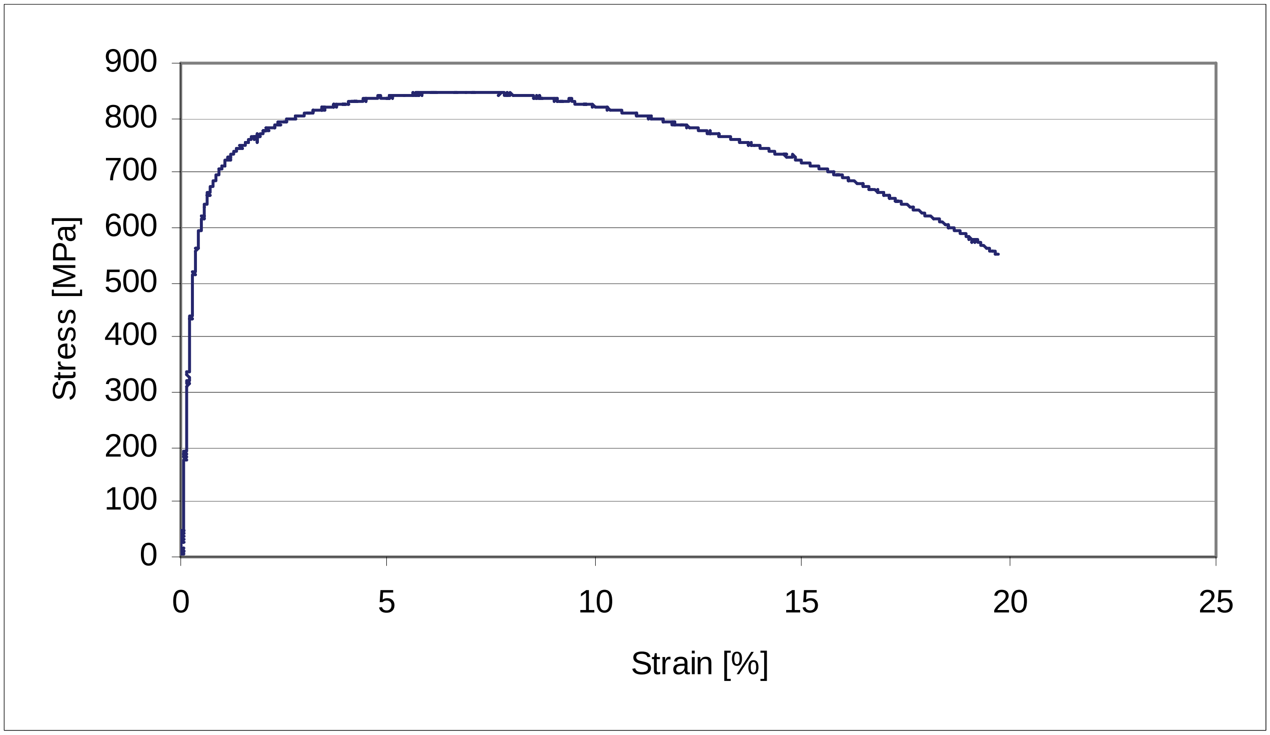


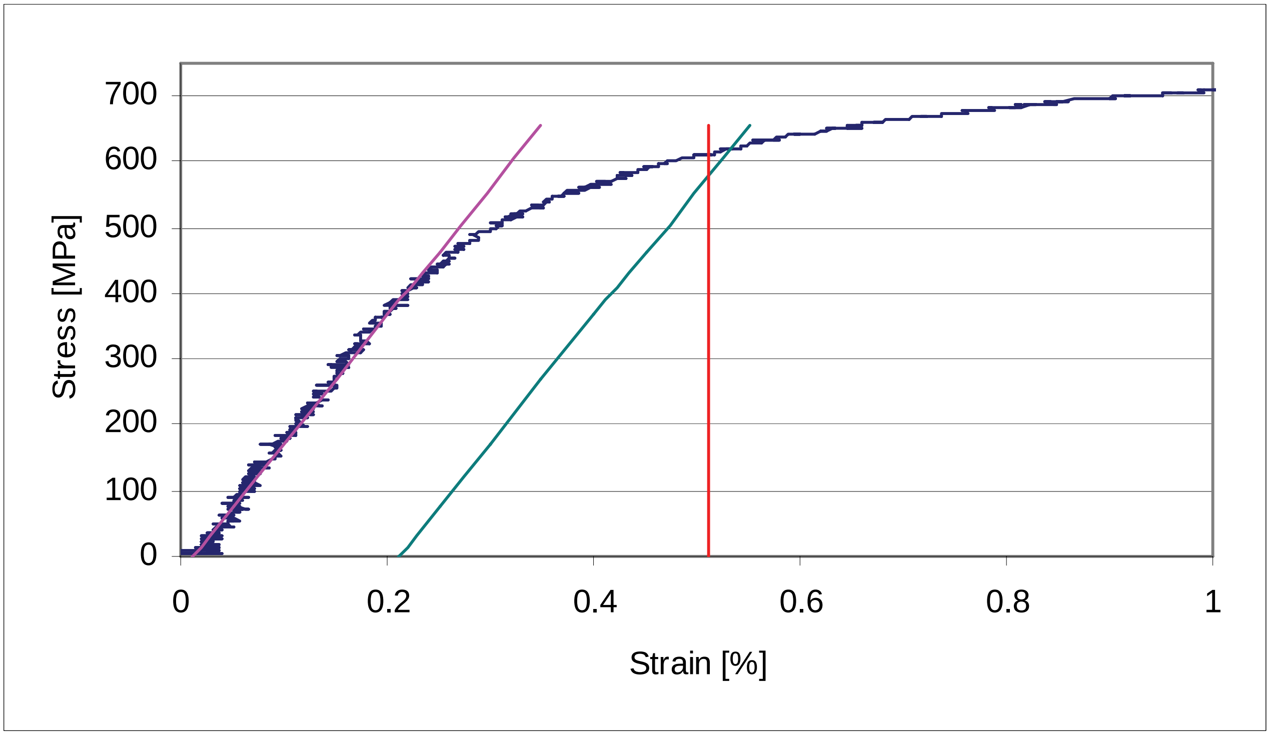
1” HSLA-100 ONE PASS PER SIDE (34/66)





1" HSLA-100 OSW – FOUR PASSES





APPENDIX L

HARDNESS RESULTS

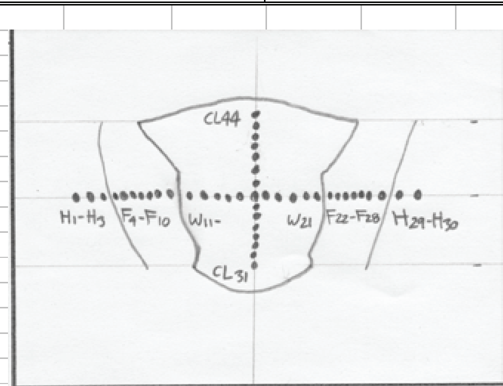
½" DH36 OSW

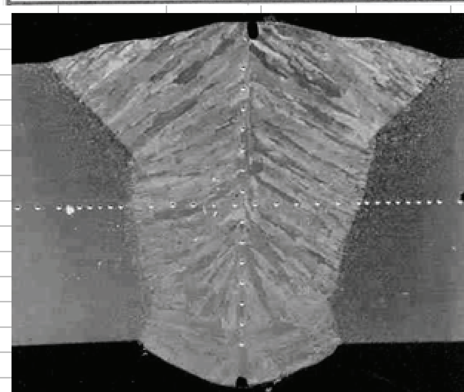
FLEET TECHNOLOGY LIMITED	HARDNESS TEST REPORT	Form F600-012B 0-040705

Procedure:	Vickers 5 kg load	**Applicable Standard:**	ASTM E92
Date:	8-Mar-06	**Technician:**	KL
Report Number:	5854	**Checked by:**	NP

Hardness Tests on Base Metal			**Load 5 (kg)**		
DH 36			DH 36		
Location	cular Readin	Hardness		cular Readin	Hardness
H1	241	160	CL31	212	206
H2	239	162	CL32	210	210
H3	237	165	CL33	210	210
F4	223	186	CL34	208	214
F5	222	188	CL35	210	210
F6	224	185	CL36	210	210
F7	220	192	CL37	211	208
F8	223	186	CL38	210	210
F9	223	186	CL39	209	212
F10	221	190	CL40	210	210
W11	211	208	CL41	210	210
W12	209	212	CL42	210	210
W13	211	208	CL43	210	210
W14	211	208	CL44	210	210
W15	208	214			
W16	208	214			
W17	208	214			
W18	208	214			
W19	208	214			
W20	208	214			
W21	210	210			
F22	218	195			
F23	222	188			
F24	225	183			
F25	221	190			
F26	225	183			
F27	224	185			
F28	224	185			
H29	230	175			
H30	239	162			
Average H		165	Average CL		210
Average F		187			
Average W		212			
Average B					

Macrophoto





	ACCEPT
	REJECT

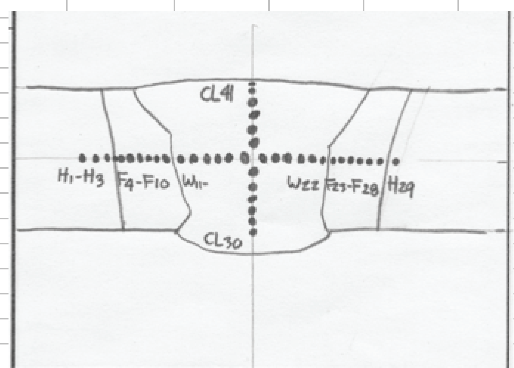
½” HSLA-65L OSW

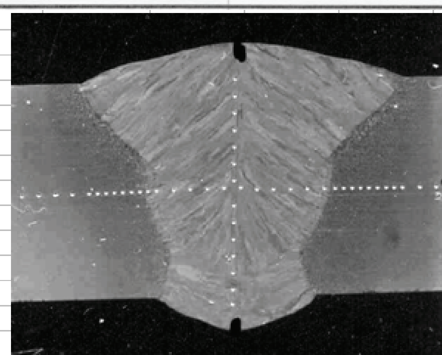
FLEET TECHNOLOGY LIMITED	HARDNESS TEST REPORT	Form F600-012B 0-040705

Procedure:	Vickers 5 kg load	**Applicable Standard:**	ASTM E92
Date:	8-Mar-06	**Technician:**	KL
Report Number:	5854	**Checked by:**	NP

Hardness Tests on Base Metal			Load 5 (kg)		
HSLA 65L - 1/2"			HSLA 65L - 1/2"		
Location	Ocular Readin	Hardness		Ocular Readin	Hardness
H1	231	174	CL30	201	229
H2	231	174	CL31	200	232
H3	226	182	CL32	201	229
F4	219	193	CL33	201	229
F5	217	197	CL34	200	232
F6	216	199	CL35	200	232
F7	216	199	CL36	201	229
F8	214	202	CL37	203	225
F9	214	202	CL38	203	225
F10	214	202	CL39	203	225
W11	203	225	CL40	205	221
W12	201	229	CL41	203	225
W13	201	229			
W14	201	229			
W15	201	229			
W16	204	223			
W17	202	227			
W18	201	229			
W19	203	225			
W20	202	227			
W21	203	225			
W22	206	218			
F23	216	199			
F24	216	199			
F25	218	195			
F26	218	195			
F27	218	195			
F28	216	199			
H29	220	192			
Average H		180	Average CL		228
Average F		198			
Average W		227			
Average B					

