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EWI Project No. 50453GTH

Hybrid Laser/Gas Metal Arc Welding (HLAW) of High Strength Steel Gas Transmission Pipelines

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Final Project Report

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Submitted to:

U.S. Department of Transportation
Pipeline and Hazardous Materials Safety Administration
Pipeline of Transportation Safety
Washington, D.C.

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Final Report

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on

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March 31, 2010

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1.0 Introduction

Natural gas consumption is predicted to double over the next 20 years, which will place increasing demands on the existing pipeline system. This increasing demand will require major investment in new pipelines and significant expansion of existing infrastructure. New pipelines will need to be constructed as economically as possible, but the trend towards higher operating pressures will require the use of higher strength steels and improved pipeline integrity. Robust, high-productivity, high-quality automated welding processes will be needed to assure first-time quality, desired material properties, and affordability when welding these higher strength materials.

EWI has identified innovative welding processes and automation that could be used to develop higher joint completion rates for pipeline welding. These processes include hybrid laser/gas metal arc welding (HLAW), which can be used for high-speed root pass welding on pipe joints with thicker root faces than current production methods allow. Tandem (or dual-tandem) gas metal arc welding (T-GMAW), which can operate at high travel speeds and up to four times the deposition rate of single-wire GMAW processes, has also been developed. T-GMAW can be used for fill pass welding of pipelines once the root pass is completed. In general, these processes are designed to improve metal transfer, minimize spatter, minimize weld defects, and increase productivity.

Advanced automation equipment can be coupled with these innovative welding processes to further improve weld bead shape, tolerance to gap variation, and maximum welding speeds on both root and fill passes.

The lessons learned from previous U.S. Department of Transportation (DOT) projects completed by EWI, and the cost-matched EWI/Joint Industry Project (JIP), were applied to the HLAW program detailed herein.[1,2] In this project, HLAW was used to penetrate root face thicknesses ranging from 3- to 11-mm, thus increasing the joint completion rate and productivity of pipeline girth welding compared to conventional techniques.

2.0 Objectives

The goal of this project was to develop the HLAW process for on-shore pipeline girth welding and to demonstrate the system under field conditions. Special emphasis was placed on understanding the mechanical properties of HLAW made on X80 and X100 material. Other areas of focus included weld overlaps and general HLAW process phenomena as described in succeeding sections.

3.0 Technical Approach

An EWI Joint Industry Project (JIP), Project 49191CPQ, “Fiber Laser Based Hybrid Automated Pipe Girth Welding”, offered for cost-match requirements, ran concurrently to the DOT project described in this report.[3] The tasks described were used to complete the objectives of the DOT work only. The first six tasks were a part of the original contract agreement between EWI and the DOT.[4] The final three tasks were agreed upon as part of a contract modification brought about by positive results from the original tasks and the cost-shared JIP.[5]

3.1 Task 1 – Development of the Hybrid Laser Arc Welding Processes

The HLAW system used to produce the welds for this task consisted of a commercially available CRC-Evans P450 bug-and-band pipe welding system that was retrofit with a HighYAG BIMO 90º laser processing head and a Fronius GMAW torch (Figure 1). A Fronius TransPulse Synergic 3200 (300-amp) GMAW power supply was integrated with a 4-kW Nd:YAG laser to allow for HLAW.

Initial HLAW root pass development was completed on machined U-grooves in a 36-inch diameter X80 pipe. The test grooves were prepared with a simulated 4-mm root face and a 12º included angle to minimize the total number of passes required to fill the joint (Figure 2). The range of process parameters used for the initial development work are summarized in Table 1.

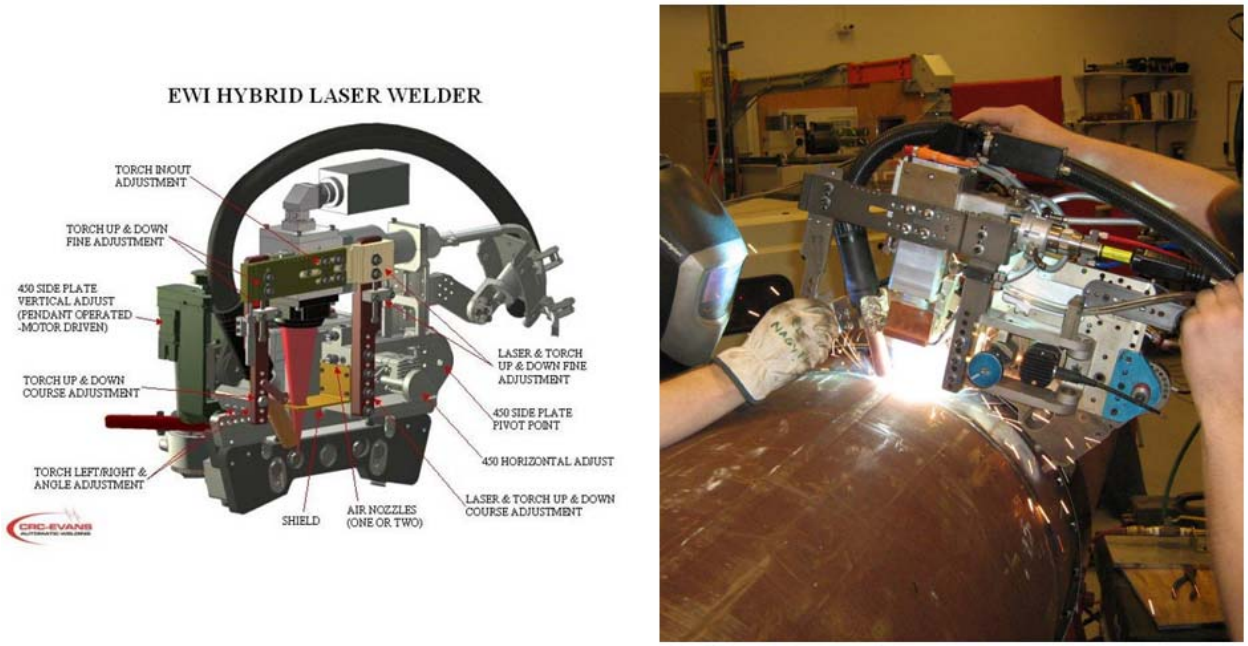


Figure 1. Prototype HLAW Head. Head as originally designed (left) and actual (right)

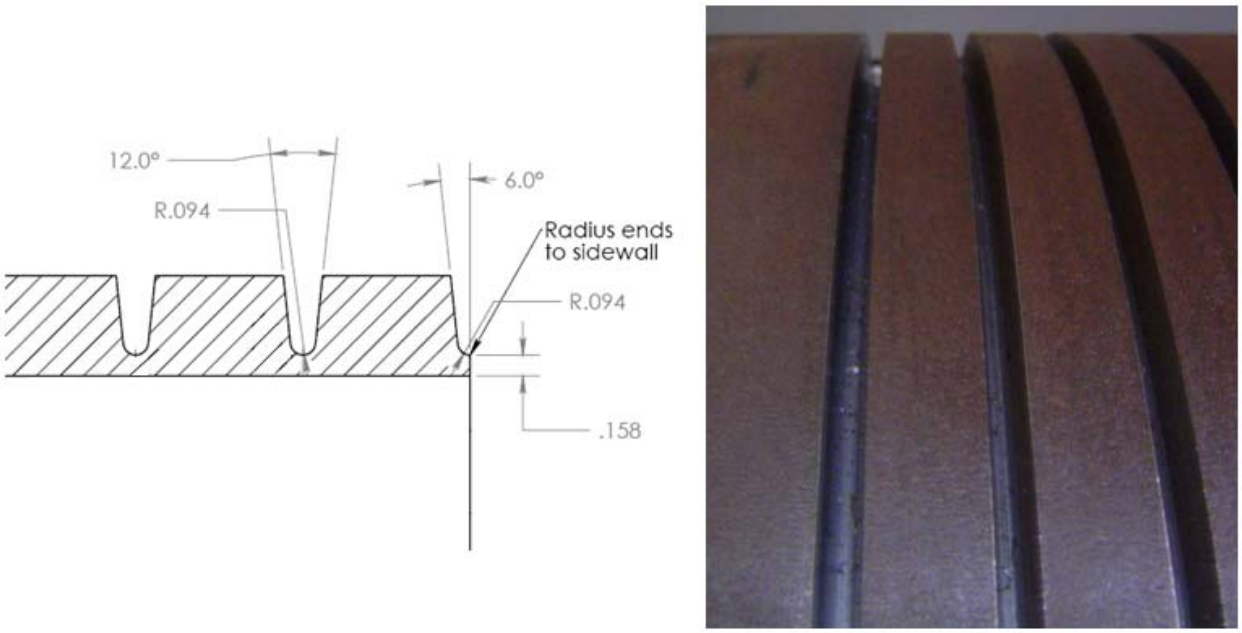


Figure 2. Machined Test Grooves. Grooves used for initial HLAW development on X80 pipe

Table 1. Initial HLAW Parameters

Laser Spot Size	600-µm
Laser Power	4-kW (Nd:YAG)
Travel Speed	60- to 70-IPM
Wire Feed Speed	300- to 400-IPM – Pulsed GMAW
GMAW Shielding Gas	90%Ar – 10%CO_2 (60 CFH)
GMAW Travel Angle	25 to 30º push
Laser Beam to GMAW Electrode Spacing	4- to 6-mm (laser leading the arc)
Filler Material	ER90S-G (0.045-in)

A Panasonic T-GMAW system was used to add a hot pass and subsequent fill passes to the test grooves. The Panasonic system consisted of two 500-Amp Panasonic power supplies coupled with a Tregaskis torch that was mounted to a six-axis robot. Cross-sections were used to evaluate the quality of the initial HLAW and T-GMAW process development.

3.2 Task 2 – Property Testing of Preferred Welding Processes

Faster travel speeds were targeted for the HLAW process development completed during this task. The CRC-Evans pipe welding equipment had a maximum travel speed of 70 IPM as delivered. While waiting for an upgrade to the pipe welding system that would allow for faster travel speeds, EWI used a CNC workstation to continue the development.

Test coupons were prepared from X80 and X100 pipe to allow for welding in the flat (1G position). Root face thicknesses of 3- and 4.5-mm were evaluated with a 12º included angle (Figure 3). Test coupons were tacked together and clamped to a CNC motion table that translated the parts under a fixed HLA welding head (same head that was used under Task 1).

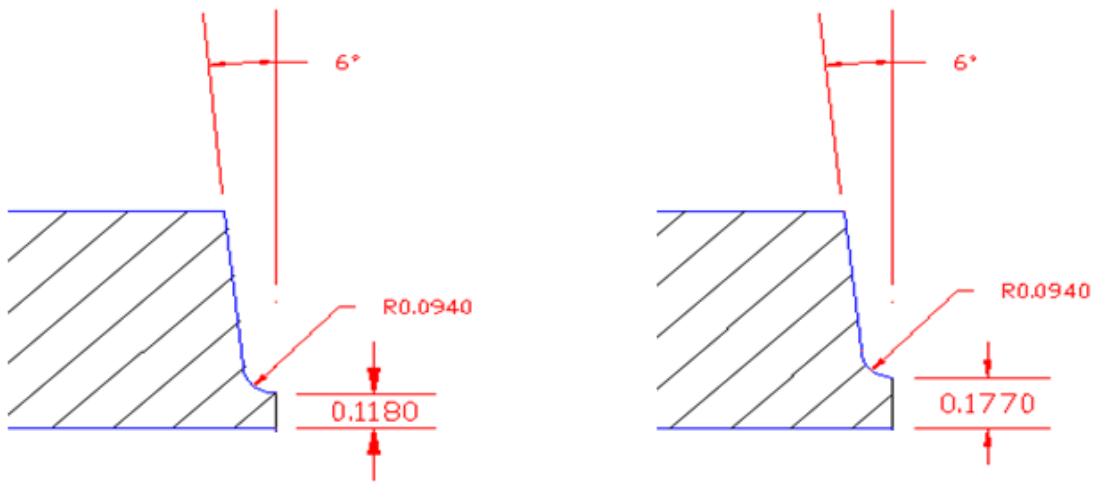


Figure 3. Joint Preparation. Joint design used for initial HLAW property testing

Due to the higher travel speed requirements for this task, additional changes were made to the HLAW system. The 4-kW Nd:YAG laser was replaced with a 10-kW Yb Fiber Laser. The 300-amp GMAW power supply was replaced with a Fronius TransPulse Synergic 5000 (500-amp) power supply.

Because mechanical properties can be significantly affected by filler metal composition and the heat input of the welding process, various filler metals and welding procedures were evaluated during this task. The range of process parameters used are shown in Table 2.

Table 2. Process Parameters for Filler Metal and Heat Input Trials

Laser Spot Size	600-µm
Laser Power	3.5- to 9.5-kW (Yb-Fiber)
Travel Speed	90- to 120-IPM
Wire Feed Speed – Pulsed GMAW	450- to 600-IPM (0.045-in) 200- to 370-IPM (0.062-in)
GMAW Shielding Gas	90%Ar – 10%CO_2 (60 CFH)
GMAW Travel Angle	25 to 30º push
Laser Beam to GMAW Electrode Spacing	0- to 8-mm (laser leading the arc)
Filler Material	ER90S-G and ER100S-1
Preheat, Interpass Temperature	215º to 250º F

To obtain an adequate weld throat thickness for mechanical testing, an automated GMAW hot pass was added to each HLAW root pass. A maximum interpass temperature of 250ºF was maintained. The parameters used for these welds are shown in Table 3.

Table 3. Hot Pass GMAW-P Parameters

Wire Feed Speed	350-IPM – Pulsed GMAW
Travel Speed	15-IPM
GMAW Shielding Gas	90%Ar – 10%CO_2 (35 CFH)
GMAW Travel Angle	17º push
Filler Material	ER90S-G and ER100S-1 (0.045-in)

API Standard 1104 was used as a guideline to begin collecting mechanical property data for selected hybrid welds on X80 and X100 material.[6] Toughness, strength, and weld soundness were tested via Charpy V-notch, transverse tensile, and bend tests, respectively. Cross-sections and Vickers hardness tests were also used to evaluate the HLAW process. For comparison purposes, hardness data for the root pass was collected with and without the addition of the hot pass. The locations of the hardness indents made after adding the hot pass were at the same relative locations as the indents made prior to adding the hot pass (approximately 1.5 mm above the root).

3.3 Task 3 – Use of Integrated Data Acquisition and Laser Sensors for Hybrid Welding

For process development and quality assurance purposes, a data acquisition (DAQ) system was constructed to record real-time process measurements for HLAW. The measurements included arc current, arc voltage, wire feed speed, and laser power. Data was sampled and viewed in real-time at a rate of 5000 Hz and stored for post-weld analysis.

Hardware for the DAQ system included Computer Weld Technology arc weld sensors, Roush LapDAQ™ for signal conditioning, computer processor and a monitor. The software was developed in LabVIEW and used in an executable format during testing.

Additionally, a seam tracking system was constructed to help automatically maintain the laser and arc position at the center of the joint. A Servo Robot Mini-i90 laser vision camera was mounted on the CRC-Evans P450 bug, approximately 12 inches ahead of the welding operation. Laser scans were transmitted to a custom-built software program which translated the joint data into motor commands for tracking. These commands were relayed to a stepper motor, also mounted on the P450 bug, which controlled cross seam position along the joint.

3.4 Task 4 – Field Deployment and Operator Training

This task focused on demonstrating the flexibility of the Yb-Fiber HLAW process and the potential for using the process in remote, outdoor locations. To accomplish this, EWI temporarily moved the HLAW system to a location outside of the EWI facility. This included the Yb-Fiber Laser power supply, CRC-Evans P450 bug-and-band pipe welding system, and all other equipment needed to run the HLAW process. A 125-kW diesel generator was used to generate the power needed to operate the HLAW system. The only portion of the HLAW process not run from the generator was compressed air for the air-knife and cooling water for the laser. Cooling water for the laser was supplied by EWI's central chiller due to difficulty in finding rental equipment for portable water cooling. However, portable process water cooling systems are readily available for purchase.

EWI was required to obtain approval from both the FAA and FDA in order to proceed with high power laser welding outdoors. An independent laser safety officer (Tom Lieb of L*A*I International) was subcontracted to assist with validating that the HLAW system was safe for outdoor welding.