Macrophoto





	ACCEPT
	REJECT

1" DH36 - OSW

FLEET TECHNOLOGY LIMITED

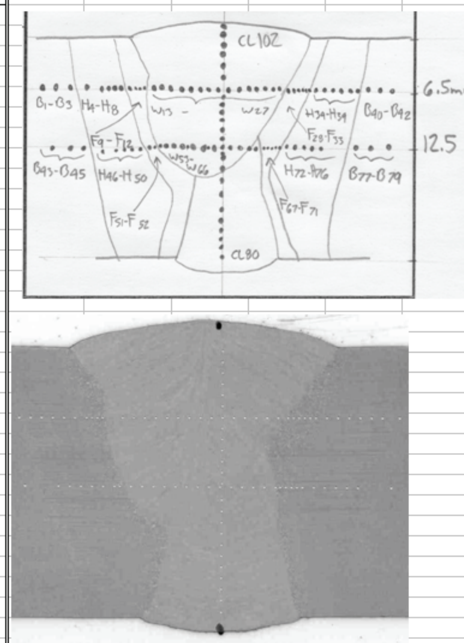
HARDNESS TEST REPORT

Form F600-012B
0-040705

Procedure:	Vickers 5 kg load	**Applicable Standard:**	ASTM E92
Date:	03/010/2006	**Technician:**	KL
Report Number:	5854	**Checked by:**	NP

Hardness Tests on Base Metal			Load 5 (kg)					
DH 36 @ 6.5mm			DH 36 @12.5mm and CL					
Location	cular Readin	Hardness	Location	cular Readin	Hardness	Location	ccular Readir	Hardness
B1	233	171	B43	233	171	CL80	202	227
B2	238	164	B44	235	168	CL81	202	227
B3	239	162	B45	241	160	CL82	202	227
H4	232	172	H46	222	188	CL83	199	234
H5	226	182	H47	220	192	CL84	202	227
H6	225	183	H48	221	190	CL85	200	232
H7	224	185	H49	213	204	CL86	201	229
H8	224	185	F50	208	214	CL87	201	229
F9	211	208	F51	204	223	CL88	201	229
F10	208	214	F52	204	223	CL89	198	237
F11	208	214	W53	203	225	CL90	203	225
F12	208	214	W54	199	234	CL91	203	225
W13	204	223	W55	201	229	CL92	201	229
W14	206	218	W56	200	232	CL93	202	227
W15	206	218	W57	201	229	CL94	203	225
W16	201	229	W58	201	229	CL95	203	225
W17	203	225	W59	202	227	CL96	200	232
W18	204	223	W60	201	229	CL97	204	223
W19	204	223	W61	199	234	CL98	205	221
W20	202	227	W62	201	229	CL99	206	218
W21	202	227	W63	204	223	CL100	206	218
W22	200	232	W64	202	227	CL101	203	225
W23	202	227	W65	201	229	CL102	199	234
W24	202	227	W66	209	212			
W25	202	227	F67	210	210			
W26	201	229	F68	209	212			
W27	200	232	F69	214	202			
F28	213	204	F70	212	206			
F29	206	218	F71	211	208			
F30	210	210	H72	218	195			
F31	206	218	H73	225	183			
F32	206	218	H74	228	178			
F33	209	212	H75	225	183			
H34	214	202	H76	227	180			
H35	222	188	B77	241	160			
H36	222	188	B78	236	166			
H37	224	185	B79	230	175			
H38	224	185						
H39	228	178						
B40	234	169						
B41	235	168						
B42	240	161						
Average H		185	Average H		188	Average CL		227
Average F		214	Average F		212			
Average W		226	Average W		228			
Average B		166	Average B		167			

Macrophoto



	ACCEPT
	REJECT

1” HSLA-65L - OSW

FLEET TECHNOLOGY LIMITED

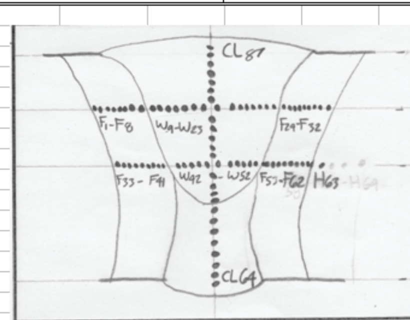
HARDNESS TEST REPORT

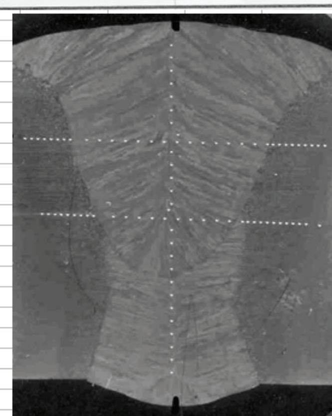
Form F600-012B
0-040705

Procedure:	Vickers 5 kg load	**Applicable Standard:**	ASTM E92
Date:	03/017/2006	**Technician:**	KL
Report Number:	5854	**Checked by:**	NP

Hardness Tests on Base Metal				**Load 5 (kg)**				
HSLA 65L @ 6.5mm			HSLA 65L @12.5mm and CL					
Location	ocular Readin	Hardness	Location	ocular Readin	Hardness	Location	ccular Readir	Hardness
F1	223	186	F33	213	204	CL64	202	227
F2	221	190	F34	209	212	CL65	203	225
F3	220	192	F35	205	221	CL66	202	227
F4	220	192	F36	205	221	CL67	202	227
F5	216	199	F37	210	210	CL68	202	227
F6	212	206	F38	207	216	CL69	203	225
F7	213	204	F39	211	208	CL70	201	229
F8	209	212	F40	211	208	CL71	198	237
W9	201	229	F41	211	208	CL72	199	234
W10	204	223	W42	206	218	CL73	201	229
W11	203	225	W43	204	223	CL74	201	229
W12	203	225	W44	203	225	CL75	196	241
W13	200	232	W45	203	225	CL76	201	229
W14	201	229	W46	202	227	CL77	199	234
W15	201	229	W47	201	229	CL78	203	225
W16	200	232	W48	202	227	CL79	203	225
W17	202	227	W49	202	227	CL80	202	227
W18	202	227	W50	203	225	CL81	204	223
W19	203	225	W51	201	229	CL82	204	223
W20	204	223	W52	204	223	CL83	202	227
W21	204	223	F53	213	204	CL84	202	227
W22	203	225	F54	214	202	CL85	203	225
W23	203	225	F55	215	201	CL86	202	227
F24	214	202	F56	214	202	CL87	201	229
F25	213	204	F57	216	199			
F26	219	193	F58	217	197			
F27	217	197	F59	216	199			
F28	216	199	F60	219	193			
F29	218	195	F61	220	192			
F30	217	197	F62	224	185			
F31	219	193	H63	232	172			
F32	221	190						
Average H			Average H		172	Average CL		228
Average F		197	Average F		204			
Average W		227	Average W		225			
Average B			Average B					

Macrophoto





	ACCEPT
	REJECT

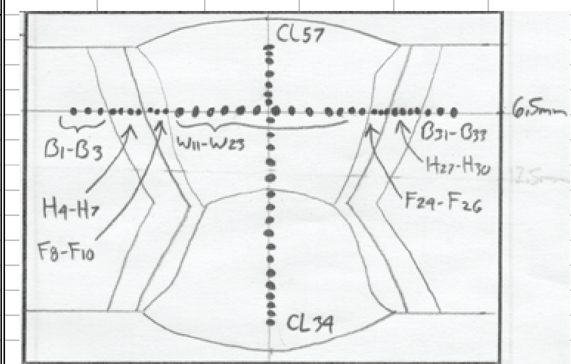
1" HSLA-100, ONE PASS PER SIDE WELD (66/34)

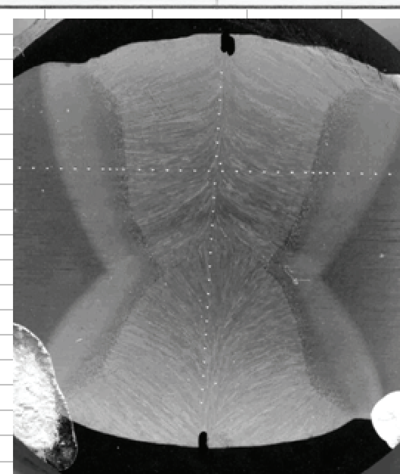
FLEET TECHNOLOGY LIMITED	HARDNESS TEST REPORT	Form F600-012B 0-040705

Procedure:	Vickers 5 kg load	**Applicable Standard:**	ASTM E92
Date:	8-Mar-06	**Technician:**	KL
Report Number:	5854	**Checked by:**	NP

Hardness Tests on Base Metal			Load 5 (kg)		
HSLA 100 1 Pass / Side 66/34			HSLA 100 1 Pass / Side 66/34		
Location	Ocular Readin	Hardness		Ocular Readin	Hardness
B1	186	268	CL34	189	260
B2	186	268	CL35	189	260
B3	184	274	CL36	188	262
H4	192	252	CL37	189	260
H5	196	241	CL38	191	254
H6	196	241	CL39	189	260
H7	186	268	CL40	189	260
F8	181	283	CL41	197	239
F9	179	289	CL42	195	244
F10	184	274	CL43	195	244
W11	192	252	CL44	190	257
W12	192	252	CL45	191	254
W13	205	221	CL46	189	260
W14	192	252	CL47	188	262
W15	191	254	CL48	188	262
W16	192	252	CL49	187	265
W17	193	249	CL50	187	265
W18	194	246	CL51	200	232
W19	193	249	CL52	193	249
W20	191	254	CL53	191	254
W21	191	254	CL54	191	254
W22	222	188	CL55	192	252
W23	194	246	CL56	191	254
F24	187	265	CL57	198	237
F25	190	257			
F26	188	262			
H27	194	246			
H28	192	252			
H29	191	254			
H30	192	252			
B31	194	246			
B32	187	265			
B33	200	232			
Average H		251	Average CL		254
Average F		272			
Average W		244			
Average B		259			

Macrophoto





	ACCEPT
	REJECT

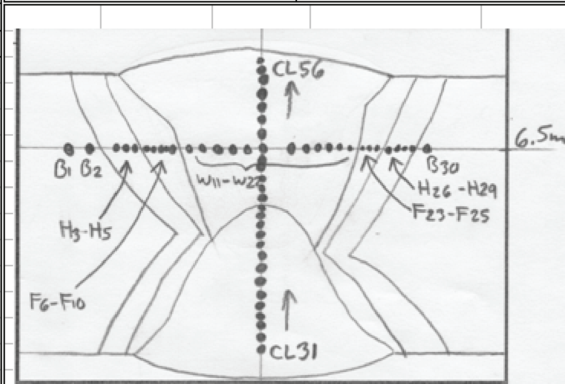
1" HSLA-100 ONE PASS PER SIDE (34/66)

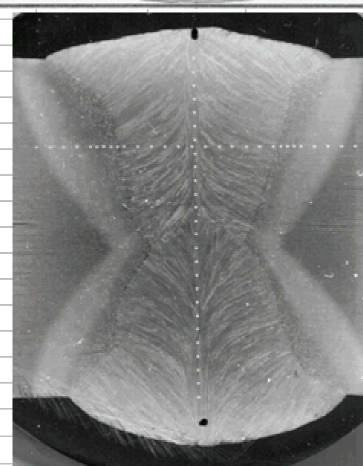
FLEET TECHNOLOGY LIMITED	HARDNESS TEST REPORT	Form F600-012B 0-040705

Procedure:	Vickers 5 kg load	**Applicable Standard:**	ASTM E92
Date:	8-Mar-06	**Technician:**	KL
Report Number:	5854	**Checked by:**	NP

Hardness Tests on Base Metal			**Load 5 (kg)**		
HSLA 100 34/66			HSLA 100 34/66		
Location	cular Readin	Hardness		cular Readin	Hardness
B1	177	296	CL31	187	265
B2	188	262	CL32	186	268
H3	189	260	CL33	188	262
H4	189	260	CL34	191	254
H5	191	254	CL35	186	268
F6	179	289	CL36	184	274
F7	174	306	CL37	187	265
F8	179	289	CL38	186	268
F9	179	289	CL39	185	271
F10	187	265	CL40	185	271
W11	186	268	CL41	183	277
W12	186	268	CL42	185	271
W13	186	268	CL43	188	262
W14	186	268	CL44	184	274
W15	188	262	CL45	182	280
W16	187	265	CL46	186	268
W17	187	265	CL47	185	271
W18	190	257	CL48	183	277
W19	187	265	CL49	183	277
W20	187	265	CL50	188	262
W21	186	268	CL51	184	274
W22	186	268	CL52	183	277
F23	180	286	CL53	185	271
F24	182	280	CL54	184	274
F25	175	303	CL55	178	293
H26	181	283	CL56	177	296
H27	181	283			
H28	179	289			
H29	177	296			
B30	181	283			
Average H		275	Average CL		272
Average F		289			
Average W		266			
Average B		280			

Macrophoto





ACCEPT
REJECT

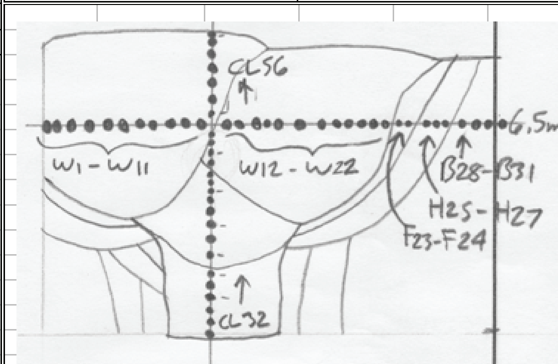
1” HSLA-100 OSW – FOUR PASSES

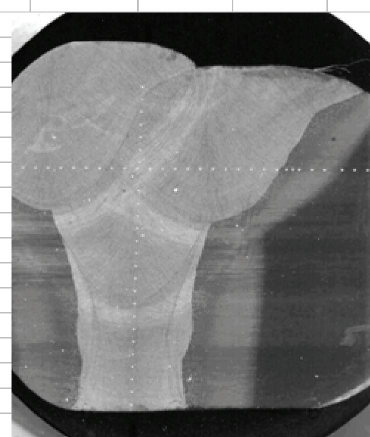
FLEET TECHNOLOGY LIMITED	HARDNESS TEST REPORT	Form F600-012B 0-040705

Procedure:	Vickers 5 kg load	**Applicable Standard:**	ASTM E92
Date:	8-Mar-06	**Technician:**	KL
Report Number:	5854	**Checked by:**	NP

Hardness Tests on Base Metal			**Load 5 (kg)**		
HSLA-100 OSW - 4 PASS			HSLA-100 OSW - 4 PASS		
Location	Ocular Readin	Hardness		Ocular Readin	Hardness
W1	171	317			
W2	174	306	CL32	182	280
W3	175	303	CL33	182	280
W4	180	286	CL34	182	280
W5	180	286	CL35	182	280
W6	181	283	CL36	181	283
W7	181	283	CL37	181	283
W8	181	283	CL38	180	286
W9	180	286	CL39	180	286
W10	177	296	CL40	180	286
W11	179	289	CL41	180	286
W12	179	289	CL42	179	289
W13	171	317	CL43	183	277
W14	171	317	CL44	182	280
W15	175	303	CL45	180	286
W16	174	306	CL46	171	317
W17	181	283	CL47	175	303
W18	181	283	CL48	175	303
W19	184	274	CL49	175	303
W20	182	280	CL50	182	280
W21	182	280	CL51	182	280
W22	183	277	CL52	184	274
F23	183	277	CL53	180	286
F24	181	283	CL54	178	293
H25	189	260	CL55	187	265
H26	194	246	CL56	181	283
H27	192	252			
B28	189	260			
B29	181	283			
B30	176	299			
B31	177	296			
Average H		252	Average CL		286
Average F		280			
Average W		292			
Average B		284			

Macrophoto





	ACCEPT
	REJECT

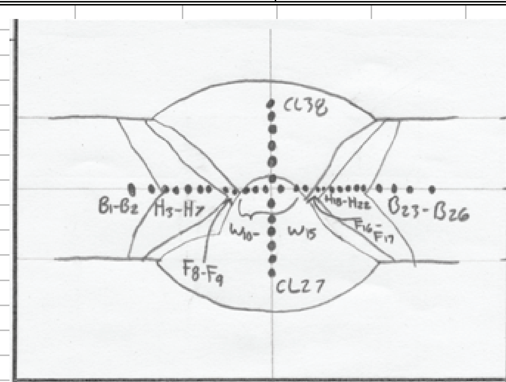
½" HSLA-100 ONE PASS PER SIDE

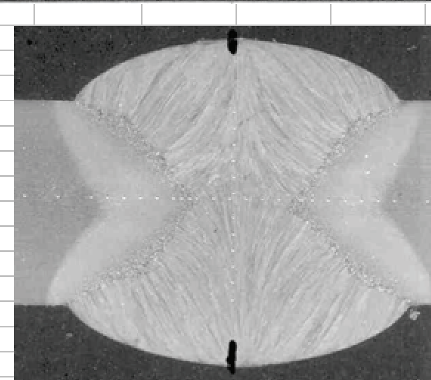
FLEET TECHNOLOGY LIMITED	HARDNESS TEST REPORT	Form F600-012B 0-040705

Procedure:	Vickers 5 kg load	**Applicable Standard:**	ASTM E92
Date:	8-Mar-06	**Technician:**	KL
Report Number:	5854	**Checked by:**	NP

Hardness Tests on Base Metal			Load 5 (kg)		
HSLA 1/2"			HSLA 1/2"		
Location	Ocular Readin	Hardness		Ocular Readin	Hardness
B1	189	260	CL27	188	262
B2	189	260	CL28	188	262
H3	193	249	CL29	188	262
H4	191	254	CL30	190	257
H5	189	260	CL31	188	262
H6	195	244	CL32	188	262
H7	197	239	CL33	187	265
F8	196	241	CL34	187	265
F9	191	254	CL35	183	277
W10	190	257	CL36	182	280
W11	188	262	CL37	182	280
W12	187	265	CL38	182	280
W13	187	265			
W14	187	265			
W15	191	254			
F16	194	246			
F17	195	244			
H18	199	234			
H19	204	223			
H20	203	225			
H21	202	227			
H22	198	237			
B23	191	254			
B24	191	254			
B25	191	254			
B26	191	254			
Average H		239	Average CL		268
Average F		246			
Average W		261			
Average B		256			

Macrophoto





	ACCEPT
	REJECT

APPENDIX M

SP-7 WELDING TECHNOLOGY PANEL PRESENTATION

Results Presentation

NSRP SP-7 Welding Panel Meeting

Provo, Utah, April 5, 2006

Evaluation of Variable Balance AC Submerged Arc Welding and Metal Cored Electrode Technology for Panel Welding

NSRP / ASE Project 2005-386

BMT Fleet Technology Limited 1

Results Presentation

PROJECT TEAM

BMT Fleet Technology Limited - Lead

Northrop Grumman Ship Systems – Lee Kvidahl

Naval Surface Warfare Center, Carderock Division – Johnnie DeLoach

Miller Electric – Ken Fisher, Ed Overshiner

Hobart Brothers – Steve Barhorst, Fuhu Chen

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Results Presentation

- OUTLINE
  - Background
  - Objectives
  - VBAC
  - Task 1 – Summarize Current One-sided Welding (OSW) Practice for Submerged Arc Welding (SAW) of DH36, HSLA-65, and HSLA-100 Steels
  - Task 2 – Develop Metal Cored Electrode Chemistries for High Heat Input Welding of DH36, HSLA-65, and HSLA-100 Steels
  - Task 3 – Develop and Qualify Tandem Welding Procedures using Variable Balance AC (VBAC) SAW and Metal Cored Electrodes
  - Comparison of Results to Current Practice
  - Potential Consumable and Labor Cost Savings
  - Conclusions
  - Recommendations for Further Work
  - Questions?

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Results Presentation

- BACKGROUND
  - High strength steels such as HSLA-65 and HSLA-100 were produced to optimize the weight of Naval platforms as well as reduce the steel and fabrication costs.
  - Distortion is one of the more major issues being addressed for thin plate (<3/8”). Foreseen cost savings have been offset by considerable rework / fit-up efforts.
  - Other Issues??? Productivity is limited when welding HSLA-100 due to a heat input restriction of 85kJ/in for ½” and greater thickness.
    - Restriction ensures that minimum specified weld metal yield strength (88 < 102ksi for under matching) is achieved when welding with MIL100S-1/S-2 type electrodes.
    - CG-HAZ impact properties can be problematic when welding HSLA-100 in the “lean” range of composition.
  - HSLA-65 CG-HAZ impact toughness requirements can be difficult to achieve consistently with high heat input procedures.

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Results Presentation

- OBJECTIVES
  - Develop metal cored electrode chemistries that will retain minimum specified weld metal mechanical properties at high heat inputs.
    - Be used with off-the-shelf highly basic fluxes.
  - Develop highly productive tandem SAW procedures for panel welding using VBAC technology and metal cored electrodes.
    - Single pass OSW of ½" and 1" DH36
    - Single pass OSW of ½" and 1" HSLA-65
    - Multi-pass OSW of 1" HSLA-100
    - Two sided welding of ½" and 1" HSLA-100, 1 pass per side, with no back gouging
  - Determine if VBAC procedures will allow for the HSLA-100 heat input restriction to be expanded past 85kJ/in for higher productivity welding.