Upon obtaining approval for outdoor welding, EWI hosted a one-day workshop to demonstrate the HLAW process in a simulated field environment. The workshop also included several presentations pertaining to recent advancements in pipeline welding and inspection. Topics included friction stir welding (FSW) of pipes, resistance cladding, and laser-based inspection. The workshop was advertised to EWI member companies through EWI's website, the EWI Insights bulletin, and e-mail invitations to specific market sectors.

A total of four HLA welds were made on two 36-in. diameter X-80 pipe joints prepared with a 4-mm root face and 12º included angle. Since internal line-up clamps were not available, the two pipe joints were tack-welded prior to the demonstration. To maintain a mismatch at or below 3-mm without the use of internal line-up clamps, it was necessary to machine the ID and OD of the pipes prior to tack-welding. A double-down technique was used to produce full-circumference, full-penetration HLAW root welds on both pipe joints. The parameters used for these welds are shown in Table 4.

Table 4. HLAW Parameters for Welding Demonstration

Laser Spot Size	400-µm
Laser Power	6-kW (Yb-Fiber)
Travel Speed	80-IPM
Wire Feed Speed	475-IPM – Pulsed GMAW
GMAW Shielding Gas	80%Ar – 20%CO_2 (60 CFH)
GMAW Travel Angle	27º push
Laser Beam to GMAW Electrode Spacing	1-mm (laser leading the arc)
Filler Material	ER90S-G (0.045-in)

3.5 Task 5 – Productivity Analysis

The potential productivity benefits of the HLAW process were analyzed and compared to competitive joining processes for pipeline welding. Data developed in previous DOT projects for GMAW and HLAW were used along with the data from this project.[1,4] Experience gained in conducting the JIP was also applied as it was cost-matched to this project.

Root-pass welding techniques were emphasized because the overall productivity of a pipeline construction is usually controlled by the cycle time of the root-pass. While welding speed was important, the costs of equipment and the time to align and set up the weld preparation were also important.

3.6 Task 6 – Progress Meetings, Pipeline Conference, Annual Panel Peer Review, and Reporting

Monthly and quarterly status reports were prepared and submitted to the appropriate project investors. A comprehensive report was also prepared that included the following information:

- Description of all hardware and consumables used
- Evaluation of innovative HLAW, T-GMAW, and GMAW root and fill pass processes
- Details of preferred welding parameters and techniques
- Mechanical test data from API 1104 procedure qualifications
- Results from field trials with pipeline contractors

In addition, technical papers were published at pipeline conferences to disseminate the technology to industry.[7,8]

3.7 Task 7 – Study of Beam-to-Wire Spacing, Travel Speed, and Solidification Morphology

Evidence from the cost-shared JIP and early trials from this project showed that variations to HLAW process parameters can influence the solidification morphology and quality of a weld. If the metal melted by the laser solidifies separately from the metal melted by the arc process, many advantages of the HLAW process are lost. For instance, if there are two separate molten puddles, alloying elements from the GMAW wire cannot migrate to the weld nugget of the laser weld. This ‘tandem’ mode of solidification can significantly affect the resulting mechanical properties.

This task investigated various beam-to-wire spacing at two travel speeds to further understand the solidification behavior of the HLAW process. To produce the large number of welds needed to complete the final three tasks (Task 7 – Task 9), EWI used custom-built laser optics that were not as susceptible to damage from weld spatter as the HighYAG optics used in previous tasks (Figure 4). Other changes to the HLAW process set-up included the following:

- Fronius GMAW power supply was replaced with a Lincoln i400 for logistical issues
- 3G and 4G welding trials used a six-axis robot to manipulate the HLAW welding head (1G welding was still done using a CNC workstation)
- Smaller laser spot sizes were investigated

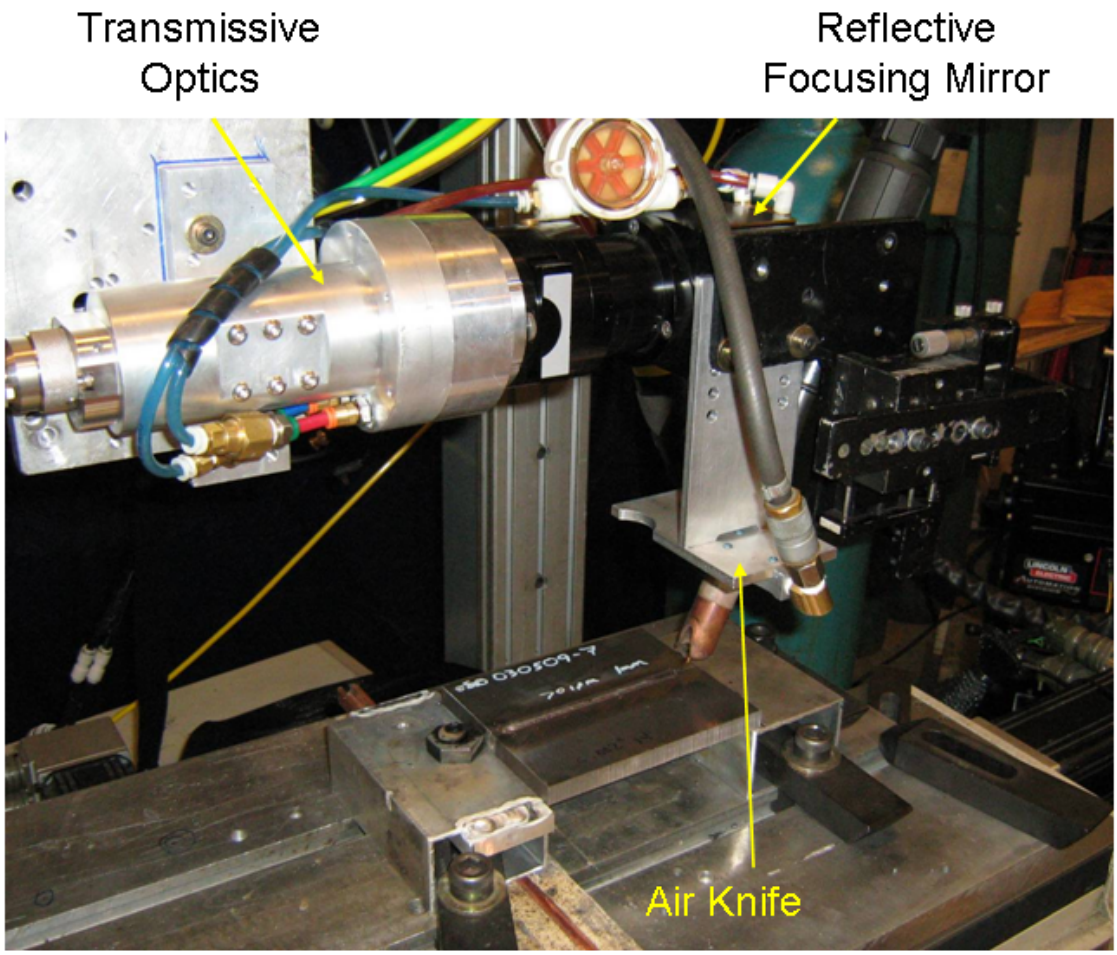
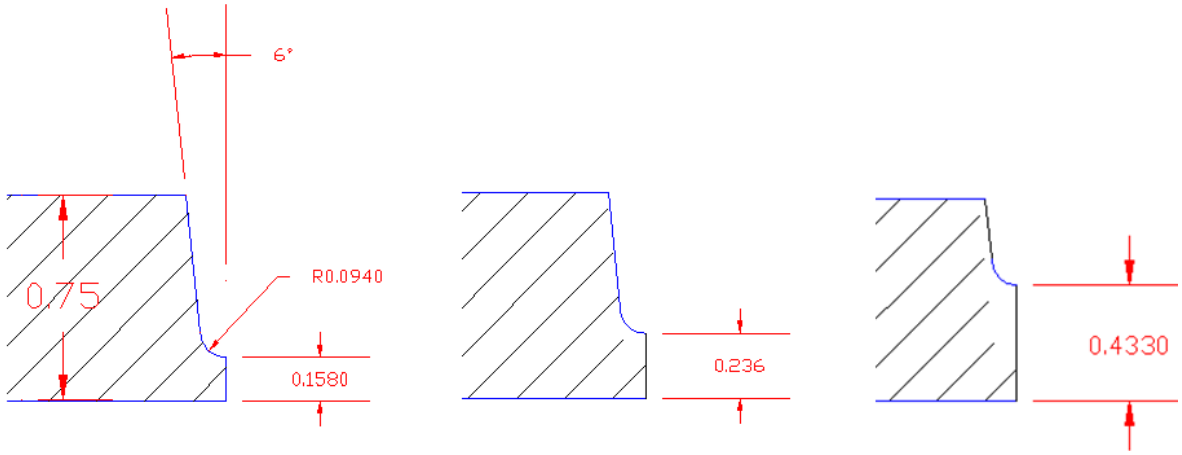


Figure 4. EWI Custom Laser Optics. Optics used for Tasks 7, 8, and 9 HLAW development

Test coupons were cut from X80 pipe material and the edges were prepared with a 4-mm root face and the same J-groove shown in Figure 5 (0.094-in. radius and 6º bevel). The range of parameters investigated in this task is shown in Table 5.

Cross-sections of the welds were used to determine the solidification characteristics and general quality of the weld. Each cross-section was classified as either 'hybrid' solidification or 'tandem' solidification. From this data, a range of process parameters for all welding positions that resulted in acceptable penetration profiles was established.



(a) 4 mm root face (b) 6 mm root face (c) 11 mm root face

Figure 5. Task 9 Joint Design. Various root face thicknesses used for mechanical property testing

Table 5. HLAW Parameters for Beam-to-Wire Spacing Trials

Laser Spot Size	400- and 600-µm
Laser Power	3.5- to 6-kW (Yb-Fiber)
Travel Speed	80-, 90-, 100-IPM
Wire Feed Speed	350- to 600-IPM – Pulsed GMAW
GMAW Shielding Gas	90%Ar – 10%CO_2 (60 CFH)
GMAW Travel Angle	25 to 30º push
Laser Beam to GMAW Electrode Spacing	0 to 7-mm (laser leading the arc)
Welding Positions	1G, 3G, 4G
Filler Material	ER90S-G (0.045-in)

3.8 Task 8 – Start-Stop Development with Hybrid Laser GMAW System

In typical arc welding processes, start and stop overlaps promote many challenges and are prone to defects. Many of the pipeline industry sponsors were concerned that having the laser and GMAW processes in the same weld pool might further complicate this problem. Thus, to further determine the feasibility of HLAW for pipeline welding, a preliminary study of start/start (1G position) and stop/stop (4G position) overlaps was completed.

As the HLAW system developed under this program was a prototype, there were insufficient controls for synchronizing the laser, GMAW, and motion system for start and stop overlaps. The goal of this task was to determine, via weld trials, if acceptable weld overlaps could be developed with the prototype equipment built for this project. Results from this task can be used to aid development of new HLAW systems that have the controls needed to assure high-quality, repeatable weld overlaps.

Overlap development was completed using a 400-µm spot size because it delivered the best results for all-position welding. A beam-to-wire spacing of 1-mm was held constant for all overlap trials. Travel speeds of 80- to 100-IPM were investigated. Several process variables were adjusted in an effort to identify the best procedure for overlaps in a narrow-groove joint configuration. These variables included:

- Laser power (constant power)
- Laser power (ramping)
- GMAW arc-start settings (WFS ramping)
- Initiation sequence (motion, GMAW power, and laser power)
- Overlap distance

Because of budget and timing constraints, this work was performed on test coupons cut from X80 and X100 pipes. The same joint configuration used in Task 7 (Figure 5a) was used for all overlap trials. Selected welds were cross-sectioned for visual quality inspection.

3.9 Task 9 – HLAW Process Evaluation for Meeting Toughness Requirements

This task consisted of a more thorough investigation into HLAW root toughness as a function of root thickness. Both X80 and X100 material were investigated. The majority of the work was focused on X80 material as it was more readily available. Three different root face thicknesses were evaluated: 4, 6, and 11 mm (Figure 5).

All welding for this task was done in the 1G position using a CNC workstation and fixed HLAW welding head. The range of process parameters used during this task is shown in Table 6.

Table 6. Parameters Used for Welding with different Root Face Thicknesses

Laser Spot Size	400-µm (4- and 6-mm root face) 333-µm (11-mm root face)
Laser Power	5-kW (4-mm root face) 7-kW (6-mm root face) 10-kW (11-mm root face)
Travel Speed	80-IPM (4- and 6-mm root face) 75-IPM (11-mm root face)
Wire Feed Speed	450- to 475-IPM – Pulsed GMAW
GMAW Shielding Gas	90%Ar – 10%CO_2 (60 CFH)
GMAW Travel Angle	25 to 30º push
Laser Beam to GMAW Electrode Spacing	2-mm (laser leading the arc)
Welding Positions	1G
Preheat and Interpass Temperatures	250ºF to 300ºF
Filler Material	ER90S-G, ER100S-1 (0.045-in)

Automated GMAW was used to add a hot pass and fill pass to the HLAW root pass to allow for mechanical testing of full section welds (Table 7).

Table 7. GMAW-P Hot Pass and Fill/Cap Pass Parameters for Various Root Face Thicknesses

Wire Feed Speed	350-IPM – Pulsed GMAW
Travel Speed	15-IPM
GMAW Shielding Gas	90%Ar – 10%CO_2 (40 CFH)
GMAW Travel Angle	10º push
Filler Material	ER90S-G and ER100S-1 (0.045-in)

API Standard 1104 was used as a guideline to collect mechanical property data for selected X80 and X100 hybrid welds. Toughness, strength, and weld soundness were tested via Charpy V-notch, transverse tensile, and bend tests, respectively. Cross-sections and hardness traverses were also used to evaluate the HLAW process.

4.0 Results

The results from this project are discussed below on a task-by-task basis.

4.1 Task 1 – Development of the Hybrid Laser Arc Welding Processes

Results from the initial HLAW development on machined grooves in X80 pipe are shown in Figure 6. The parameters used to produce the welds are shown in Table 8.

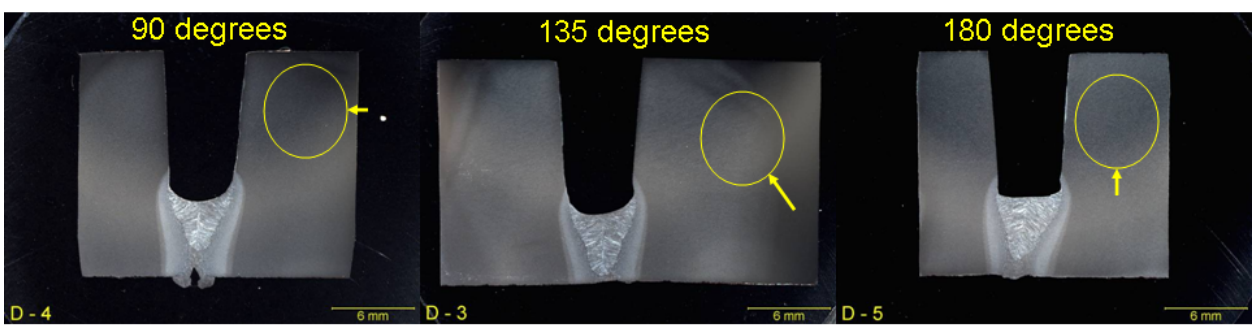


Figure 6. Initial HLAW Results (4-mm Root Face). Cross sections from X80 pipe welds on machined groove. Sections were taken from various positions around the pipe. Note the 'tandem' solidification resulting from a 6-mm beam-to-wire spacing.

Table 8. HLAW Parameters for Initial Welding Trials

Laser Spot Size	600-µm
Laser Power	4-kW (Nd:YAG)
Travel Speed	70-IPM
Wire Feed Speed	365-IPM – Pulsed GMAW
GMAW Shielding Gas	90%Ar – 10%CO_2 (60 CFH)
GMAW Travel Angle	30º push
Laser Beam to GMAW Electrode Spacing	6-mm (laser leading the arc)
Filler Material	ER90S-G (0.045-in)

A 'tandem' mode of solidification occurred when using the 6-mm beam-to-wire spacing. A distinct GMAW solidification profile can be seen in the cross-sections, indicating that filler metal did not mix with the laser weld. Further discussion on the effect of beam-to-wire spacing will be covered in the results from Task 7.

Results from cursory T-GMAW hot pass and fill pass trials are shown in Figure 7. Lack of fusion defects were found in all cross-sections. The parameters used to make the welds are shown in Table 9.