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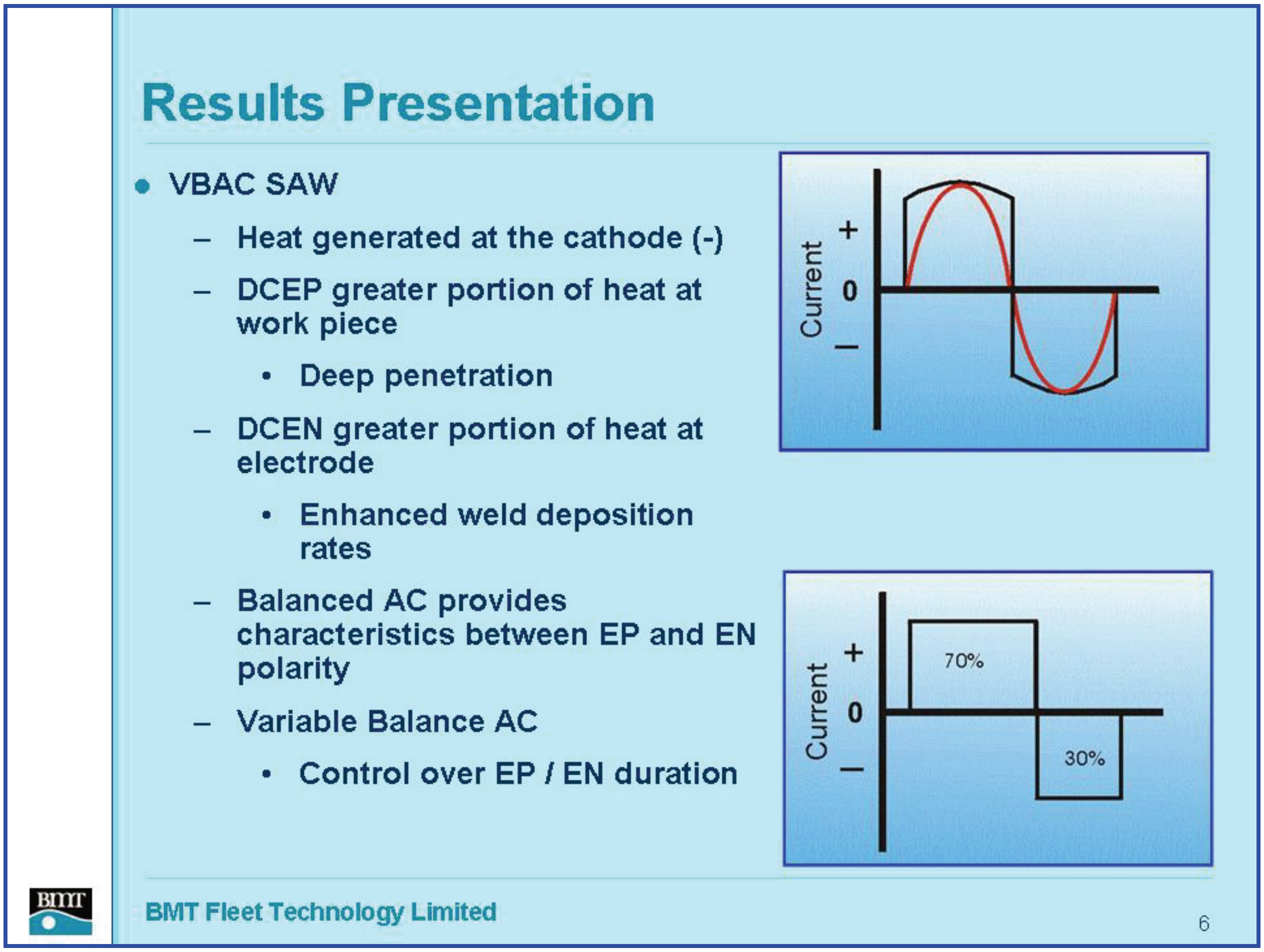
Results Presentation
VBAC SAW
– Heat generated at the cathode (-)
– DCEP greater portion of heat at work piece
• Deep penetration
– DCEN greater portion of heat at electrode
• Enhanced weld deposition rates
– Balanced AC provides characteristics between EP and EN polarity
– Variable Balance AC
• Control over EP / EN duration
Current
+
0
–
Current
+
0
–
70%
30%
BMT Fleet Technology Limited
6

Results Presentation

- Task 1 – Summarize Current Practice for Panel Welding
- DH36 Welding at NGSS
  - Series Arc Sine Wave AC onto a Flux Copper Backing (FCB)
  - 3/16" Lead and 1/8" Trail Lincoln L-61 Electrodes (AWS EM12K)
  - Lincoln 780 Flux for both backing and welding

Plate Thickness	Joint Preparation Details			Pass (#)	WFS (ipm)	Amps (A)	Volts (V)	Travel Speed (ipm)	Heat Input (kJ/in)	"Arc Time" (min/ft of joint) *
	Included Angle	Root Face	Root Opening							
½"	Square Groove	N.A.	¼"	1	60 Series Arc	780	41	12	160	1
1"	Single-V 45°	¼"	5/32"	1	60 Series Arc	780	41	12	160	4.4
				2 to 5	N.A. Single Arc	650	32	14	89	

** Arc time per foot of joint doesn't consider interpass operations*

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Results Presentation

- Task 1 – Summarize Current Practice for Panel Welding, cont.
- HSLA-65
  - Tandem Arc onto a Flux Copper Backing (FCB)
  - 5/32" DC+ Lead and AC Trail, MIL-100S-1 w/ Lincoln MIL800-H flux (Nittetsu NSH-1R backing flux) – Spaced at 5.5"

Plate Thickness	Joint Preparation Details			Pass (#)	WFS (ipm)	Amps (A)	Volts (V)	Travel Speed (ipm)	Total Heat Input (kJ/in)	"Arc Time" (min/ft of joint) *
	Included Angle	Root Face	Root Opening							
½"	Single-V 45°	3/32"	0"	1	N.A.	L-875	29	27.5	94.3	0.44
					N.A.	T-525	34			
1"	Single-V 45°	5/32"	0"	1	N.A.	L-1050	29	23.5	160.5	1.3
					N.A.	T-900	36			
				2	N.A.	825	34	15.5	108.6	

** Arc time per foot of joint doesn't consider interpass operations*

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Results Presentation

- Task 1 – Summarize Current Practice for Panel Welding, cont.
- HSLA-100
  - Single Arc DC+, 1/8" MIL-100S-1/S-2 w/ MIL-800H flux
  - Heat input restricted to 85 kJ/in
  - Back gouging to sound weld metal prior to completing second side

Plate Thickness	Joint Preparation Details			Pass (#)	WFS (ipm)	Amps (A)	Volts (V)	Travel Speed (ipm)	Heat Input (kJ/in)	"Arc Time" (min/ft of joint) *
	Included Angle	Root Face	Root Opening							
½"	Square Groove	N.A.	N.A.	1	N.A.	650	30	14	83.5	1.7
				2	N.A.	650	30	14	83.5	
1"	Double-V 60°	5/16"	0"	1-4	N.A.	650	30	14	83.5	6.8
				5-8	N.A.	650	30	14	83.5	

** Arc time per foot of joint doesn't include interpass operations*

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Results Presentation

- Task 2 – Metal Cored Electrode Development

  – DH36 Targets – Modified AWS EC1 Classification
    - Min. 58ksi YS, 71 to 95ksi UTS, and 20% Elongation
    - Impacts of 20ft-lbs @ -20F

  – HSLA-65 Targets – MIL-100S-1C per MIL-E-23765/2E
    - Min. 65ksi YS, 20% Elongation
    - Impacts of 30 ft-lbs @ -20F

  – HSLA-100 Targets – MIL-100S-1C per MIL-E-23765/2E
    - 88 to < 102ksi YS (under matching applications) and 18% Elongation
    - Impacts of 35 ft-lbs at -60F

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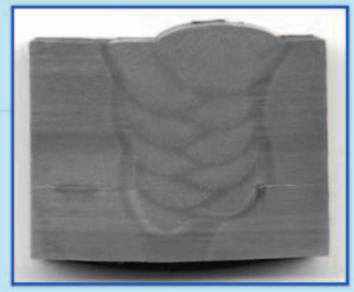
Results Presentation



- Task 2 – Metal Cored Electrode Development
  - Welding Parameters:
    - Standard AWS A5.XX Test
    - 575A, 30V, 18 ipm TS, Heat Input 57.5 kJ/in
    - 2 passes per layer, 5 layers
    - Each test plate made from same 1" thick DH36, HSLA-65, and HSLA-100 base metal used for procedure qualifications
  - Mechanical Testing
    - All weld metal tensile and impact specimens extracted from the T/2 position along the weld centerline
  - Deposited Chemical Analysis
    - Sample extracted from fractured tensile specimens

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Results Presentation

Specimen	Diameter (in.)	Area (in^2)	Yield Load (lbs)	Yield Strength (psi)	Minimum YS Requirement (psi)	Maximum Load (lbs)	Ultimate Tensile Strength (psi)	UTS Requirement (psi)	Elongation (%)	Elongation Requirement (%)
DH36-2 OK 10.62	.502	.198	17,958	90,698	58,000	19,850	100,253	71,000 to 95,000	27	20
HSLA-65-2 MIL800-H	.479	.180	18,000	100,000	65,000	20,790	115,500	NA	21	20
HSLA-100-3 MIL800-H	.502	.198	21,050	106,312	88,000 to < 102,000	24,110	121,767	NA	20	18

Specimen	Test Temperature (°F)	Energy (ft-lbs)	Average* (ft-lbs)	Requirement (ft-lbs)
DH36 (OK10.62 Flux)				
-1	-20	85	89	20
-2		87		
-3		95		
-4		94		
-5		74		
HSLA-65 (MIL800-H Flux)				
-1	-20	61	59	30
-2		58		
-3		58		
-4		62		
-5		54		
HSLA-100 (MIL800-H Flux)				
-1	-60	48	43	35
-2		43		
-3		38		
-4		43		
-5		43		

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Results Presentation

- Task 2 – Metal Cored Electrode Development
  - Electrode Formulations and Deposited Chemical Analysis
    - All weld metal chemical analysis sample extracted from reduced section of fractured tensile specimen

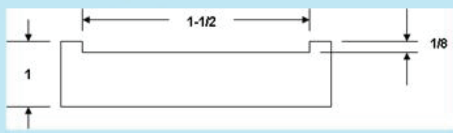
	Compositions (%)																	
	C	Mn	Si	S	P	Ni	Cr	Mo	Al	B	Cu	Zr	Nb	Ti	V	N	O	Pcm
DH-36 Formulation	0.060	1.400	0.550	0.002	0.002	0.500	0.015	0.150	0.004	0.004	0.060	0.008	0.002	0.015	0.001			0.191
DH36 / OK 10.62	0.070	1.510	0.410	0.009	0.017	0.480	0.051	0.160	0.023	0.002	0.110	0.005	0.021	0.012	0.030	0.010	0.040	0.197
HSLA-65 Formulation	0.035	1.600	0.450	0.002	0.002	1.800	0.100	0.350	0.004	0.004	0.030	0.008	0.010	0.030	0.004			0.210
HSLA-65 / MIL800-H	0.060	1.680	0.360	0.008	0.015	1.750	0.120	0.360	0.024	0.001	0.089	0.005	0.025	0.010	0.045	0.010	0.037	0.231
HSLA-100 Formulation	0.050	1.750	0.450	0.002	0.002	2.300	0.175	0.450	0.007	0.004	0.030	0.008	0.010	0.030	0.007			0.252
HSLA-100 / MIL800-H	0.060	1.360	0.330	0.005	0.013	2.000	0.450	0.430	0.037	0.001	0.750	0.045	0.032	0.008	0.005	0.010	0.030	0.268

Results Presentation

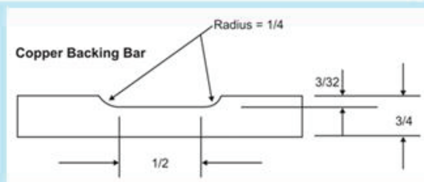
- Task 3 – Procedure Development
  - DH36 and HSLA-65 Tandem Set-up

Results Presentation

- Task 3 – Procedure Development
  - Inconsistent results with existing FCB configuration
  - Root bead shape and height (for a given procedure) a function of flux particle size and distribution as well as consistency of flux compression between copper bar and back of plate along the length of the weld
    - Same procedure varies from one plate to the next (inconsistent root bead height and widths, undercutting, etc)
    - Excessive melt through (increased root bead height) resulted in loss of cap.



Original Design



Modified Design

  - Small groove design provides improved local flux compression and weld bead support

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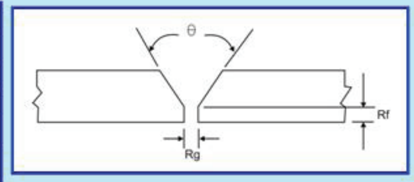
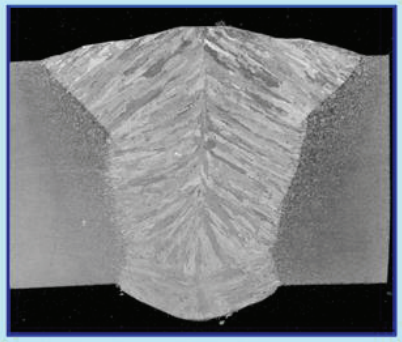
Results Presentation

- Task 3 – Procedure Development - ½” DH36 Steel
  - Lead 1/8” and Trail 5/32”

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	Single-V Θ = 30°, Rf = 1/8", Rg = 3/32"	
Electrode Spacing	5 1/4"	
Flux	ESAB OK 10.62	
Welding Parameters		
	Lead Electrode	Trailing Electrode
Amperage (A)	800	700
Voltage (V)	37.5	37.5
WFS (ipm)	200	100
Travel Speed (ipm)	30	
Benchark Travel Speed (ipm)	12	
Travel Angle (°)	15 drag	5 push
CTWD (in)	3/4	1 3/4
Heat Input (kJ/in)	112.5 (combined)	
Benchmark Heat Input (kJ/in)	160 (combined)	





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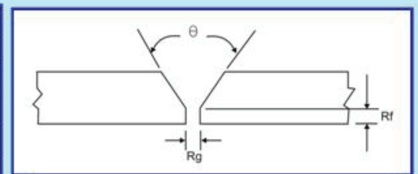
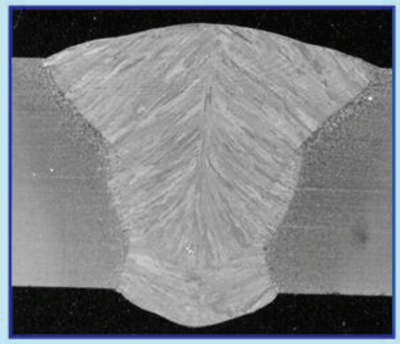
Results Presentation

- Task 3 – Procedure Development - ½" HSLA-65
  - Lead 1/8" and Trail 5/32"

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	Single-V Θ = 30°, Rf = 1/8", Rg = 3/32"	
Electrode Spacing	5 ¼"	
Flux	Lincoln MIL800-H	
Welding Parameters		
	Lead Electrode	Trailing Electrode
Amperage (A)	800	700
Voltage (V)	37.5	37.5
WFS (ipm)	200	100
Travel Speed (ipm)	30	
Benchark Travel Speed (ipm)	27.5	
Travel Angle (°)	15 drag	5 push
CTWD (in)	3/4	1 3/4
Heat Input (kJ/in)	112.5 (combined)	
Benchmark Heat Input (kJ/in)	94.3 (combined)	





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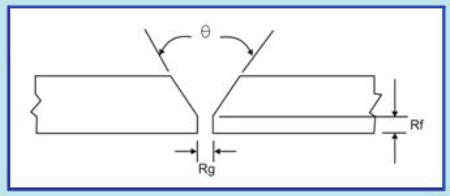
Results Presentation

- Task 3 – Procedure Development – 1” DH36 Steel
  - 5/32” Lead and Trail

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	Θ=30° Included Angle Rg = 3/32" Rf = 3/16"	
Electrode Spacing	4"	
Flux	ESAB OK 10.62	
Tandem Welding Parameters		
	Lead Electrode	Trailing Electrode
Amperage (A)	1150	980
Voltage (V)	32.5	36.5
WFS (ipm)	225	175
Travel Speed (ipm)	20.5 - 1 pass only	
Benchmark Travel Speed (ipm)	12 for1st pass, and 14 for 2nd, 3rd, 4th, and 5th passes	
Travel Angle (°)	15 drag	0
CTWD (in)	1/2	1 3/4
Heat Input (kJ/mm)	214.1 (combined)	
Benchmark Heat Input (kJ/in)	160.5 for 1st pass and 89 for 2nd, 3rd, 4th, and 5th passes	



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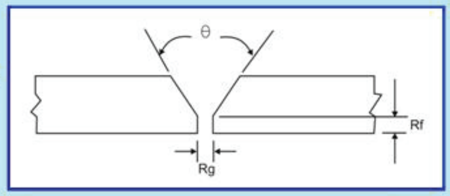
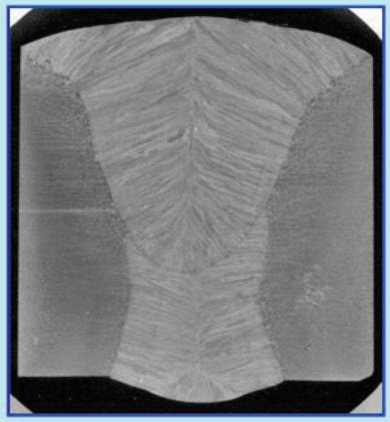
Results Presentation

- Task 3 – Procedure Development – 1" HSLA-65 Steel
  - 5/32" Lead and Trail

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	ϴ=30° Included Angle Rg = 3/32" Rf = 3/16"	
Electrode Spacing	4"	
Flux	Lincoln MIL800-H	
Tandem Welding Parameters		
	Lead Electrode	Trailing Electrode
Amperage (A)	1180	950
Voltage (V)	32.5	36.5
WFS (ipm)	225	175
Travel Speed (ipm)	20.5 - 1 pass only	
Benchmark Travel Speed (ipm)	23.5 for 1st pass and 15.5 for 2nd pass	
Travel Angle (°)	15 drag	0
CTWD (in)	1/2	1 3/4
Heat Input (kJ/mm)	214.1 (combined)	
Benchmark Heat Input (kJ/in)	160.5 for 1st pass and 108.6 2nd pass	





Results Presentation

- Task 3 – Procedure Development – HSLA-100
  - 5/32” Lead and Trail
  - Min 60°F Preheat and Max 300°F Interpass Temperatures

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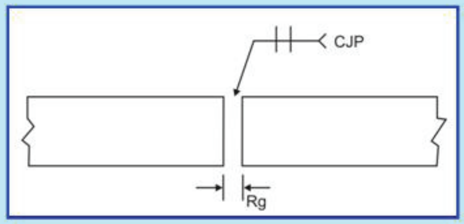
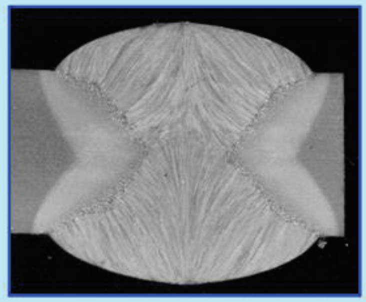
Results Presentation

- Task 3 – Procedure Development – HSLA-100
- ½" Thickness – Two Sided Weld, One Pass Per Side, No Back Gouging

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	Square Groove, Rg = 0	
Electrode Spacing	7/8"	
Travel Angle (°)	0 Lead	15 push Trail
CTWD (in)	3/4 Lead	1 3/4 Trail
Flux	Lincoln MIL800-H	
Welding Parameters		
	Lead Electrode	Trailing Electrode
Side 1		
Amperage (A)	950	600
Voltage (V)	30	35
WFS (ipm)	150	100
Travel Speed (ipm)	45 for 1st Pass	
Side 2		
Amperage (A)	950	600
Voltage (V)	30	35
WFS (ipm)	150	100
Travel Speed (ipm)	45 for 2nd Pass	
Benchark Travel Speeds	14 for 1st and 2nd Pass	
Heat Input (kJ/in)	66 (combined) for each pass	
Benchmark Heat Input (kJ/in)	83.5	





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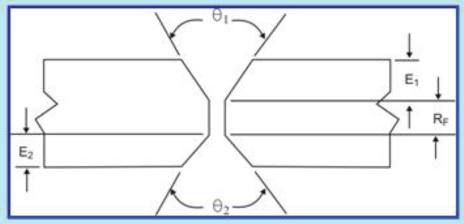
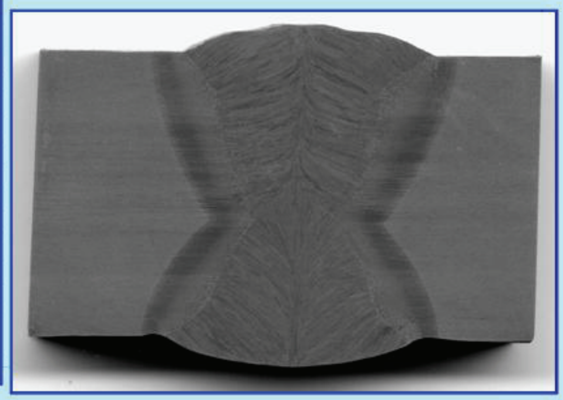
Results Presentation

- Task 3 – Procedure Development – HSLA-100
- 1” Thickness – Two Sided Weld, One Pass Per Side, No Back Gouging – 66/34 Balance

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	Θ1=70° Included Angle, Θ2=90° Included Angle, Rg = 0, Rf = 5/16, E1=7/16, E2=1/4	
Electrode Spacing	7/8"	
Travel Angle (°)	0 Lead	15 push Trail
CTWD (in)	1 1/4 Lead	1 1/2 Trail
Flux	Lincoln MIL800-H	
Welding Parameters		
	Lead Electrode	Trailing Electrode
Side 1		
Amperage (A)	1000	850
Voltage (V)	32.5	36
WFS (ipm)	175	195
Travel Speed (ipm)	38 for 1st Pass	
Side 2		
Amperage (A)	950	725
Voltage (V)	32.5	35
WFS (ipm)	160	160
Travel Speed (ipm)	45 for 2nd Pass	
Benchark Travel Speeds	14 for 8 passes (4 per side)	
Heat Input (kJ/in)	99.6 (combined) for 1st Pass and 75 kJ/in for 2nd Pass	
Benchmark Heat Input (kJ/in)	83.5 each pass	