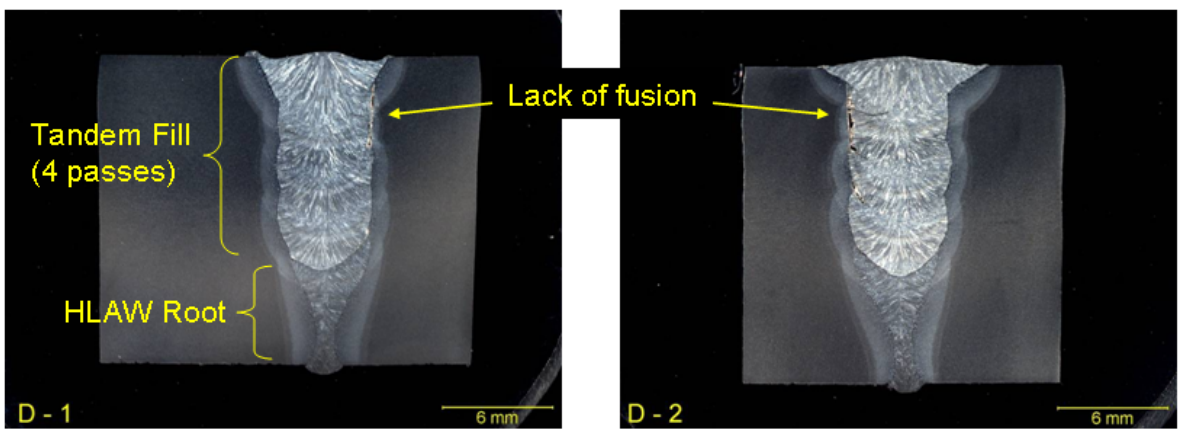


Figure 7. Tandem GMAW Fill Passes. Cross sections from X80 pipe welds on machined groove. Lack of fusion defects resulted from the initial tandem GMAW development work.

Table 9. T-GMAW-P Parameters for Hot Pass Trials

Lead Electrode – Short Circuit Metal Transfer	230 Amps, 18.5 Volts
Trail Electrode – Short Circuit Metal Transfer	230 Amps, 20 Volts
Travel Speed	60 IPM
GMAW Shielding Gas	90%Ar – 10%CO_2
Filler Material	ER90S-G (0.045-inch)

4.2 Task 2 – Property Testing of Preferred Welding Processes

The preferred HLAW parameters that were developed for X80 and X100 test joints with a 3-mm root face are shown below. Two different heat-inputs and filler metals were evaluated for each base material. The welds made using the lower travel speed (90 IPM) had a heat input that was about 25% higher than the welds made using the high travel speed (110 IPM) (Table 10).

Table 10. HLAW Parameters and Heat Input for Weld Property Testing

Base Material	Weld ID	Laser Power (kW)	Beam-to-Wire Spacing (in)	Travel Speed (IPM)	Wire Diameter (in)	Filler Metal	Amps	Volts	GMAW Heat Input (kJ/in)	Pre-heat (F)
X-80	618-3	5.0	0.04	90	0.045	ER100S-1 (Lincoln)	300	25	5.00	250
	618-4	5.5	0.04	110	0.045	ER100S-1 (Lincoln)	300	25	4.09	250
	618-2	5.0	0.04	90	0.045	ER90S-G	295	25	4.92	250
	617-1	5.5	0.04	110	0.045	ER90S-G	295	25	4.02	250
X-100	528-18	5.0	0.16	90	0.062	ER100S-1 (ESAB)	340	24.5	5.55	240
	528-11	5.0	0.16	110	0.062	ER100S-1 (ESAB)	315	23	3.95	215
	529-6	5.0	0.16	90	0.045	ER100S-1 (Lincoln)	305	26	5.29	250
	529-10	5.0	0.16	110	0.045	ER100S-1 (Lincoln)	295	25	4.02	250

A sample of the results from the Vickers hardness tests is shown in Figure 8 and Figure 9. Prior to adding the hot pass, fusion zone (FZ) and heat affected zone (HAZ) hardness levels for the X80 material averaged 321- and 278-HVN respectively. After the hot pass was added the hardness dropped to an average of 263- and 235-HVN, respectively. A similar trend was seen on the X100 material. The following tables summarize the data to further illustrate the effect of the hot pass, Table 11.

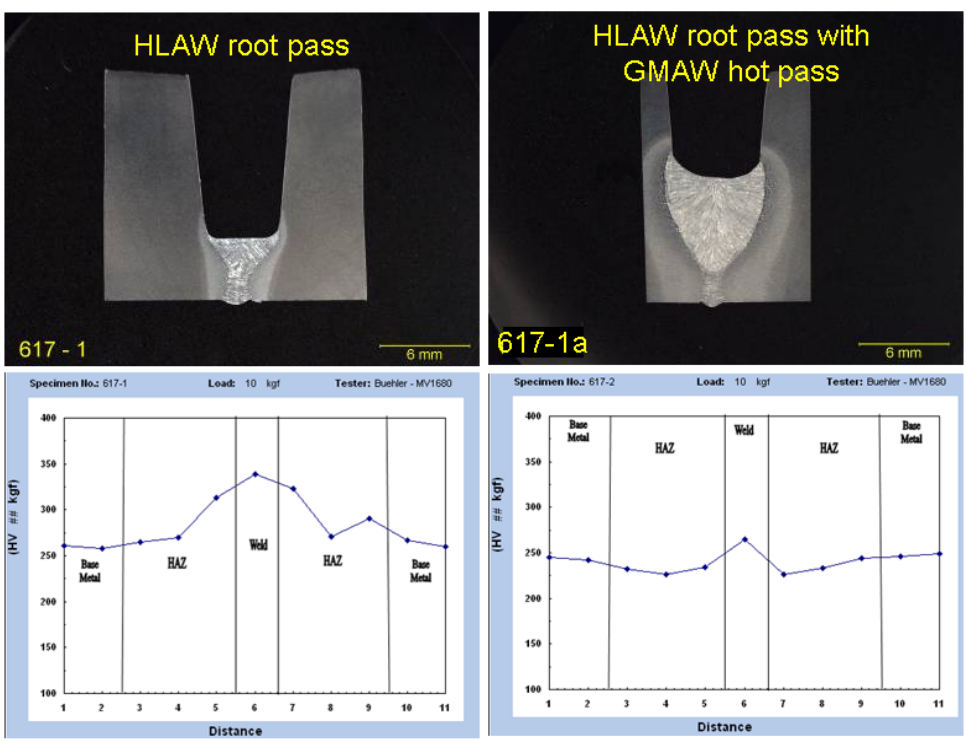


Figure 8. Hardness Results for X80 Hybrid Welds (3-mm Root Face). Image on the left shows the as-welded hardness (250°F preheat). Image on the right illustrates the tempering from a hot-pass.

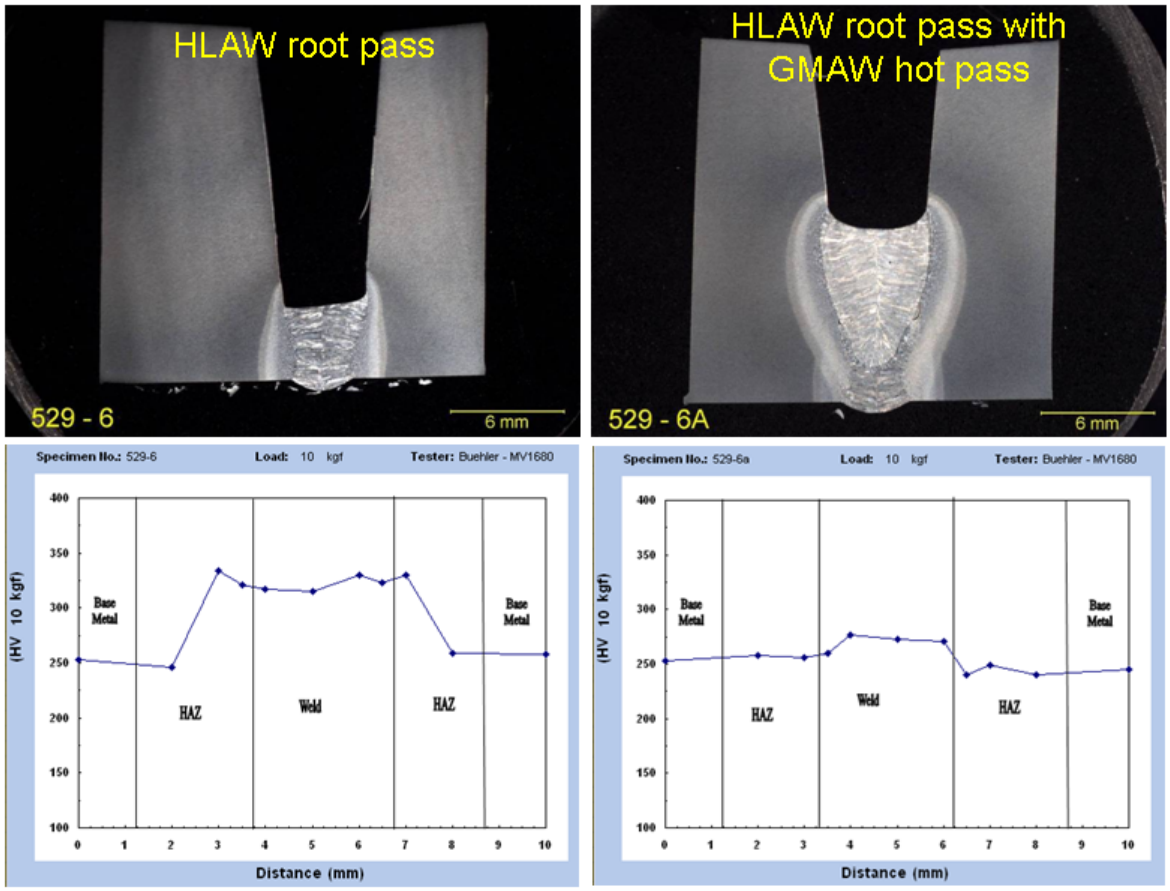


Figure 9. Hardness Results for X100 Hybrid Welds (3-mm Root Face). Image on the left shows the as-welded hardness (250°F preheat). Image on the right illustrates the tempering from a hot-pass.

Table 11. Hardness Values for X80 and X100 Pipe

Material	Weld ID	Process	Heat Input	Filler	Average Base Material HVN	Average HAZ HVN	Average Fusion Zone HVN
X80	618-3	HLAW Root Pass	High	ER100S-1 (0.045-in)	260	270	309
	618-4	HLAW Root Pass	Low	ER100S-1 (0.045-in)	260	283	313
	618-2	HLAW Root Pass	High	ER90S-G (0.045-in)	260	271	321
	617-1	HLAW Root Pass	Low	ER90S-G (0.045-in)	260	289	339
				Average:	**260**	**278**	**321**
	618-3	After GMAW Hot Pass		ER100S-1 (0.045-in)	249	233	266
	618-4	After GMAW Hot Pass		ER100S-1 (0.045-in)	249	239	256
	618-2	After GMAW Hot Pass		ER90S-G (0.045-in)	249	233	264
	617-1	After GMAW Hot Pass		ER90S-G (0.045-in)	249	233	265
				Average:	**249**	**235**	**263**

Material	Weld ID	Process	Heat Input	Filler	Average Base Material HVN	Average HAZ HVN	Average Fusion Zone HVN
X100	528-18	HLAW Root Pass	High	ER100S-1 (ESAB 0.062-in)	255	291	323
	528-11	HLAW Root Pass	Low	ER100S-1 (ESAB 0.062-in)	255	325	343
	529-6	HLAW Root Pass	High	ER100S-1 (Lincoln 0.045-in)	255	298	321
	529-10	HLAW Root Pass	Low	ER100S-1 (Lincoln 0.045-in)	255	293	327
				Average:	**255**	**302**	**329**
	528-18	After GMAW Hot Pass		ER100S-1 (ESAB 0.062-in)	242	269	269
	528-11	After GMAW Hot Pass		ER100S-1 (ESAB 0.062-in)	242	276	259
	529-6	After GMAW Hot Pass		ER100S-1 (Lincoln 0.045-in)	242	249	270
	529-10	After GMAW Hot Pass		ER100S-1 (Lincoln 0.045-in)	242	261	287
				Average:	**242**	**264**	**271**

For both filler metals tested on the X80 material, the HLAW root passes made at the higher heat inputs resulted in lower hardness levels. The lowest 'as welded' root pass hardness levels were obtained with the ER100S-1 filler. The same trend was seen on the X100 material when the 0.062-in. ESAB filler metal was used. The welds made using the 0.045-in. Lincoln filler did not follow the same trend. A more substantial set of data points and weld trials would be required to determine if this was a direct result of the filler metal composition or some other factor.

X80 welds 618-2 (high heat-input) and 617-1 (low heat-input), along with X100 welds 529-6 (high heat-input) and 529-10 (low heat-input) were selected for additional mechanical testing. For the two X80 welds that were tested, all four cross-weld tensile specimens yielded above 80 ksi with an Ultimate Tensile Strength (UTS) above 100 ksi. For both welds, one tensile specimen failed in the base metal and one in the weld metal. For the failures that occurred in the weld metal it appears as though porosity was entrapped in the hot pass (Figure 10). Welds that failed in the base metal resulted in better elongation.

Figure 10. Tensile Results for X80 Hybrid Welds (3-mm Root Face). Specimen on the left shows a failure in the weld metal due to porosity located in the GMAW hot pass. Both specimens yielded above 80 ksi at room temperature.

Charpy V-notch specimens from the X80 welds were prepared with a T-L notch orientation (per AWS 4.0) along the weld centerline. Weld 617-1 (low heat input) exhibited better toughness at elevated temperatures (Figure 11). Transition temperatures (based on a fracture appearance of 50% shear) ranged from -96°C to -59°C (-110°F to -85°F).

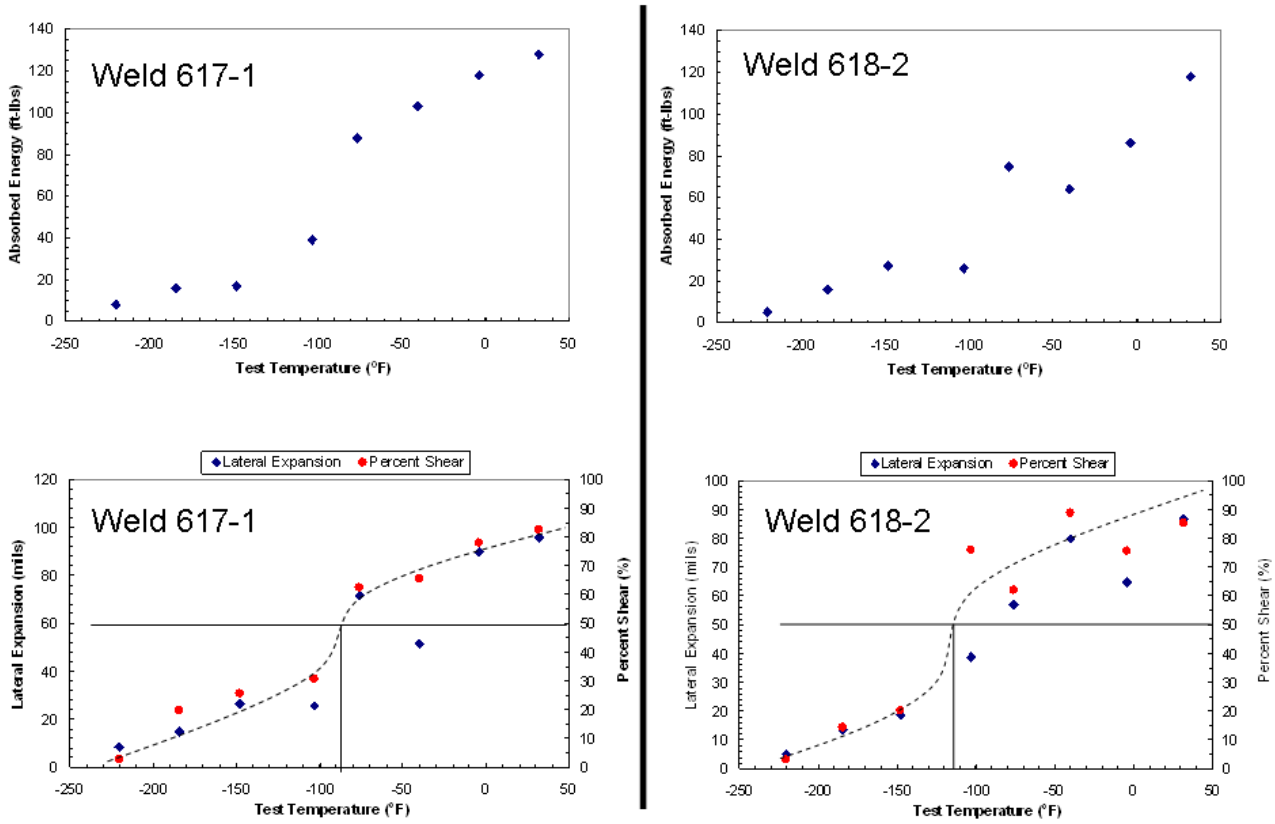


Figure 11. Toughness Results for X80 Hybrid Welds (3mm Root Face). Graphs on the left show results from the lower heat input weld (110 IPM travel speed). Graphs on the right show results from the higher heat input weld (90 IPM travel speed).