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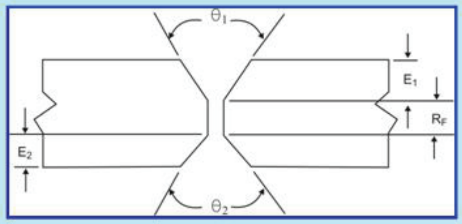
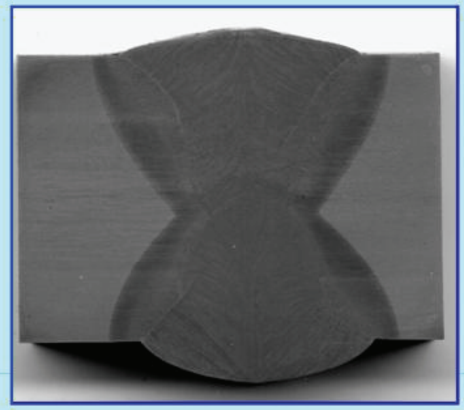
Results Presentation

- Task 3 – Procedure Development – HSLA-100
- 1" Thickness – Two Sided Weld, One Pass Per Side, No Back Gouging – 34/66 Balance

Mode	Constant Voltage	
Balance (EP/EN)	34/66	
Joint Preparation	ϴ1=70° Included Angle, ϴ2=90° Included Angle, Rg = 0, Rf = 5/16, E1=7/16, E2=1/4	
Electrode Spacing	7/8"	
Travel Angle (°)	0 Lead	15 push Trail
CTWD (in)	1 1/4 Lead	1 1/2 Trail
Flux	Lincoln MIL800-H	
Welding Parameters		
	Lead Electrode	Trailing Electrode
Side 1		
Amperage (A)	1000	680
Voltage (V)	32.5	36
WFS (ipm)	200	200
Travel Speed (ipm)	38 for 1st Pass	
Side 2		
Amperage (A)	1050	800
Voltage (V)	32.5	36
WFS (ipm)	200	200
Travel Speed (ipm)	45 for 2nd Pass	
Benchark Travel Speeds	14 for 8 passes (4 per side)	
Heat Input (kJ/in)	90 (combined) for 1st Pass and 83.9 kJ/in for 2nd Pass	
Benchmark Heat Input (kJ/in)	83.5 each pass	





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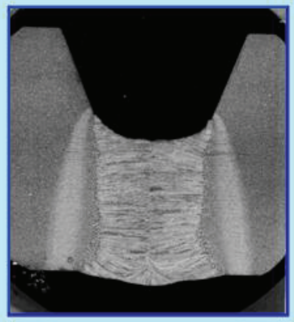
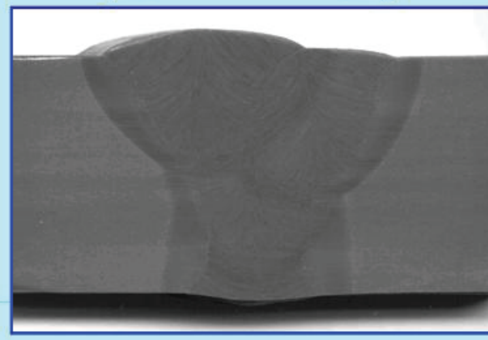
Results Presentation

- Task 3 – Procedure Development – HSLA-100
- 1" Thickness – Tandem Multi-pass OSW onto a FCB – 4 Passes

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	Θ=45° Included Angle Rg = 1/8 Rf = 5/32	
Electrode Spacing	7/8"	
Travel Angle (°)	0 Lead	15 push Trail
CTWD (in)	1 1/4 Lead	1 1/4 Trail
Flux	Lincoln MIL800-H	
Tandem Welding Parameters		
	Lead Electrode	Trailing Electrode
Pass 1		
Amperage (A)	800	660
Voltage (V)	33	34
WFS (ipm)	145	145
Travel Speed (ipm)	35	
Pass 2		
Amperage (A)	860	680
Voltage (V)	33	34
WFS (ipm)	145	145
Travel Speed (ipm)	40	
Pass 3		
Amperage (A)	900	680
Voltage (V)	32.5	35
WFS (ipm)	145	145
Travel Speed (ipm)	45	
Pass 4		
Amperage (A)	920	700
Voltage (V)	32.5	35
WFS (ipm)	145	145
Travel Speed (ipm)	45	
Benchark Travel Speeds	Unknown for OSW'ing	
Heat Input (kJ/in)	83.8 1st Pass, 77.3 for 2nd, 70.7 for 3rd, and 72.6 for 4th	
Benchmark Heat Input (kJ/in)	Unknown for OSW'ing	





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Results Presentation

- **Task 3 – Procedure Qualification Test Matrix**
  - All plates radiographed at 90° and +/-20° to surface
- **½" Plates**
  - 2 Cross Weld Tensiles
  - 1 Macro / Micro / Hardness
  - 4 Side Bends
  - Charpy V-notch Impact @ T/2
    - 5 Weld Centerline, 5 Fusion Line, 5 Fusion Line + 1mm, and 5 Fusion Line + 3mm
- **1" Plates**
  - 2 Cross Weld Tensiles
  - 1 All Weld Metal Tensile (centered at ¼" below Side #1 surface)
  - 1 Macro / Micro / Hardness
  - 4 Side Bends
  - Charpy V-notch Impact @ 1/16" from Side #1 surface
    - 5 Weld Centerline, 5 Fusion Line, 5 Fusion Line + 1mm, and 5 Fusion Line + 3mm

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Results Presentation

- Task 3 – Procedure Qualification Test Results
- ½" Plates

Procedure	Cross Weld Tensile Test: Requirement (ksi)	Result (ksi)	Base Metal UTS (ksi)	Joint Efficiency	Charpy V-notch Impacts: Requirement	Location	AVG Energy (ft-lbs)	Side Bends
DH36 OSW	71	80.7	80.1	101%	20 ft-lbs @ -20F	CL	111	Acceptable
		80.5	80.1	100%	17 ft-lbs @ -4F	FL	62	
						FL+1	60	
						FL+3	106	
HSLA-65 OSW	NA	82.1	80	103%	30 ft-lbs @ -20F	CL	100	Acceptable
		81.5	80	102%		FL	59	
						FL+1	58	
						FL+3	227	
HSLA-100 1 Pass Per Side	NA	122.1	119.7	102%	60 ft-lbs @ 0F	CL	77	Acceptable
		119.9	119.7	100%		FL	78	
						FL+1	60	
						FL+3	118	
					35 ft-lbs @ -60F	CL	54	
						FL	47	
						FL+1	34	
						FL+3	32	

Heat Input 66 kJ/in

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Results Presentation

- Task 3 – Procedure Qualification Test Results - 1" Plates

Procedure	Cross Weld Tensile Test: Requirement (ksi)	Cross Weld Tensile Test: Result (ksi)	Cross Weld Tensile Test: Base Metal UTS (ksi)	Cross Weld Tensile Test: Joint Efficiency	All Weld Metal Tensile Test: Yield Strength (ksi)	All Weld Metal Tensile Test: UTS (ksi)	All Weld Metal Tensile Test: Elongation (%)	Charpy V-notch Impacts: Requirement	Charpy V-notch Impacts: Location	Charpy V-notch Impacts: AVG Energy (ft-lbs)	Side Bends
DH36 OSW	71 to 95	87.4 86.9	77.8 77.8	112% 112%	83.2	110.5	27.7	20 ft-lbs @ -20F 17 ft-lbs @ -4F	CL FL FL+1 FL+3	75 26 21 50	Acceptable
					Requirement Yield Strength 58ksi, UTS 71 to 95ksi, and Elongation 20%						
HSLA-65 OSW	NA	81.2 80.7	78 78	104% 103%	84.8	100.1	24.7	30 ft-lbs @ -20F	CL FL FL+1 FL+3	91 37 44 71	Acceptable
					Requirement Yield Strength 65ksi and Elongation 20%						
HSLA-100 1 pass per side 66/34	NA	117.1 118.5	117.4 117.4	100% 101%	94.8	116	21.8	60 ft-lbs @ 0F	CL FL FL+1 FL+3	81 59 79 173	Acceptable
					Requirement Yield Strength 88 < 102ksi and Elongation 18%						
								35 ft-lbs @ -60F	CL FL FL+1 FL+3	48 37 67 118	
HSLA-100 1 pass per side 34/66	NA				98	119	21.3	60 ft-lbs @ 0F	CL FL FL+1 FL+3	74 81 Not Tested	Acceptable
					Requirement Yield Strength 88 < 102ksi and Elongation 18%						
								35 ft-lbs @ -60F	CL FL FL+1 FL+3	42 46 64 Not Tested	
HSLA-100 4 pass OSW	NA				89.8	123	20.4	60 ft-lbs @ 0F	CL FL FL+1 FL+3	77 68 Not Tested	Acceptable
					Requirement Yield Strength 88 < 102ksi and Elongation 18%						
								35 ft-lbs @ -60F	CL FL FL+1 FL+3	43 52 73 Not Tested	

99.6 kJ/in

90 kJ/in

Porosity Visible on Fracture Surface of Tensile Specimen

Results Presentation

- Task 3 – Procedure Qualification Test Results
- Hardness - Average HV_5

Procedure	Thickness	Average Hardness (HV5) Location			
		CL	FL	HAZ	BM
DH36	1/2"	210	187	165	154
	1"	226	214	185	166
HSLA-65	1/2"	227	198	180	168
	1"	228	204	172	164
HSLA-100 (66/34)	1/2"	261	246	239	256
	1"	254	272	251	259
HSLA-100 (34/66)	1"	266	289	275	280
HSLA-100 OSW - 4 Pass	1"	286	280	252	284

Results Presentation

- Productivity Comparison with Current Practice

Procedure		Thickness (in)	Side	Pass (#)	Travel Speed (ipm)	Total Arc Time per ft of Joint (min)	Productivity Improvement Over Benchmarks (%)
Benchmarks	DH36 - Series AC	0.5	1	1	12	1.00	
		1	1	1	12	4.40	
				2 to 5	14		
	HSLA-65 - Tandem Arc	0.5	1	1	27.5	0.44	
		1	1	1	23.5	1.30	
				2	15.5		
	HSLA-100 - Single Arc	0.5	1	1	14	1.70	
			2	2	14		
		1	1	1 to 4	14	6.80	
			2	5 to 8	14		
VBAC Procedures	DH36 - Tandem OSW	0.5	1	1	30	0.40	250%
		1	1	1	20.5	0.59	746%
	HSLA-65 - Tandem OSW	0.5	1	1	30	0.40	10%
		1	1	1	20.5	0.59	245%
	HSLA-100 - Tandem 64/36 (EP/EN) - 2 passes	0.5	1	1	45	0.53	321%
			2	2	45		
		1	1	1	38	0.58	1172%
			2	2	45		
	HSLA-100 - Tandem 34/66 (EP/EN) - 2 Passes	1	1	1	38	0.58	1172%
			2	2	45		
	HSLA-100 - Tandem 64/36 (EP/EN) OSW - 4 Passes	1	1	1	35	1.18	576%
				2	38		
				3 to 4	45		