Results of the bend tests on X80 welds were mixed. Two face bends and two root bends were completed on each weld. Both face bends for Weld 618-2 (high heat-input) failed, but the root bends both passed (Figure 12). The face bend failures were once again the result of porosity located in the hot pass. All four bend tests for Weld 617-1 passed (Figure 13). It is important to note that the bend tests completed during this task were not performed to API Standard 1104. Per API Standard 1104, a 1.75-in. mandrel/plunger radius is specified for all root, face, and side bends. For this task a 0.75-in. mandrel radius was used, which resulted in much greater strain on the welds than what is required per API Standard 1104.

Results from the two cross-weld tensile specimens for X100 weld 529-10 (low heat-input) were inconsistent. One weld yielded and eventually failed in the weld metal at a load of less than 80-ksi. No obvious inclusions or pores were noted upon completion of the test. The second tensile specimen from this weld yielded at a load of 106 ksi and failed in the weld metal at 111 ksi. Tensile results from Weld 529-6 (high-heat input) were more consistent. Both tensile specimens from this weld yielded above 100 ksi and failed in the weld metal at a load just above 106 ksi (Figure 14).

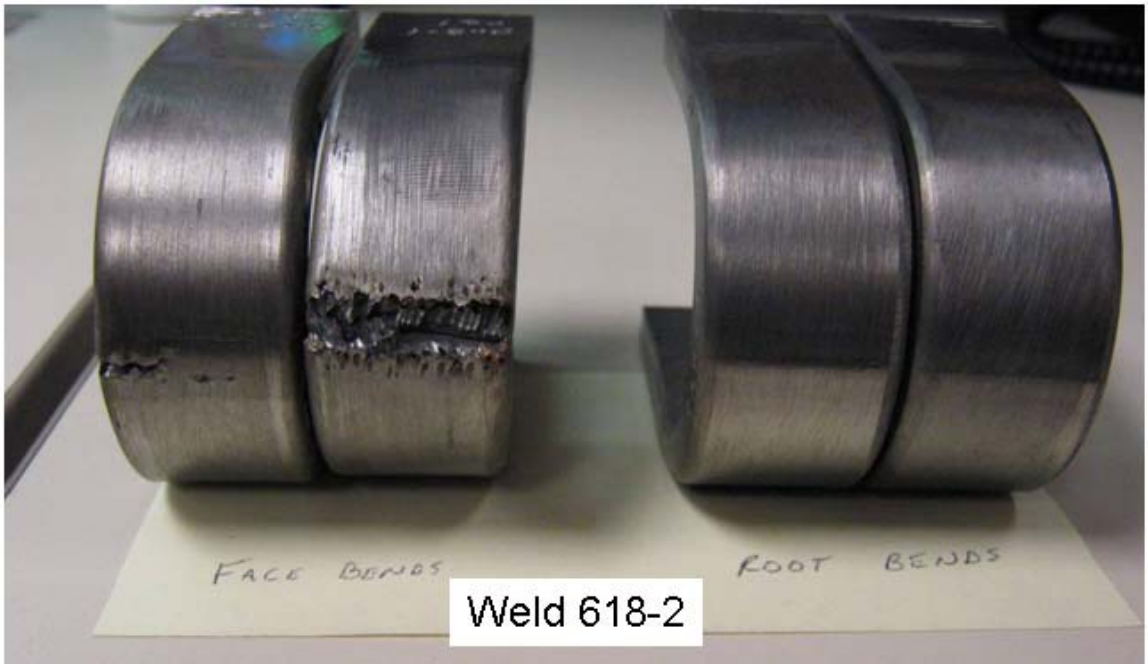


Figure 12. Bend Test Results for X80 Hybrid Welds (3-mm Root Face). Specimens on the left show failures due to porosity in the GMAW hot pass. Specimens on the right show acceptable weld soundness in the HLAW root pass.

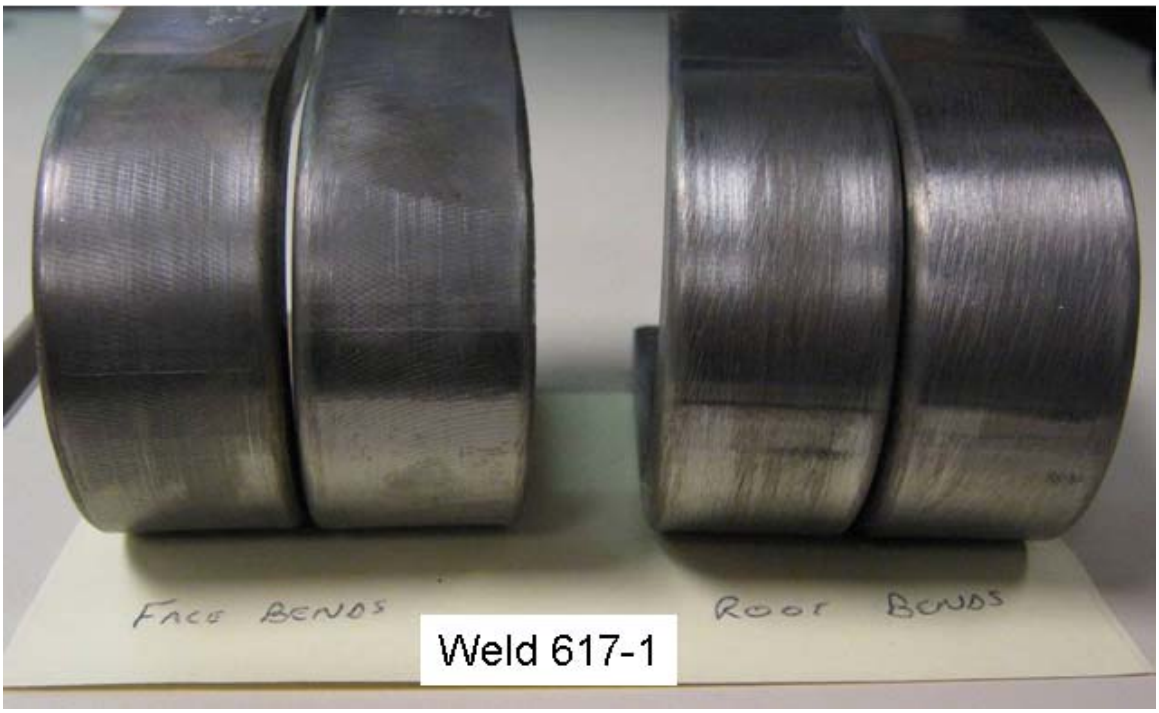


Figure 13. Bend Test Results for X80 Hybrid Welds (3-mm Root Face). Acceptable face bends resulted when porosity was not entrapped in the hot pass. Specimens on the right show acceptable weld soundness in the HLAW root pass.

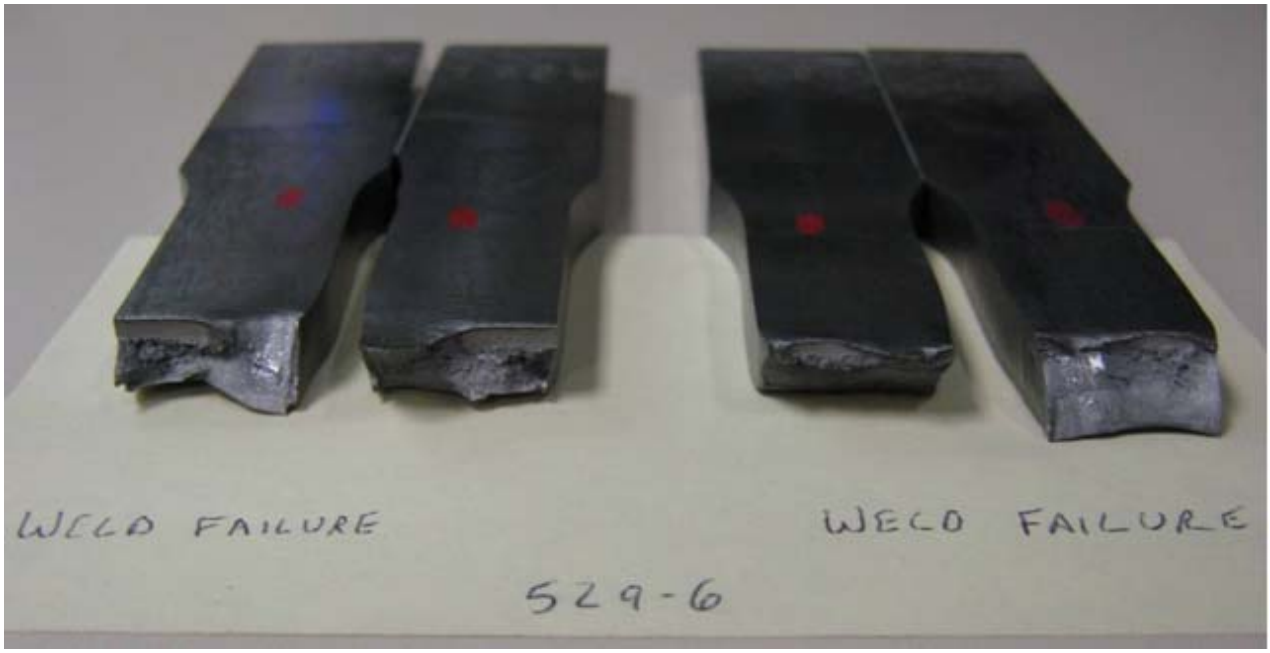


Figure 14. Tensile Results for X100 Hybrid Welds (3-mm Root Face). Both specimens yielded in the weld metal above 100 ksi

Charpy V-notch specimens from the X100 welds were also prepared with a T-L notch orientation (per AWS 4.0) along the weld centerline. The toughness and fracture appearance curves for these welds were more erratic than the X80 welds, and did not reveal an obvious ductile-to-brittle transition temperature (Figure 15). Weld 529-10 (low heat input) exhibited very poor toughness even at elevated temperatures. Weld 529-6 (high heat input) had better toughness at elevated temperatures, but still exhibited inconsistent results.

Results of the bend tests on X100 welds corresponded well to the tensile and toughness data. Weld 529-10 (low heat-input), which exhibited poor tensile strength and toughness, failed three of the four bend tests. The two root bends broke and one of the face bends exhibited a large crack down the centerline of the hot pass (Figure 16). Weld 529-6 (high heat-input), which showed better tensile strength and toughness, passed three of the four bend tests. One face bend exhibited a large crack down the centerline of the hot pass (Figure 17).

This task provided a small sampling of data for X80 and X100 material welded with the HLAW process. More significant and consistent data was obtained during testing for welds made in Task 9.

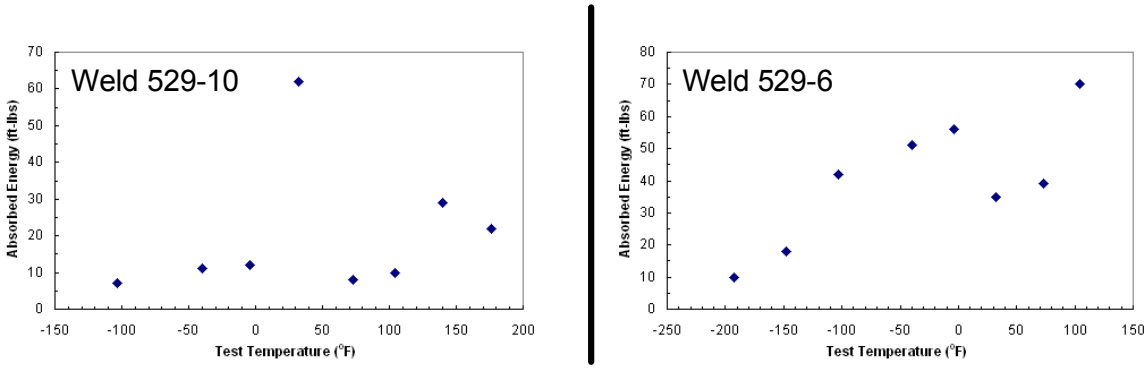


Figure 15. Toughness Results for X100 Hybrid Welds (3-mm Root Face). Graphs on the left show results from the lower heat input weld (110 IPM travel speed). Graphs on the right show results from the higher heat input weld (90 IPM travel speed).

Figure 16. Bend Test Results for X100 Hybrid Welds (3-mm Root Face). Failures resulted from face and root bends on the weld made with lower heat input.

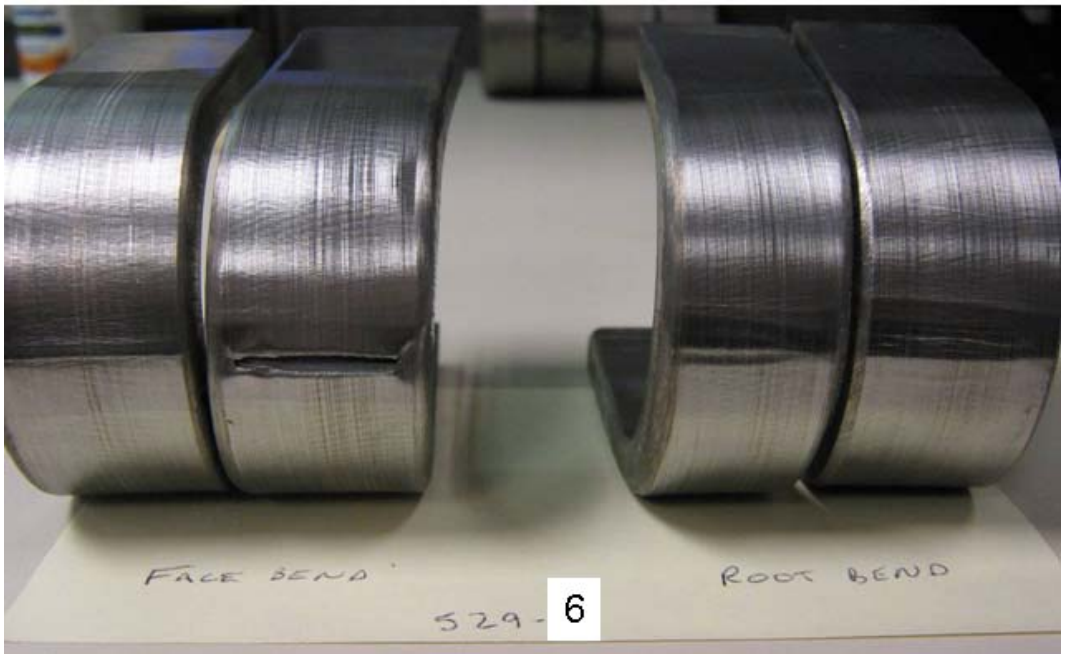


Figure 17. Bend Test Results for X100 Hybrid Welds (3-mm Root Face). Root bends improved using a higher heat input welding process. Face bends still failed in the GMAW hot pass.

4.3 Task 3 – Use of Integrated Data Acquisition and Laser Sensors for Hybrid Welding

The data acquisition system constructed for HLAW successfully combined arc and laser welding process variables into one unit. This allowed arc welding waveforms to be directly compared to its laser welding counterpart. Timing between arc pulses and laser power pulses were studied for optimization. The system was primarily used for early process development, and was not needed once optimized parameters were found.

The seam tracking system did not reach a successful conclusion. During construction and testing it was discovered that there were three significant variables which contributed to variations in torch position.

- Imperfect band alignment
- Imperfect joint alignment
- Gravitational bug shift

Both imperfect band and joint alignment were expected and unavoidable in real-world conditions. The gravitational bug shift however, was not expected, and was not repeatable. Therefore, the seam tracking objective was scraped. Instead cross tracking was performed manually during welding.