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Results Presentation

- Productivity Comparison – Deposition Rates
  - DH36 and HSLA-65 Procedures
    - 75 lbs/hr (112.5 kJ/in) – (½" Thickness)
    - 112 lbs/hr (214.1 kJ/in) – (1" Thickness)
  - HSLA-100 Steel Procedures
    - 81 lbs/hr (66 kJ/in) – (½" thickness)
    - 66/34 = 104 lbs/hr 1st pass (99.6 kJ/in), and, 89 lbs / hr 2nd pass (75 kJ/in) - (1" Thickness)
    - 34/66 = 112 lbs/hr for 1st (90kJ/in) and 2nd (83 kJ/in) - (1" Thickness)
    - OSW = 81 lbs/hr for each of the 4 passes (70 to 83.9 kJ/in) - (1" Thickness)

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Results Presentation

- Cost Analysis
  - Metal cored $/lb cost approximately the same as an EM12K solid wire, and, 30% less than an alloyed solid wire
  - Assumed $55/hr labor rate
  - Cost reductions are for arc time only, and do not include further savings that can be achieved by elimination of interpass operations (chipping slag, back gouging, realignment of electrodes, etc) typical for the benchmark procedures

	Procedure	Thickness (in)	Side	Pass (#)	Weld Weight per Foot (lbs)	Electrode Cost ($/lb)	Electrode Cost per Foot ($)	Travel Speed (ipm)	Total Arc Time per ft (min)	Labor Cost ($/hr)	Labor Cost per Foot ($)	Total Electrode and Labor Cost per Foot ($)	Potential Cost Reduction
Benchmarks	DH36 - Series AC	0.5	1	1	0.43	1.75	0.75	12	1.00	55	0.92	1.67	
		1	1	1	1.6	1.75	2.80	12	4.40	55	4.03	6.83	
				2 to 5				14					
	HSLA-65 - Tandem Arc	0.5	1	1	0.62	3.5	2.17	27.5	0.44	55	0.40	2.57	
		1	1	1	1.6	3.5	5.60	23.5	1.30	55	1.19	6.79	
				2				15.5					
	HSLA-100 - Single Arc	0.5	1	1	0.43	3.5	1.51	14	1.70	55	1.56	3.06	
			2	2				14					
		1	1	1 to 4	0.95	3.5	3.33	14	6.80	55	6.23	9.56	
			2	5 to 8				14					
VBAC Procedures	DH36 - Tandem	0.5	1	1	0.5	1.75	0.875	30	0.40	55	0.37	1.24	-26%
		1	1	1	1.09	1.75	1.9075	20.5	0.59	55	0.54	2.45	-64%
	HSLA-65 - Tandem	0.5	1	1	0.5	3.1	1.55	30	0.40	55	0.37	1.92	-26%
		1	1	1	1.09	3.1	3.379	20.5	0.59	55	0.54	3.92	-42%
	HSLA-100 - Tandem 64/36 (EP/EN)	0.5	1	1	0.72	3.1	2.232	45	0.53	55	0.49	2.72	-11%
			2	2				45					
		1	1	1	0.94	3.1	2.914	38	0.58	55	0.53	3.45	-64%
			2	2				45					
	HSLA-100 - Tandem 34/66 (EP/EN)	1	1	1	1.09	3.1	3.379	38	0.58	55	0.53	3.91	-59%
			2	2				45					
	HSLA-100 - Tandem OSW - 4 Pass	1	1	1	1.59	3.1	4.929	35	1.18	55	1.08	6.01	-37%
				2				38					
				3 to 4				45					

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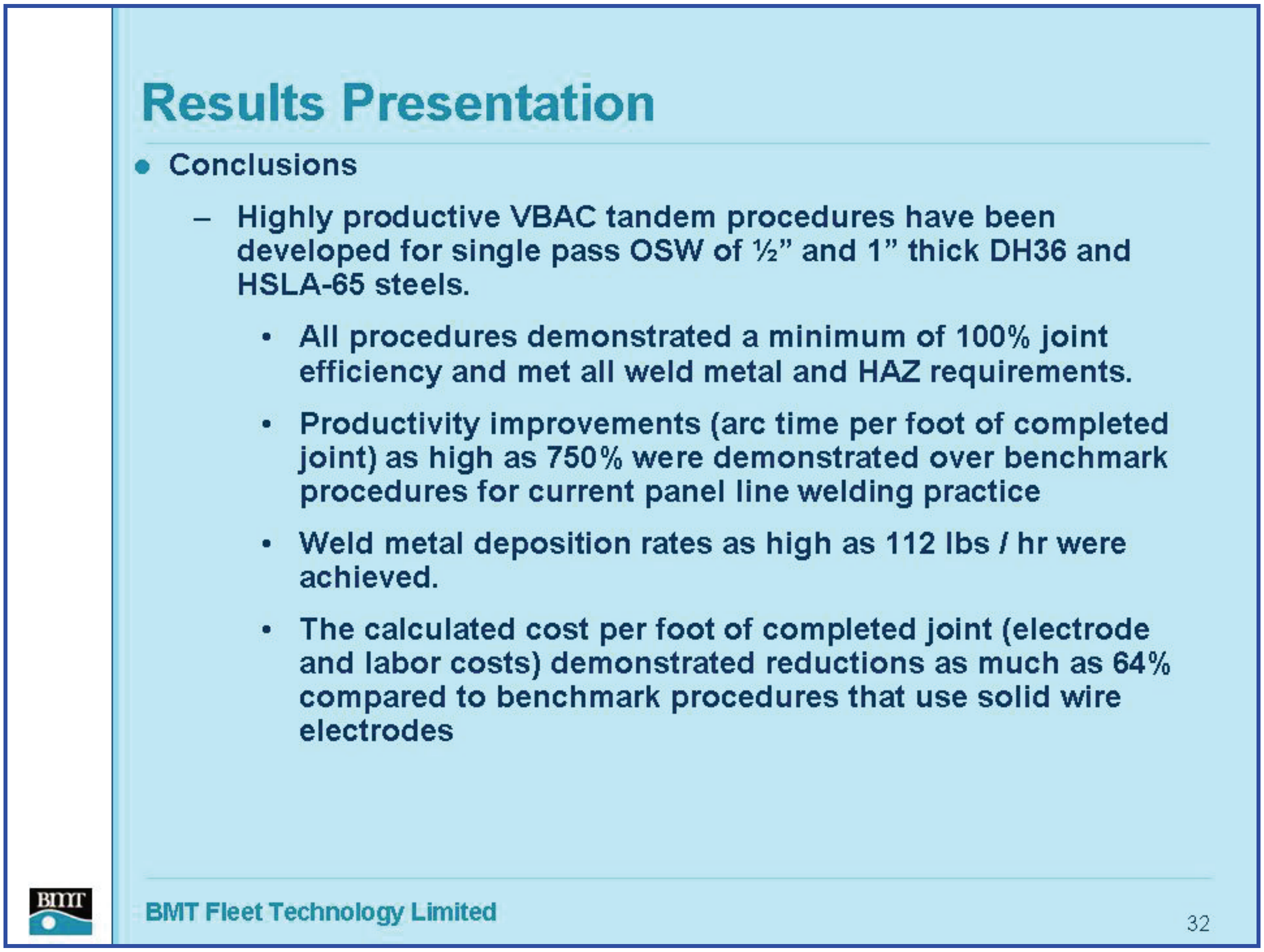
Results Presentation
Conclusions
– Highly productive VBAC tandem procedures have been developed for single pass OSW of ½” and 1” thick DH36 and HSLA-65 steels.
• All procedures demonstrated a minimum of 100% joint efficiency and met all weld metal and HAZ requirements.
• Productivity improvements (arc time per foot of completed joint) as high as 750% were demonstrated over benchmark procedures for current panel line welding practice
• Weld metal deposition rates as high as 112 lbs / hr were achieved.
• The calculated cost per foot of completed joint (electrode and labor costs) demonstrated reductions as much as 64% compared to benchmark procedures that use solid wire electrodes
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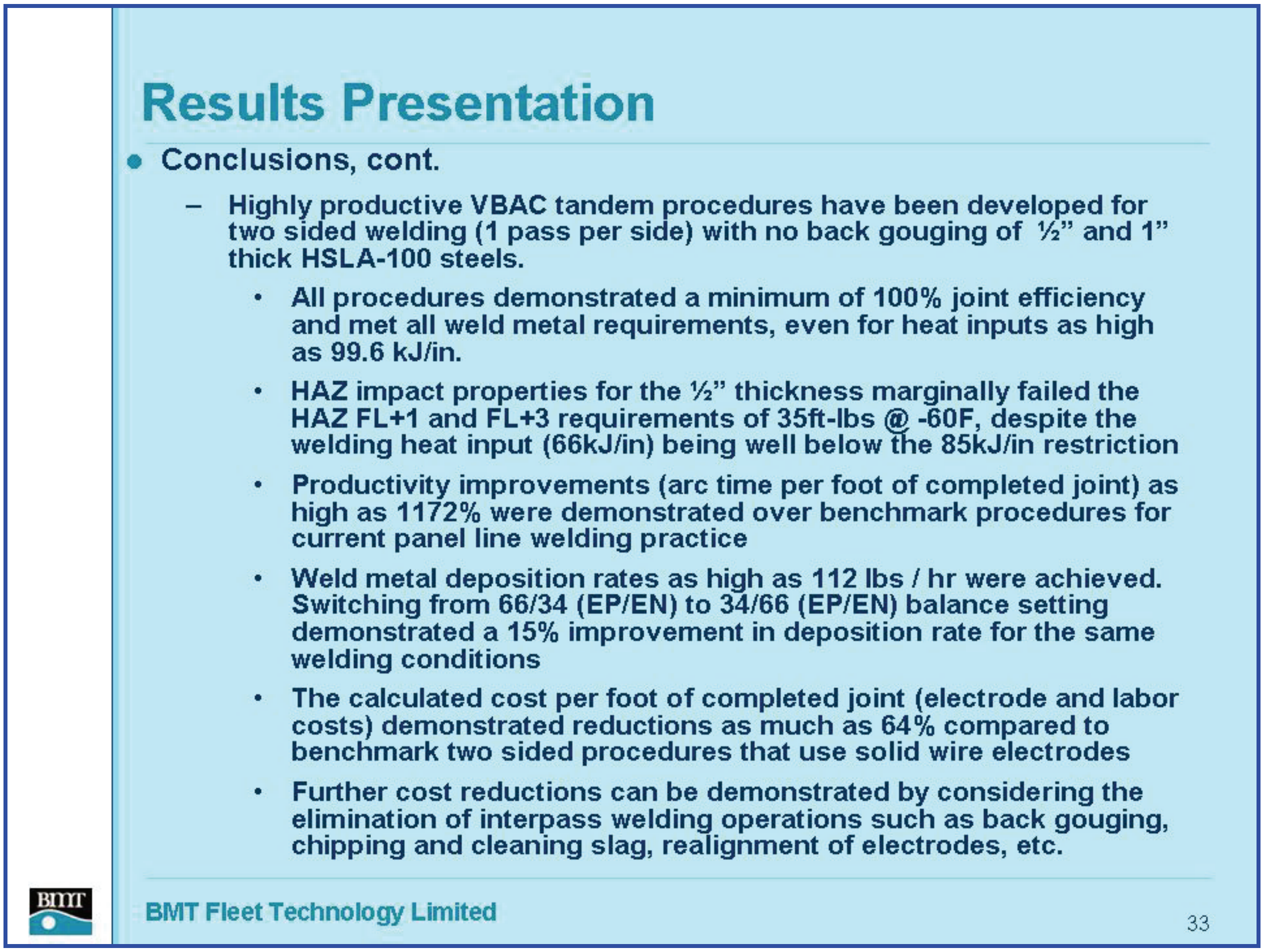
Results Presentation
Conclusions, cont.
– Highly productive VBAC tandem procedures have been developed for two sided welding (1 pass per side) with no back gouging of ½" and 1" thick HSLA-100 steels.
• All procedures demonstrated a minimum of 100% joint efficiency and met all weld metal requirements, even for heat inputs as high as 99.6 kJ/in.
• HAZ impact properties for the ½" thickness marginally failed the HAZ FL+1 and FL+3 requirements of 35ft-lbs @ -60F, despite the welding heat input (66kJ/in) being well below the 85kJ/in restriction
• Productivity improvements (arc time per foot of completed joint) as high as 1172% were demonstrated over benchmark procedures for current panel line welding practice
• Weld metal deposition rates as high as 112 lbs / hr were achieved. Switching from 66/34 (EP/EN) to 34/66 (EP/EN) balance setting demonstrated a 15% improvement in deposition rate for the same welding conditions
• The calculated cost per foot of completed joint (electrode and labor costs) demonstrated reductions as much as 64% compared to benchmark two sided procedures that use solid wire electrodes
• Further cost reductions can be demonstrated by considering the elimination of interpass welding operations such as back gouging, chipping and cleaning slag, realignment of electrodes, etc.
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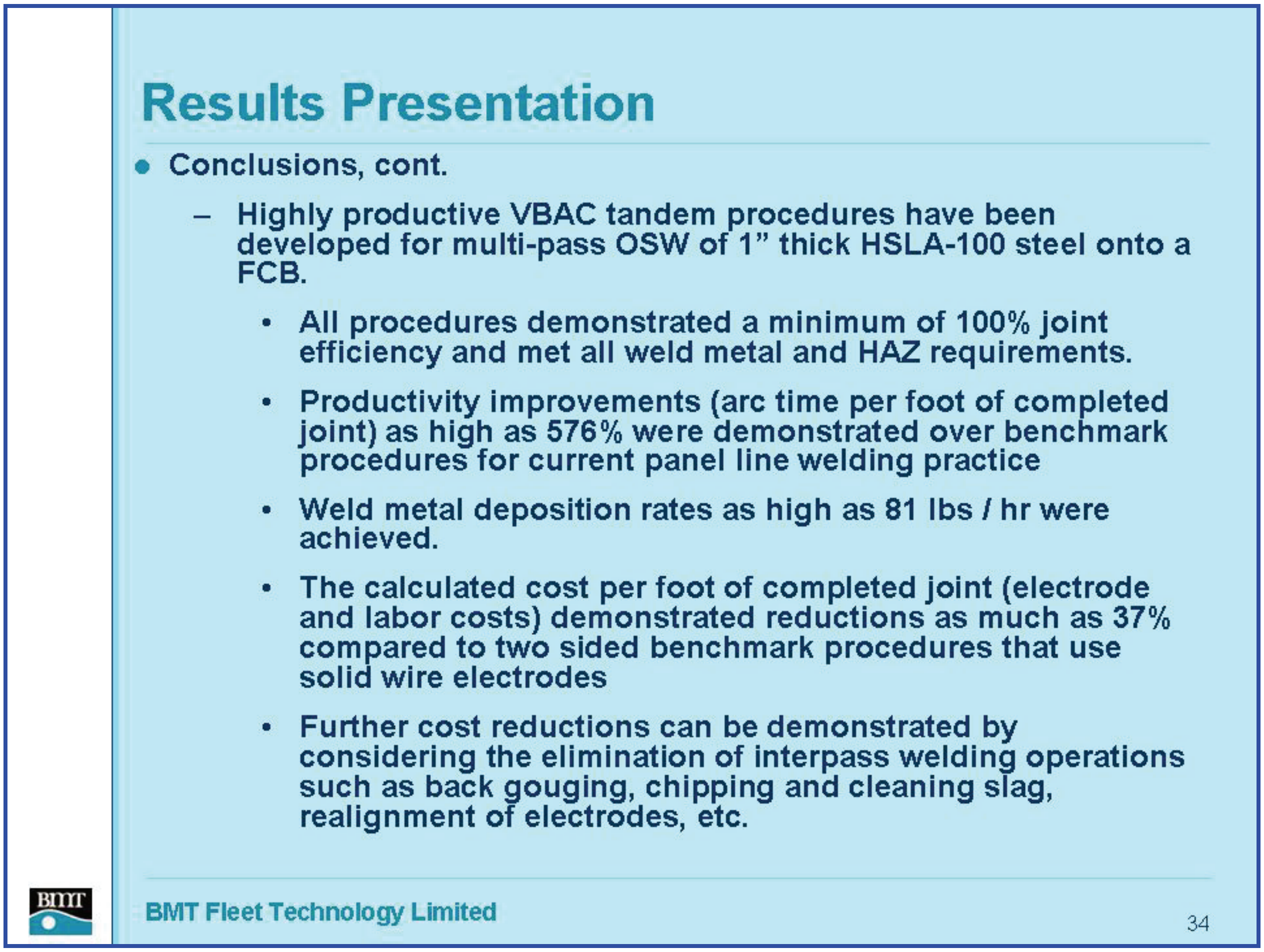
Results Presentation
Conclusions, cont.
– Highly productive VBAC tandem procedures have been developed for multi-pass OSW of 1” thick HSLA-100 steel onto a FCB.
• All procedures demonstrated a minimum of 100% joint efficiency and met all weld metal and HAZ requirements.
• Productivity improvements (arc time per foot of completed joint) as high as 576% were demonstrated over benchmark procedures for current panel line welding practice
• Weld metal deposition rates as high as 81 lbs / hr were achieved.
• The calculated cost per foot of completed joint (electrode and labor costs) demonstrated reductions as much as 37% compared to two sided benchmark procedures that use solid wire electrodes
• Further cost reductions can be demonstrated by considering the elimination of interpass welding operations such as back gouging, chipping and cleaning slag, realignment of electrodes, etc.
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Results Presentation