4.4 Task 4 – Field Deployment and Operator Training

To enable a demonstration to be performed outside the EWI facility, both FDA and FAA approvals were required since EWI is seven nautical miles from Port Columbus International Airport (CMH).

An FDA/CDRH Accession number and FAA approval were received for the demonstrations to be conducted (FAA 7400).

In order to meet all FAA and FDA safety requirements, several features were added to the HLAW system prior to the outdoor demonstration and workshop. These additions included:

- E-stop circuit located on the CRC-Evans control stand that would prevent the laser from firing when depressed.
- Three proximity switches mounted to the P450 bug to ensure the laser could not be fired if the bug was not properly situated on the pipe.
- Four LED's mounted to the P450 bug to alert observers when the laser was on.

Another safety feature that was in effect was a 'dead-man' switch that had to be depressed in order to fire the laser. An EWI employee was also stationed at the E-stop located on the laser power supply as a redundancy. In addition, a large tent (Figure 18) was set up outside EWI's building to protect the equipment from the environment and to control access to the demonstration area. The "parking lot" demonstration of hybrid laser girth welding demonstrated the advantages of fiber laser capabilities:

- Local Power – Diesel Generator
- Local Cooling – Simulated; small chillers were difficult to rent
- Compact Envelope
- 5.5 kW used at 2.0 m/min. TS (80 in/min.)

Two demonstrations of the technology were conducted, the first in April 2008 as a deliverable on the cost-matched JIP, and the second in September 2009 as a deliverable for this project. In both cases complete girth weld root passes were produced. The later DOT demo was conducted at 2.0 m/min. travel speed and with an unbacked joint (no internal root pass) as parameters were further developed from the 1.8 m/min. travel speed used for the JIP demo which used an internal root pass.

Because of the large number of people in attendance (27) at the 2009 demonstration, and space limitations in the tent, two separate demonstrations were performed. To save time, two pipe bands were attached and aligned to the pipe joints prior to each demonstration (Figure 19). After welding one side of the pipe the P450 bug was transferred to the other band and run in the opposite direction to complete the weld. Each demonstration produced successful, full-penetration welds using the double-down technique. Videos and pictures were taken during the demonstration, but no mechanical testing was completed on the demonstration welds (Figure 20).

Following the workshop, the participants were asked to provide feedback as to how useful they found each aspect of the workshop to be. Of the 27 participants, 17 responded to the survey. The survey gave participants the opportunity to rate the workshop as a whole, as well as each individual presentation. They were also asked to rate the tour of the EWI laboratory, the demonstration of the resistance cladding operation and the demonstration of the HLAW process. Overall, the feedback was very positive (Figure 21).

Figure 18. Welding Power Generator and Welding Tent for HLAW Demonstration

Figure 19. Example of Set-Up for Demonstration Welds. Two bands were attached to the pipe and aligned with the joint prior to making the demonstration welds.

Figure 20. Demonstration Welds. From left to right – view of HLAW process from outside the pipe, view of full penetration HLAW process from inside the pipe, finished weld appearance on ID of the pipe

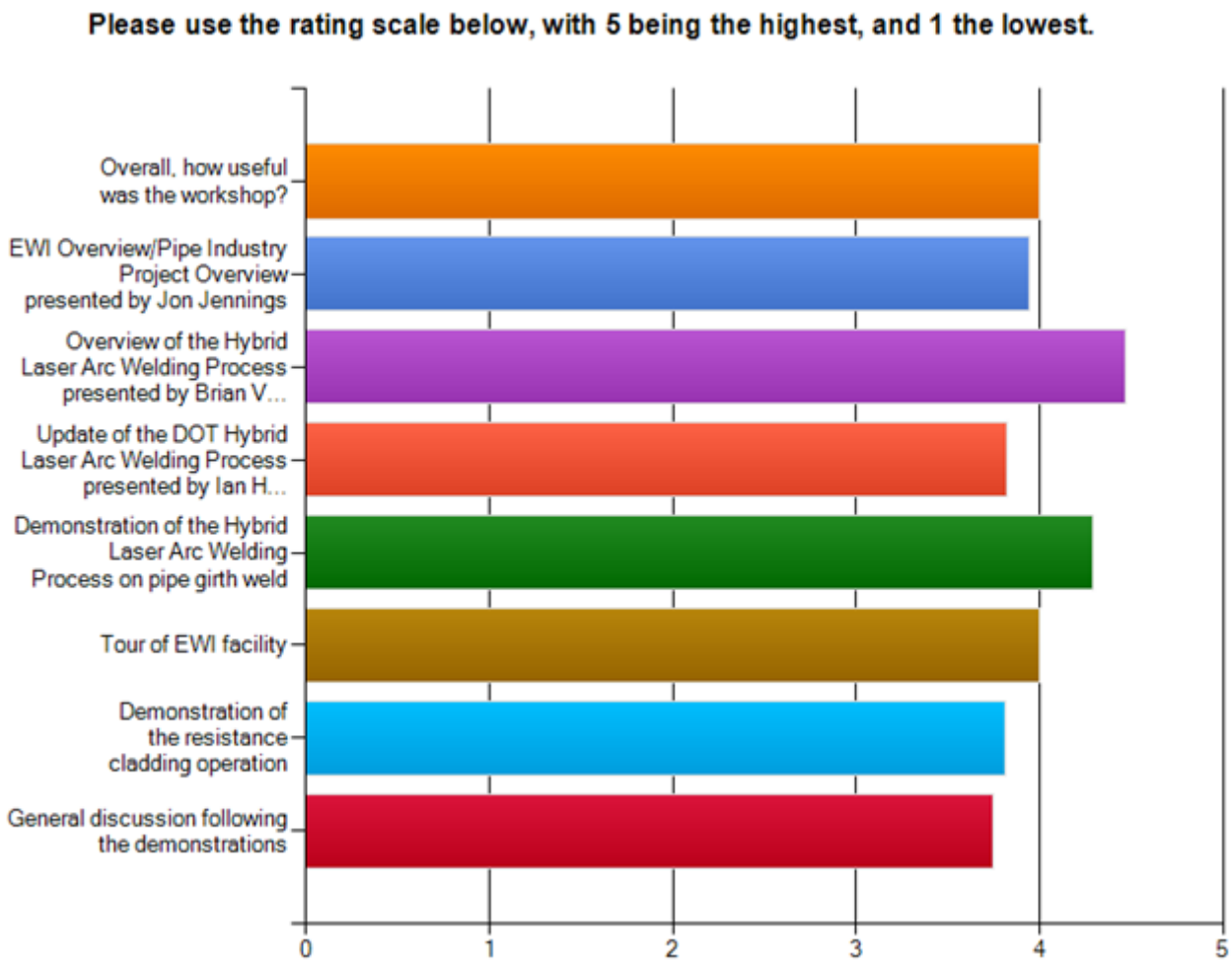


Figure 21. Feedback from HLAW Workshop and Demonstration

4.5 Task 5 – Productivity Analysis

The results from the Productivity Analysis are attached as Appendix A.

4.6 Task 6 – Progress Meetings, Pipeline Conference, Annual Panel Peer Review, and Reporting

Papers were presented at the International Pipeline Conference in Calgary, Alberta, Canada in September 2008, and at Rio Pipeline 2009 in Rio de Janeiro, Brazil.[7,8]

Two Annual Peer Reviews conducted during the project were scored highly.

4.7 Task 7 – Study of Beam-to-Wire Spacing, Travel Speed, and Solidification Morphology

Results from the 1G trials at 80-IPM are shown in Figure 22. The parameters used to produce the welds are shown in Table 12.

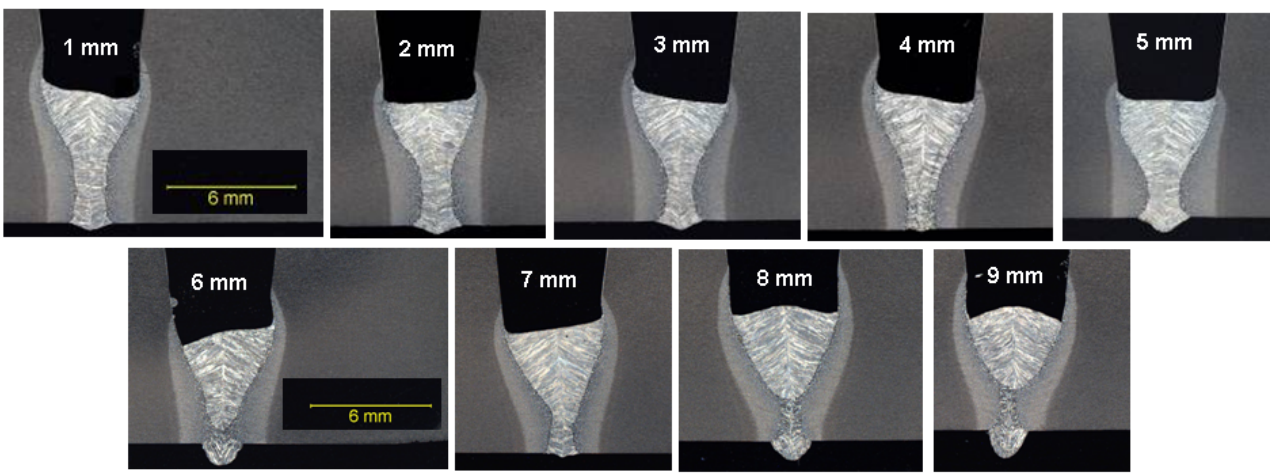


Figure 22. Effect of Beam-to-Wire Spacing (1G – 80IPM, 600µm spot size). Solidification transferred from hybrid to tandem at a spacing between 5 and 6-mm

Table 12. HLAW Parameters for Beam-to-wire Spacing Trials

Laser Spot Size	600-µm
Laser Power	5-kW (Yb-Fiber)
Travel Speed	80-IPM
Wire Feed Speed	450-IPM
GMAW Shielding Gas	90%Ar – 10%CO_2 (65 CFH)
GMAW Travel Angle	30º push
Laser Beam to GMAW Electrode Spacing	1- to 9-mm (laser leading the arc)
Welding Positions	1G
Filler Material	ER90S-G (0.045-in)

Using these parameters, the solidification morphology changed from hybrid to tandem at a beam-to-wire spacing between 5- and 6-mm. All welds made with spacing at or below 5-mm resulted in a desirable top and backside profile, and displayed a hybrid solidification mode. Welds made with spacing equal to or greater than 6-mm did not result in consistent top or backside profiles and solidified in the tandem mode (Figure 23).

Results from the 1G trials at 100-IPM are shown in Figure 24. With the exceptions of the travel speed and wire feed speed, the same parameters used for the 80-IPM trials were used for these welds (Table 13).

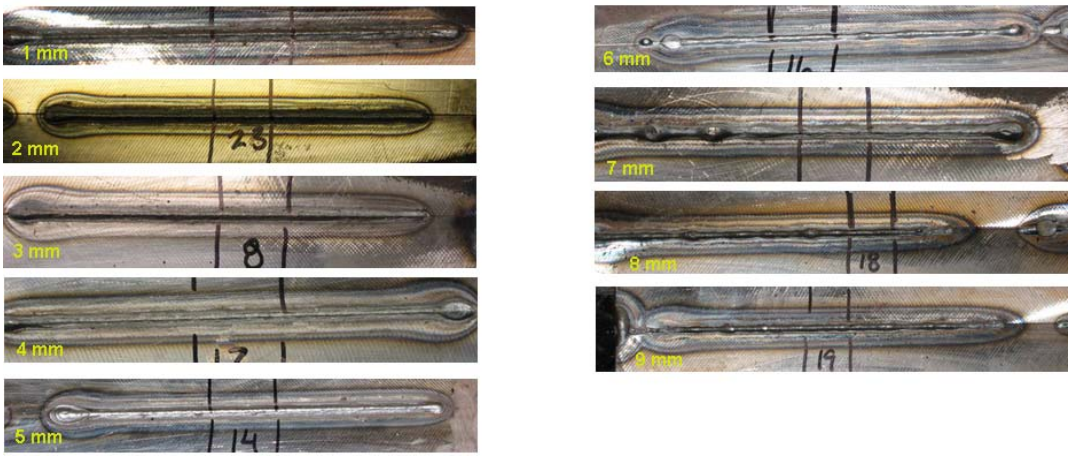


Figure 23. Effect of Beam-to-Wire Spacing (1G – 80IPM , 600µm spot size). A smooth root profile resulted at a spacing of 1, 2, 3, 4, and 5 mm (hybrid solidification). Backside humping occurred at larger spacing (tandem solidification).

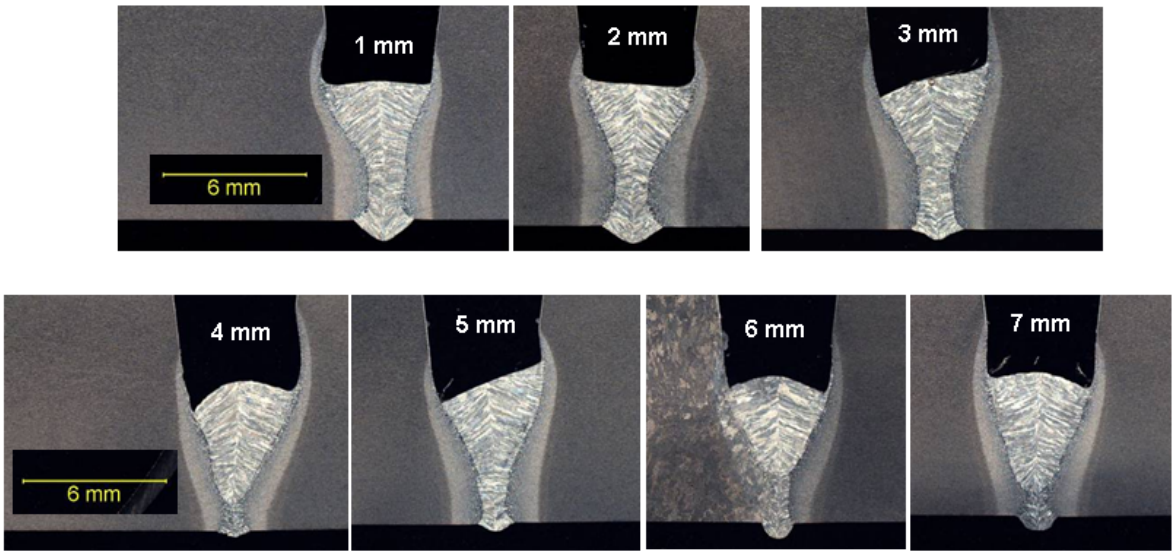


Figure 24. Effect of Beam-to-Wire Spacing (1G – 100IPM , 600µm spot size). Solidification transferred from hybrid to tandem at a spacing between 3 and 4 mm when the travel speed increased to 100 IPM.

Table 13. HLAW Parameters for the 1G Position at 100 in/min Travel Speed

Laser Spot Size	600-µm
Laser Power	5-kW (Yb-Fiber)
Travel Speed	100-IPM
Wire Feed Speed	575-IPM
GMAW Shielding Gas	90%Ar – 10%CO_2 (65 CFH)
GMAW Travel Angle	30º push
Laser Beam to GMAW Electrode Spacing	1- to 7-mm (laser leading the arc)
Welding Positions	1G
Filler Material	ER90S-G (0.045-in)

At the higher travel speed, the solidification morphology changed from hybrid to tandem at a closer beam-to-wire spacing. A transition can be seen in the cross-sections at spacings between 3 and 4 mm. All welds made with spacing at or below 3 mm resulted in a desirable top and backside profile and displayed a hybrid solidification mode.

Similar to the trials at 80 IPM, an unfavorable interaction between the laser keyhole and GMAW pool occurred at a spacing of 4 mm. At that spacing, backside solidification inconsistencies started to appear and the solidification mode appeared to be tandem. However, an improvement to the weld quality was seen as the spacing was increased to 5-mm. Further increase of the spacing had a negative impact on solidification morphology and backside consistency (Figure 25). This was a similar trend to the results at 80 IPM.

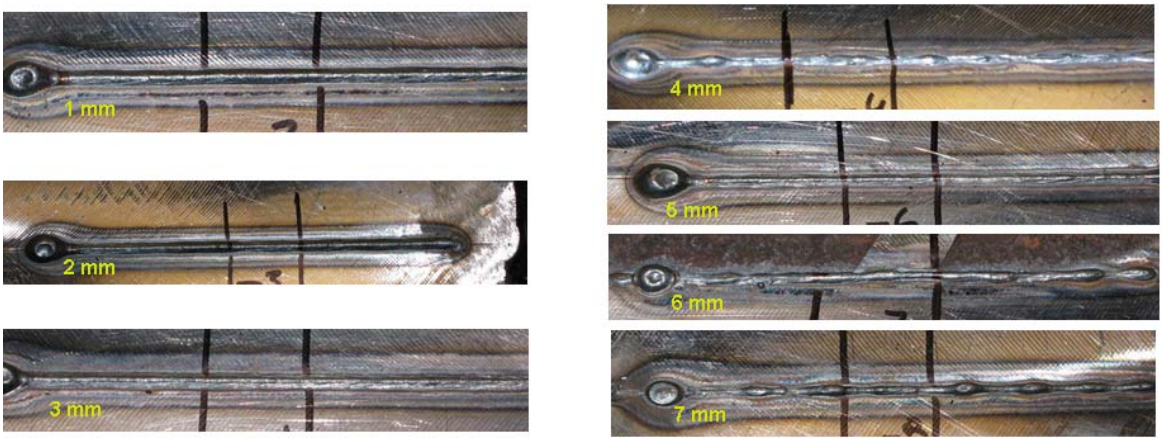


Figure 25. Effect of Beam-to-Wire Spacing (1G – 100IPM , 600µm spot size). A smooth root profile resulted at a spacing of 1, 2, 3, and 5 mm (hybrid solidification). Backside humping occurred at 4, 6, and 7 mm (tandem solidification).

Initial attempts to produce an acceptable 3G (vertical down) HLAW weld at 100-IPM using the same parameters used for the 1G position were not successful. Weld metal was expelled from the joint prior to solidifying. The travel speed was reduced to 90 IPM in an attempt to produce welds suitable for solidification morphology data. The parameters used are shown in Table 14.

Table 14. HLAW Parameters for 3G Welding Position

Laser Spot Size	600-µm
Laser Power	5-kW (Yb-Fiber)
Travel Speed	90-IPM
Wire Feed Speed	600-IPM
GMAW Shielding Gas	90%Ar – 10%CO_2 (65 CFH)
GMAW Travel Angle	30º push
Laser Beam to GMAW Electrode Spacing	1- to 4-mm (laser leading the arc)
Welding Positions	3G
Filler Material	ER90S-G (0.045-in)

Although the solidification profile remained in the hybrid mode at a spacing of 4 mm, trials were stopped because the backside profile became erratic at that point. Root concavity was observed at a spacing of 1- and 2-mm. Solidification cracks were observed at a spacing of 3 and 4 mm (Figure 26).

Additional changes were made to the welding parameters in order to reduce the amount of root concavity. The laser spot size was reduced to 400-µm and the travel speed was lowered to 80-IPM. The increased power density resulting from using a smaller spot size allowed for less laser power to be used. The wire feed speed was also reduced (Table 15).

Cross-sections from these welds show a reduction in the amount of root concavity (Figure 27). A weld made with 3-mm spacing did not result in an acceptable backside profile, so no additional spacing was investigated.

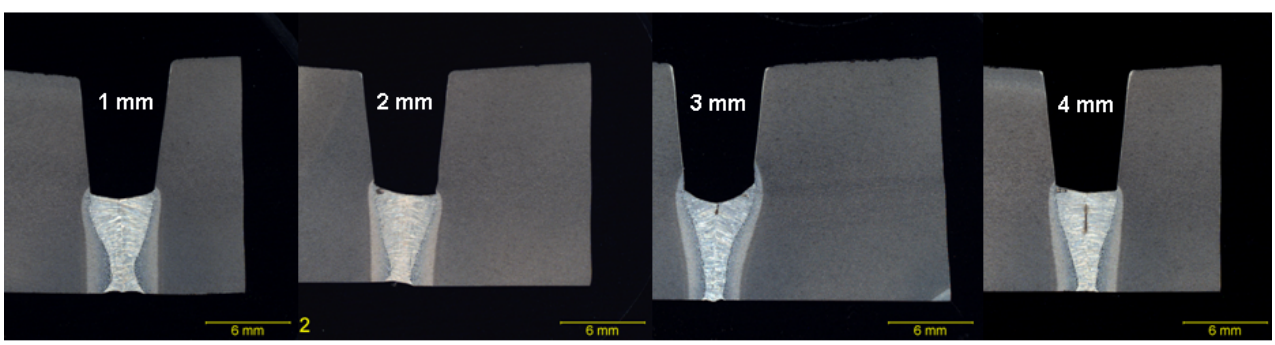


Figure 26. Effect of Beam-to-Wire Spacing (3G – 90IPM, 600µm spot size). Solidification remained hybrid at spacing up to 4 mm. Root concavity was noticed when a 1 and 2 mm spacing was used. Centerline cracking occurred at a spacing of 3 and 4 mm.

Table 15. HLAW Parameters for Reduced Root Concavity in the 3G Position

Laser Spot Size	400-µm
Laser Power	4-kW (Yb-Fiber)
Travel Speed	80-IPM
Wire Feed Speed	450-IPM
GMAW Shielding Gas	90%Ar – 10%CO_2 (65 CFH)
GMAW Travel Angle	30º push
Laser Beam to GMAW Electrode Spacing	0 to 3-mm (laser leading the arc)
Welding Positions	3G
Filler Material	ER90S-G (0.045-in)

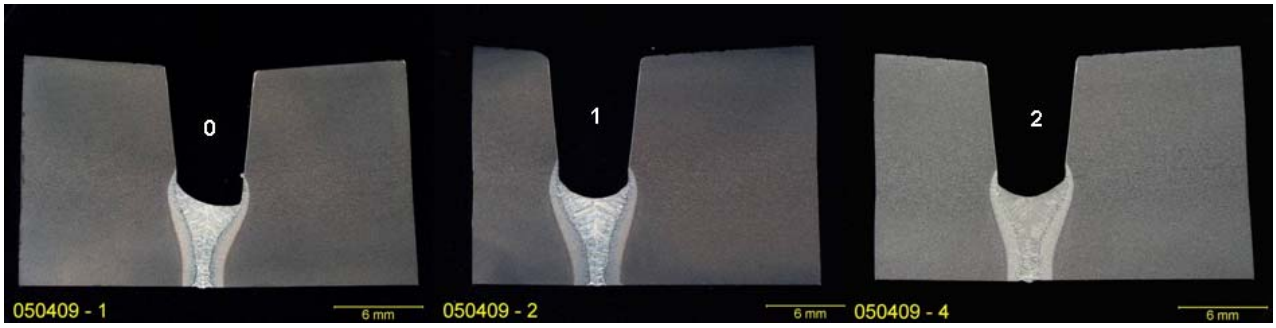


Figure 27. Effect of Beam-to-Wire Spacing (3G – 80IPM , 400µm spot size). Less root concavity resulted when a smaller spot size and slower travel speed was used.

Initial 4G welding trials were completed using the 600-µm spot size and travel speeds of 90 and 100 IPM. Similar to the 3G trials, welds of acceptable quality were not obtained using these parameters. Root concavity and topside inconsistencies (in the U-groove) were among the biggest issues. However, welds made in the 4G position using the parameters that were successful in the 3G position had much better results. Beam-to-wire spacing of 1 to 3 mm resulted in hybrid solidification and consistent back-side profiles with minimal root concavity (Figure 28). Welds made using these parameters and a spacing larger than 3 mm began to lose both topside and backside consistency.

Because of the positive results using a smaller spot size and lower travel speed in the 3G and 4G positions, a few welds were made using the same parameters in the 1G position and similar results were obtained (Figure 29).

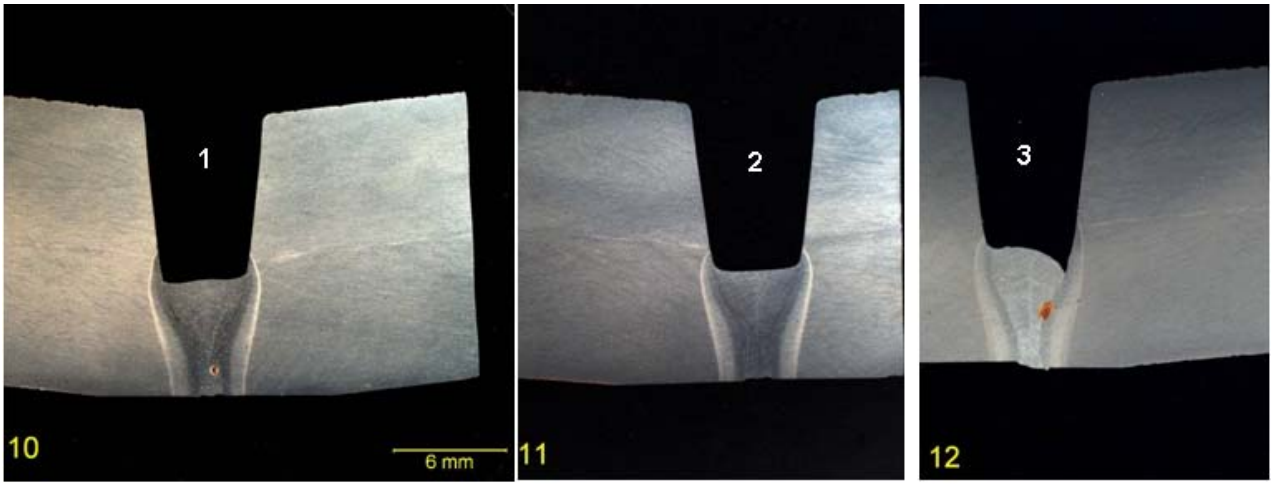


Figure 28. Effect of Beam-to-Wire Spacing (4G – 80IPM , 400µm spot size). Acceptable weld profiles resulted at spacing at or below 3 mm

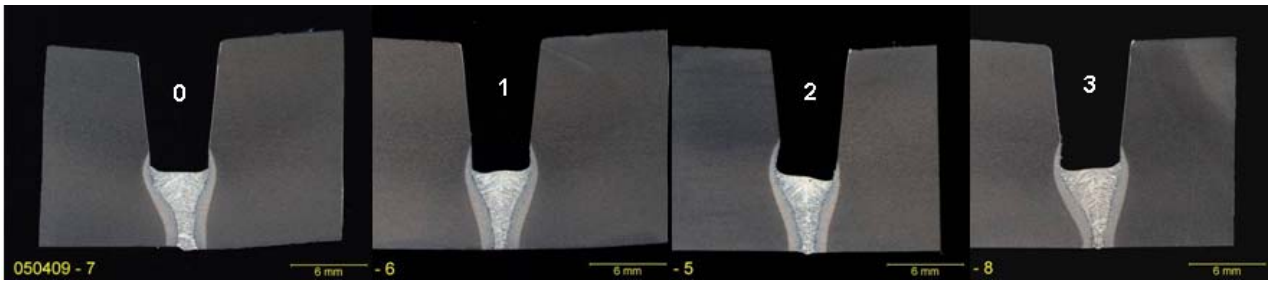


Figure 29. Effect of Beam-to-Wire Spacing (1G – 80IPM , 400µm spot size). Successful welding parameters from 3G and 4G welding were confirmed in the 1G position

4.8 Task 8 – Start-Stop Development with Hybrid Laser GMAW System

Start/start overlap development was completed in the 1G position. For the first (bottom) weld, the best HLAW starts occurred when first initiating the travel (90 IPM), followed by starting the GMAW process, and then firing the laser at a constant power (5 kW for this root thickness). No intentional delays were programmed between the starting of each process. The only delays came from mechanical or electrical delays inherent to the systems being used (fractions of a second). This sequence resulted in a full penetration weld with acceptable topside and backside profiles (Figure 30). Because the GMAW was fired just prior to the laser, a small area of partial penetration weld could be present in the groove at the very start of the weld. This area was consumed by the start of the second (top) weld, so that full penetration was obtained at the overlap.

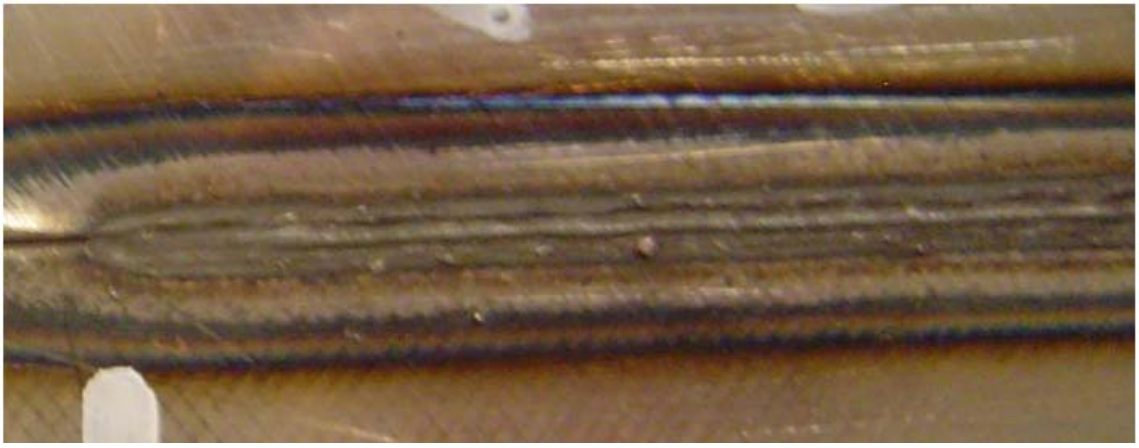


Figure 30. Target HLAW Root Profile. Smooth profile with positive reinforcement

To minimize the throat thickness at the start of the bottom weld the 'arc-start' feature of the Lincoln i400 was used. This feature allowed the user to program lower WFS at the start of the GMAW process for a specified time. For these trials, an arc-start WFS of 350 IPM was used for two seconds. After two seconds the WFS automatically ramped to the programmed feed speed of 475 IPM. This resulted in roughly a 3-in. long section at the start of the weld with a reduced throat thickness.

When the same sequence and parameters were used to start the overlapping weld, large humps would form on the backside of the overlap area (Figure 31). The humps were the result of an unstable keyhole caused by insufficient laser power for the increased thickness being penetrated. In order to establish a stable keyhole through the first weld, higher laser power was used. However, top welds that were made using a constant laser power of 6.5 to 8 kW still produced a single hump on the backside of the weld where the laser first penetrated the joint (Figure 31).

By implementing a two-stage ramp of the laser power, overlaps with better consistency were obtained (Figure 32). Instead of using an instantaneous 8 kW of laser power, the laser was programmed to initially fire at 2 kW, ramp to 3 kW, and then rapidly ramp to 8.5 kW within one second (Figure 33). The short ramp-up time ensured that the HLAW process was in full penetration mode prior to reaching the start of the bottom weld (Figure 34).

Stop/stop overlap development was completed in the 4G position. The first (bottom) weld was made using similar parameters from successful 3G and 4G welding in Task 7 (80 IPM, 5 kW). There were no issues with these welds. The second (top) weld was made using a higher laser power (7 to 8 kW) than the bottom weld in order to fully penetrate the increased thickness at the overlap. The sequence used to stop the weld was as follows:

- Stop the travel
- Turn off the laser
- Turn off the GMAW

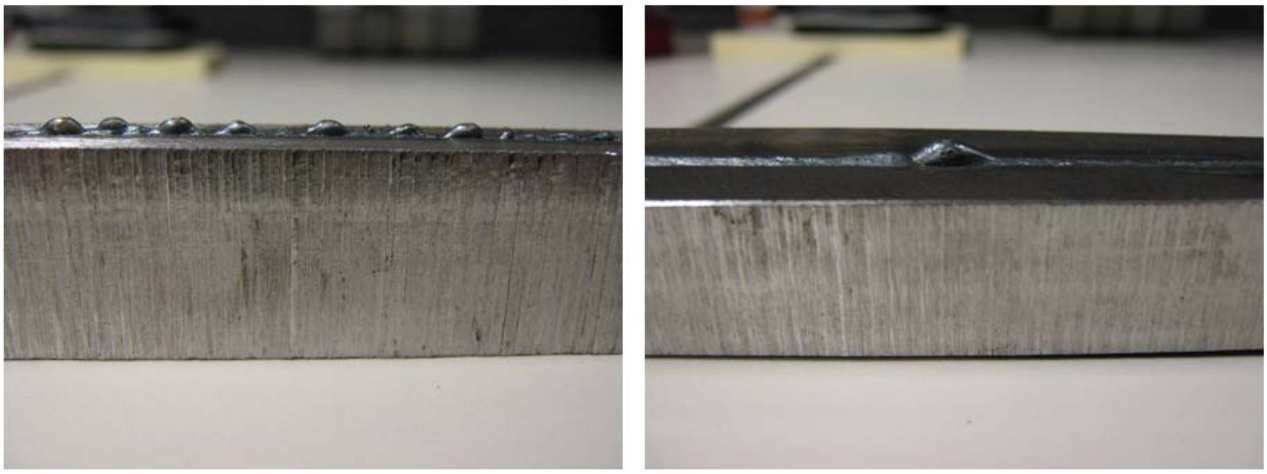


Figure 31. Unacceptable Root Profile. Backside humping seen on the left resulted from an unstable keyhole at insufficient laser power. The large hump seen on the right resulted when full penetration was attempted at the start of an overlap weld.