- Recommendations for Further Work
  - Evaluate Range of HSLA-100 Compositions (Lean and Rich) for 1” Thickness
  - Evaluate 2” Thick HSLA-100
    - Compare productivity of Tandem VBAC to other practices, *“can even higher heat inputs be adopted for 2 inch thickness due to the greater heat sink capacity?”*
      - Lower Preheats and Interpass Temperatures?
      - Improved Weld Metal and HAZ Properties?
    - Qualification for Aircraft Carriers (Explosion Bulge and Dynamic Tear Testing)
  - Production Trials and Demonstrations

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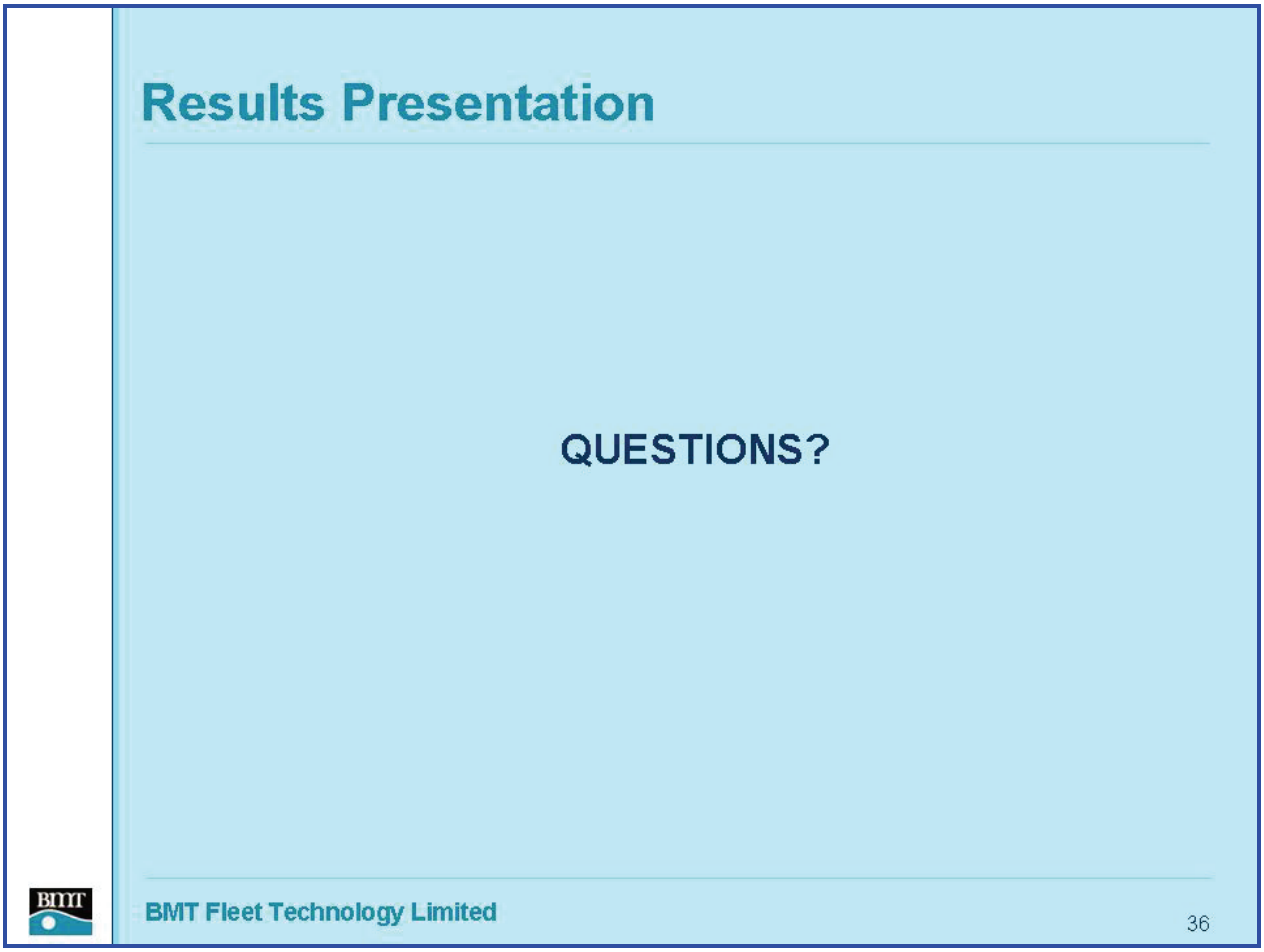
Results Presentation
QUESTIONS?
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