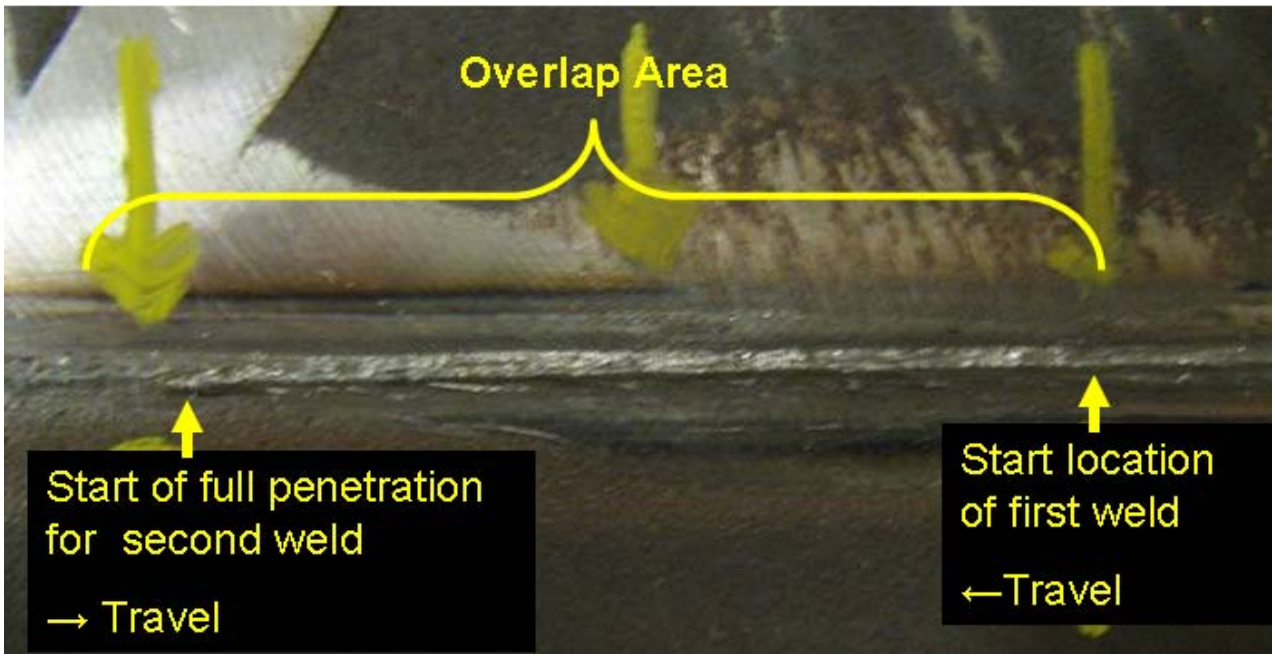


Figure 32. Acceptable Start Overlap. By implementing a two-stage ramp of the laser power, overlaps with better consistency were obtained. Large backside humps were eliminated by ramping the laser power.

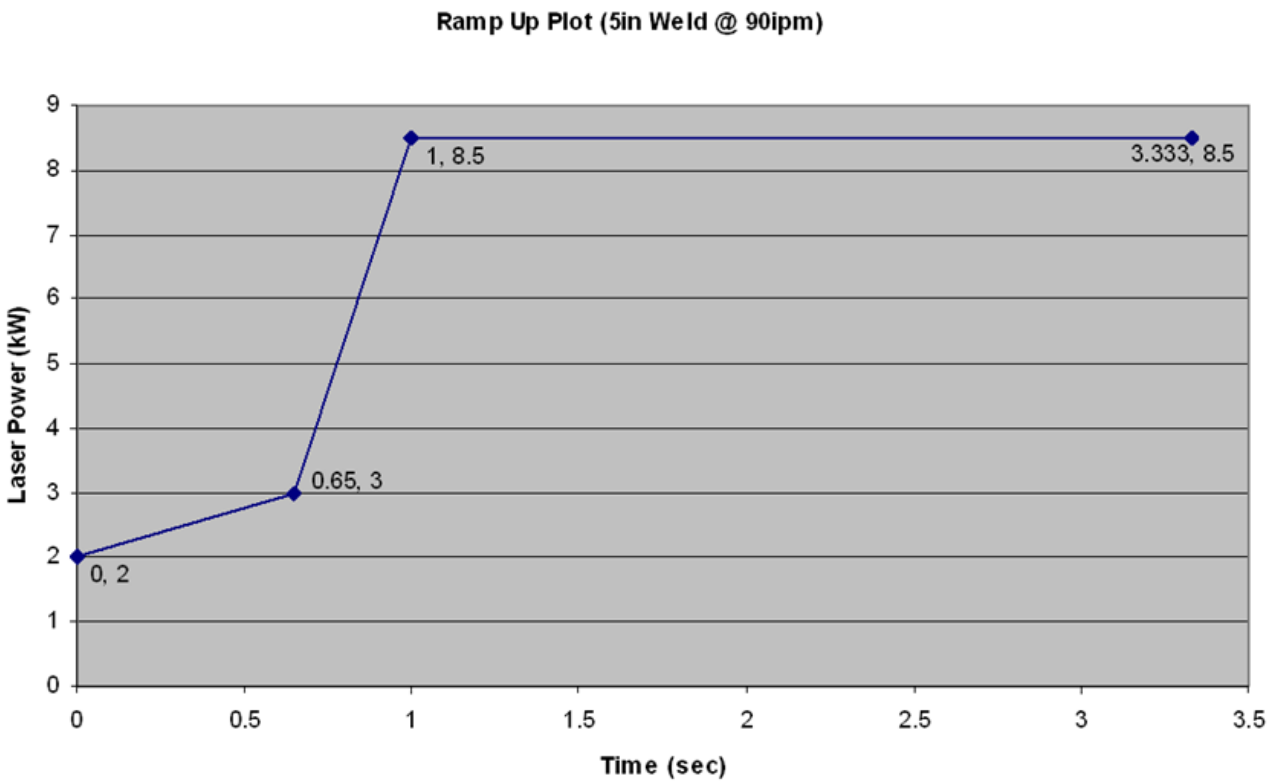


Figure 33. Ramp-up Plot. The use of laser power ramping on the start overlap allowed for the hybrid weld to transition from partial penetration to full penetration through a thinner amount of solid material.

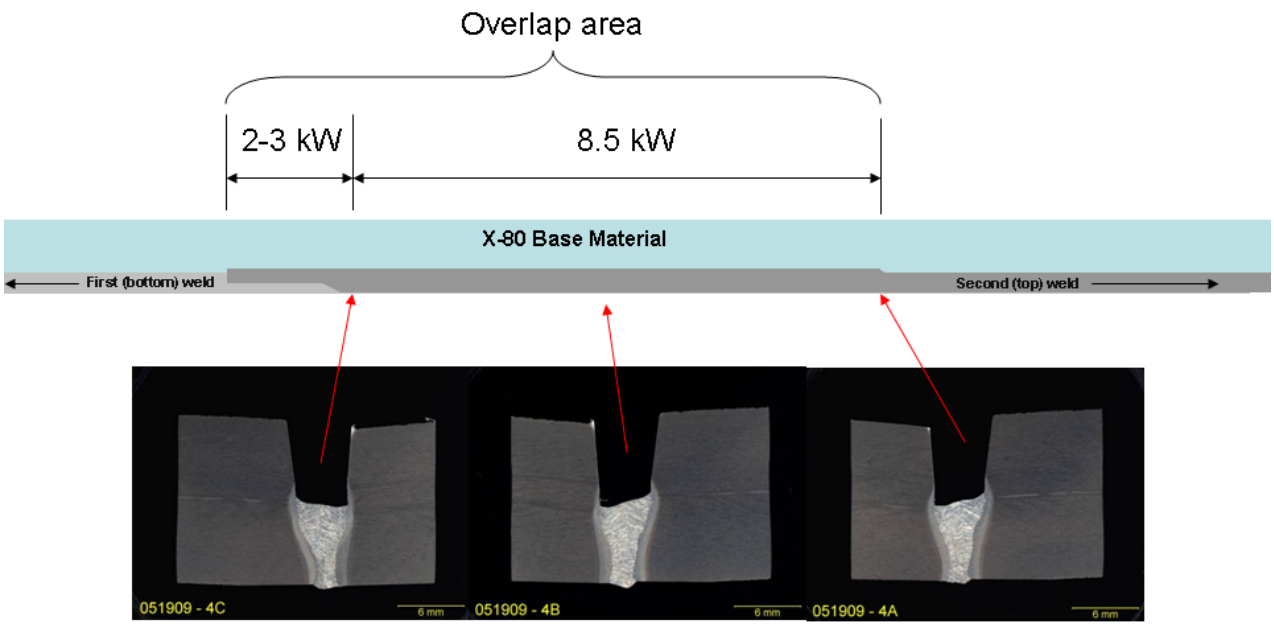


Figure 34. Schematic of Start Overlap. The short ramp-up time ensured that the HLAW process was in full penetration mode prior to reaching the start of the bottom weld

Although these overlaps had a good backside profile, centerline cracking was occurring at the final stop location (Figure 35). Several adjustments were made to the GMAW crater fill parameters and stop sequence of the weld; but, these changes did not prevent the crater cracks from forming.

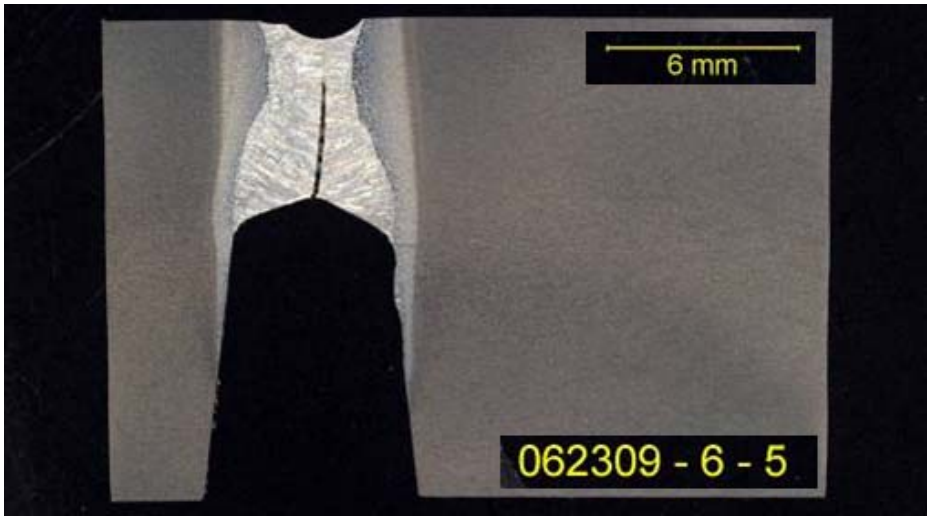


Figure 35. Cracking at Stop Overlap. Cracks resulted at the stop overlap when the HLAW process was shut off while still in the full penetration mode

To eliminate weld cracking at the stop of the second weld, a two-stage ramp down of laser power was implemented (Figure 36). 5 kW of laser power was used until the stop location of the first weld was overlapped. At that point, the laser power was decreased to 2 kW. By doing this, the top weld transitioned from full penetration to partial penetration as soon as the bottom weld was overlapped (Figure 37). At the end of the overlapping weld, the stop sequence was initiated (stop travel, stop laser, stop GMAW) and a small crater fill was added (0.2 seconds, 300 WFS).

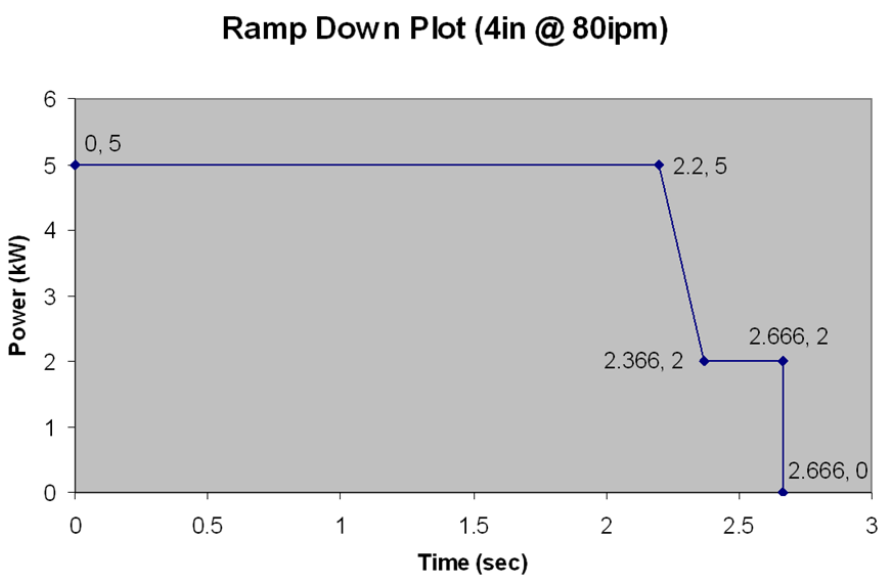


Figure 36. Ramp-down Plot. The use of laser power ramping on the stop overlap allowed for the hybrid weld to transition from full penetration to partial prior to terminating the weld.

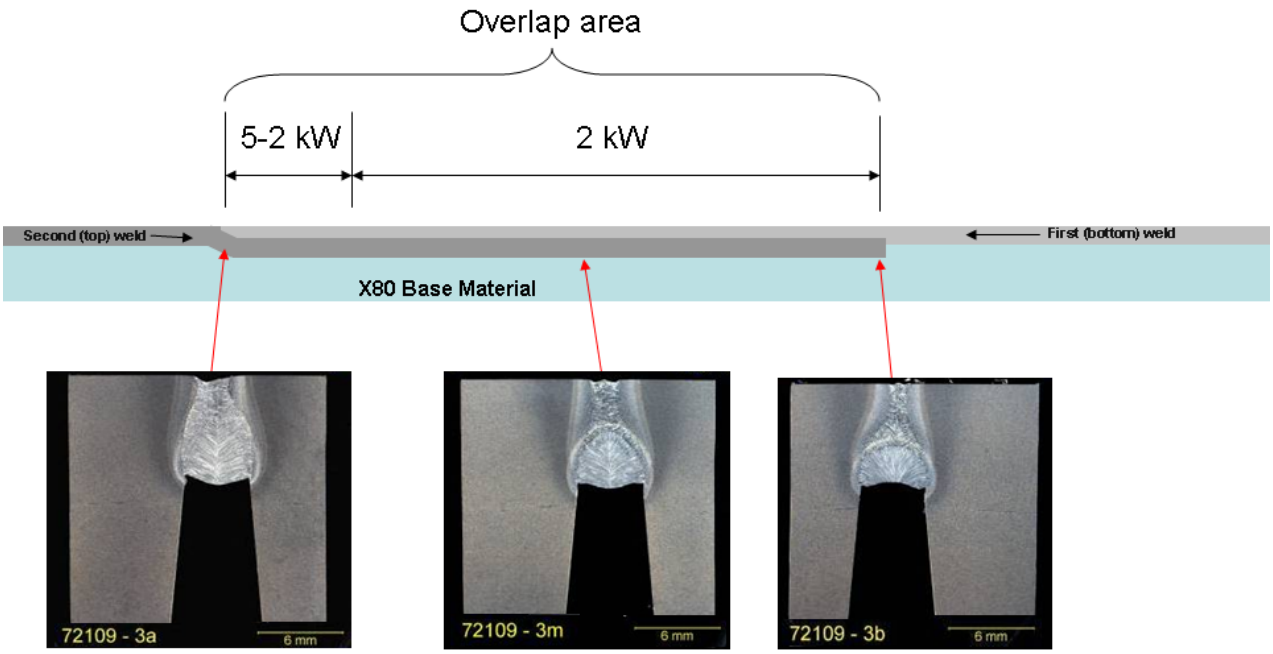


Figure 37. Schematic of Stop Overlap. The ramp-down of laser power ensured that the HLAW process was in partial penetration mode prior to stopping the weld.

4.9 Task 9 – HLAW Process Evaluation for Meeting Toughness Requirements

The hardness results from the X80 weld trials are shown in Figure 38, Figure 39 and Figure 40. The maximum hardness near the root of each weld after adding a hot pass was:

- 253 HVN (4-mm root face)
- 277 HVN (6-mm root face)
- 337 HVN (11-mm root face)

In the case of the 4-mm root face, the hot pass caused a significant amount of softening in the HLAW root pass. Prior to adding the hot pass, the maximum hardness across the 4-mm root face was 315 HVN (62 HVN higher). For the 6-mm root face, the change in maximum hardness at the root was not as significant, but it was still measureable (a difference of approximately 25 HVN). The hot pass on the 11-mm root face did not impact the hardness at the root of the weld.

Results from the CVN tests for the X80 welds are shown in Figure 41, Figure 42, and Figure 43. These results typically met conventional service requirements (HVN 350 max) for both regular service conditions and arctic service where the transition temperature of interest is -62°C (-80°F) in the latter case. A more detailed analysis can be found in the Discussion section of this report. The absorbed energy at the weld centerline and HAZ increased as the throat thickness increased. For the 4-mm root face, absorbed energy was higher in the HAZ than along the weld centerline. The 6- and 11-mm root face exhibited higher absorbed energy along the weld centerline. Transition temperatures (based on a fracture appearance of 50% shear) ranged from -96°C to -59°C (-140°F to -75°F).

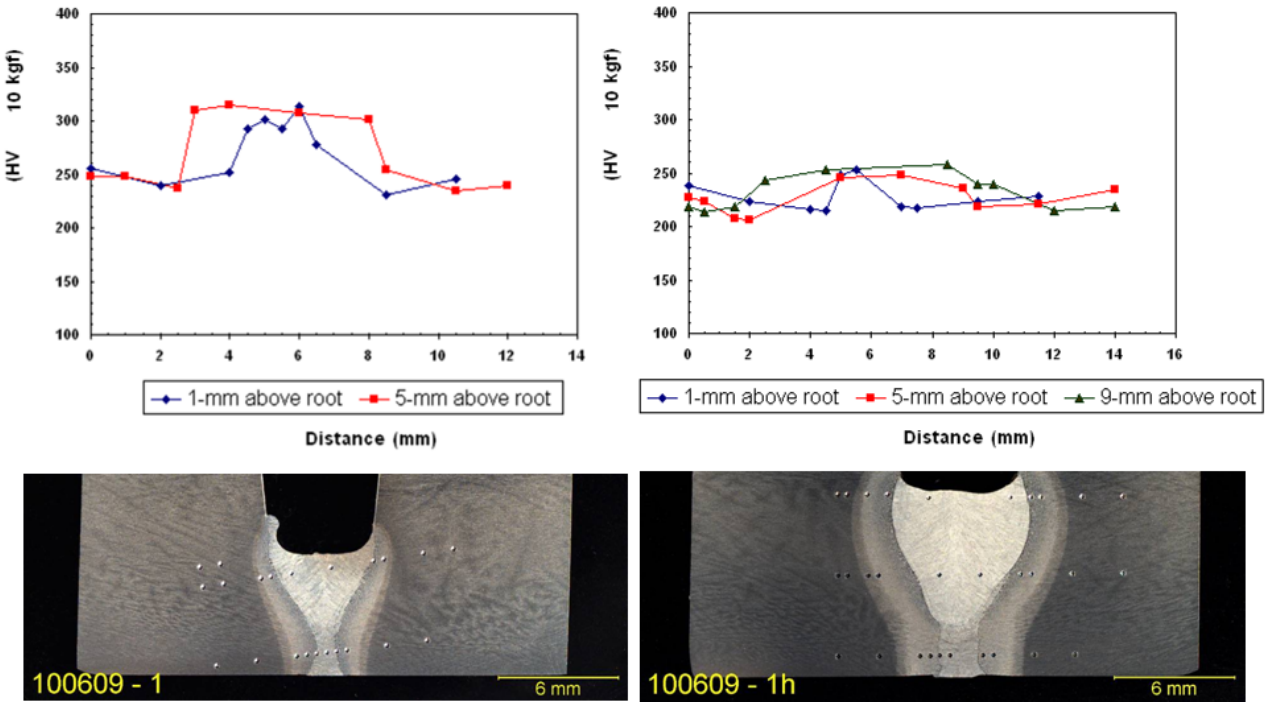


Figure 38. X80 Hardness Profile – 4-mm Root Face. As-welded HLAW root pass on left, with hot pass on right

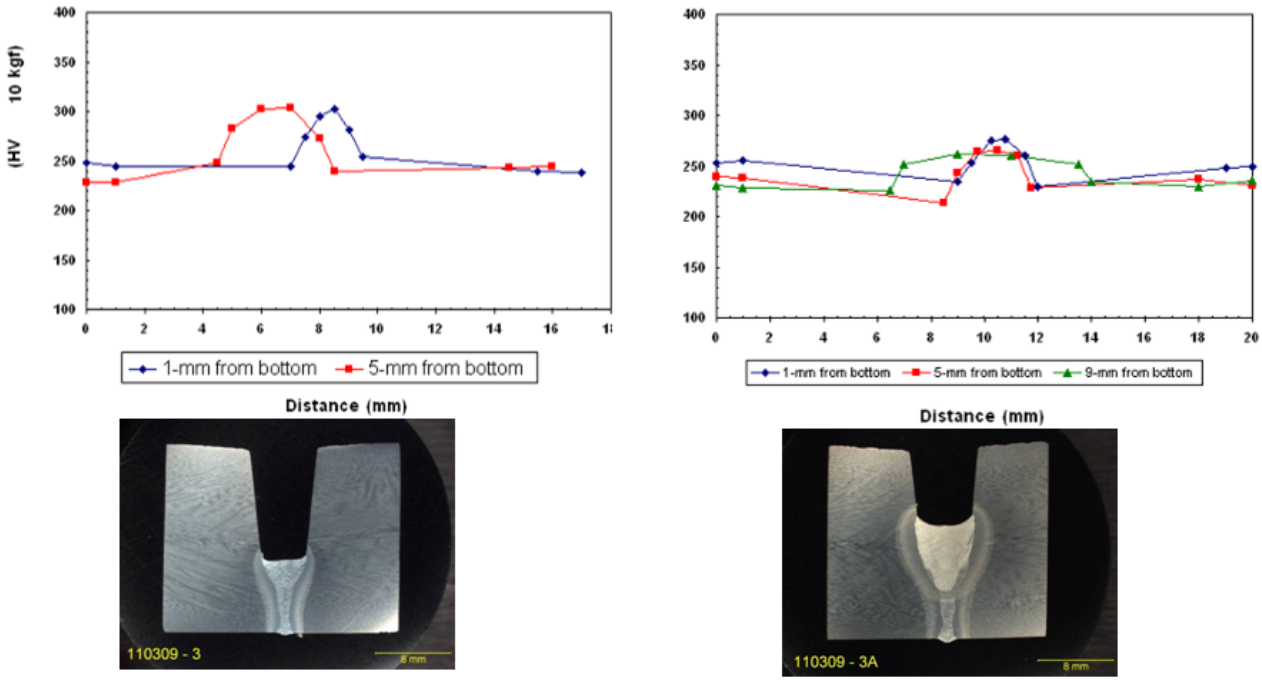


Figure 39. X80 Hardness Profile – 6-mm Root Face. As-welded HLAW root pass on left, with hot pass on right

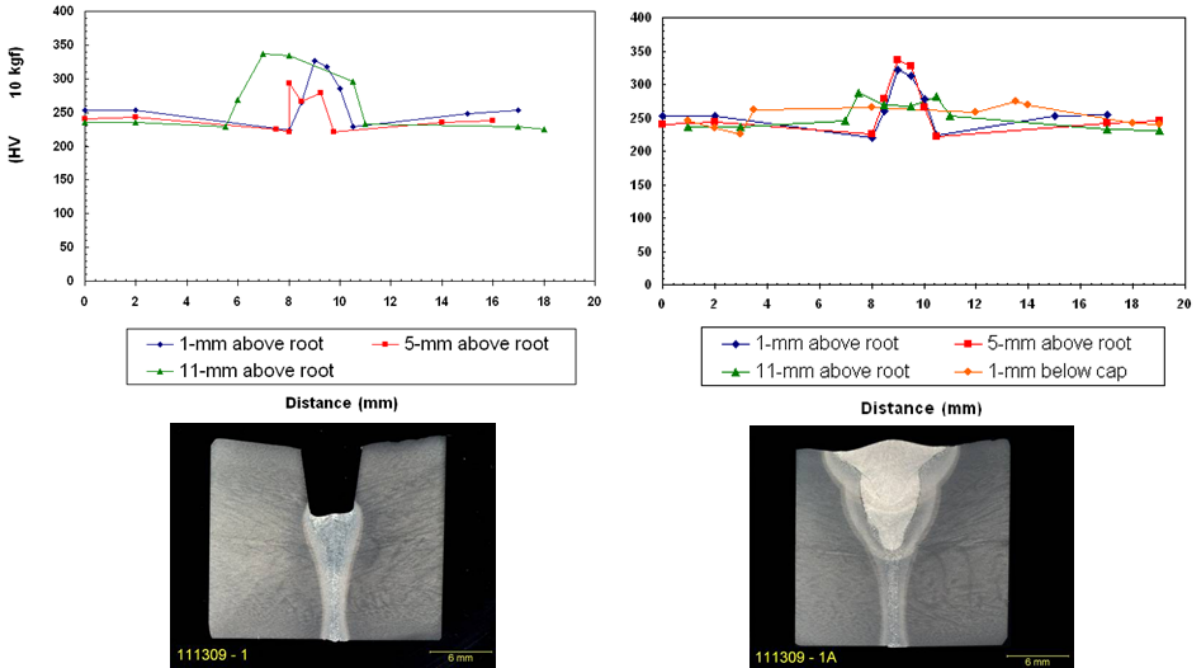


Figure 40. X80 Hardness Profile – 11-mm Root Face. As-welded HLAW root pass on left, with hot and fill pass on right

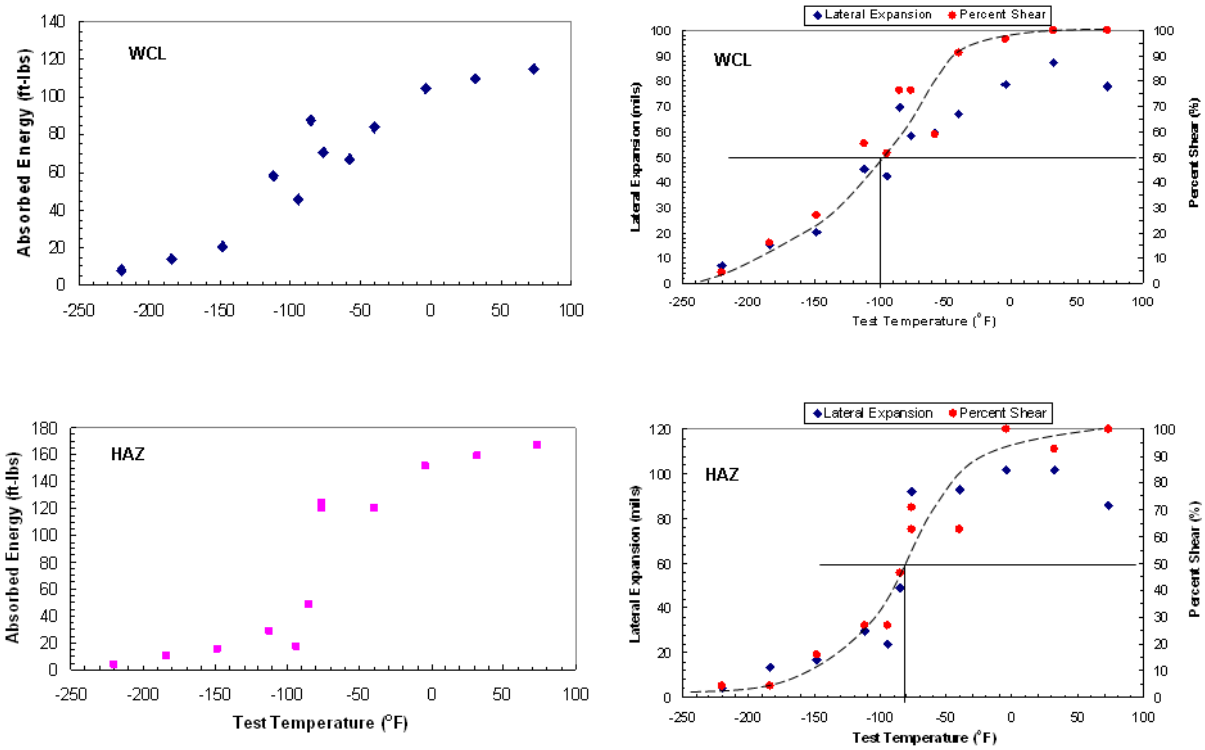


Figure 41. X80 Toughness Results – 4-mm Root Face. Absorbed Energy for the WCL and HAZ notch locations on the left. Lateral Expansion and Percent Shear on the right.

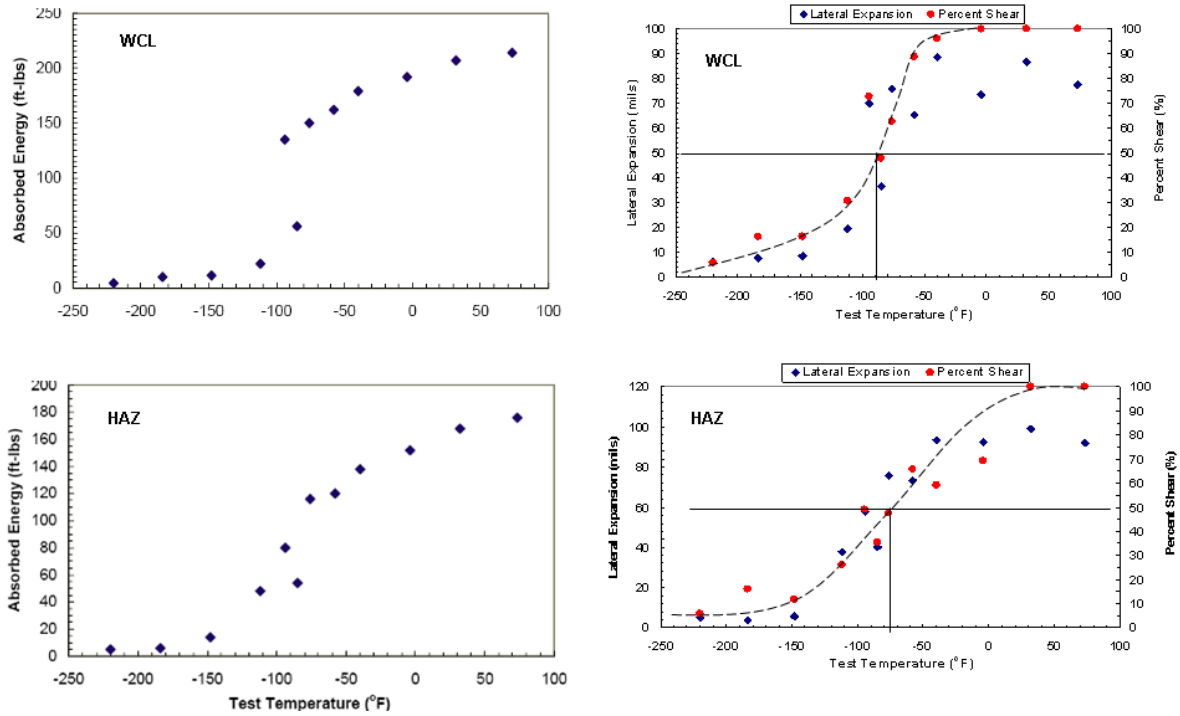


Figure 42. X80 Toughness Results – 6-mm Root Face. Absorbed Energy for the WCL and HAZ notch locations on the left. Lateral Expansion and Percent Shear on the right.

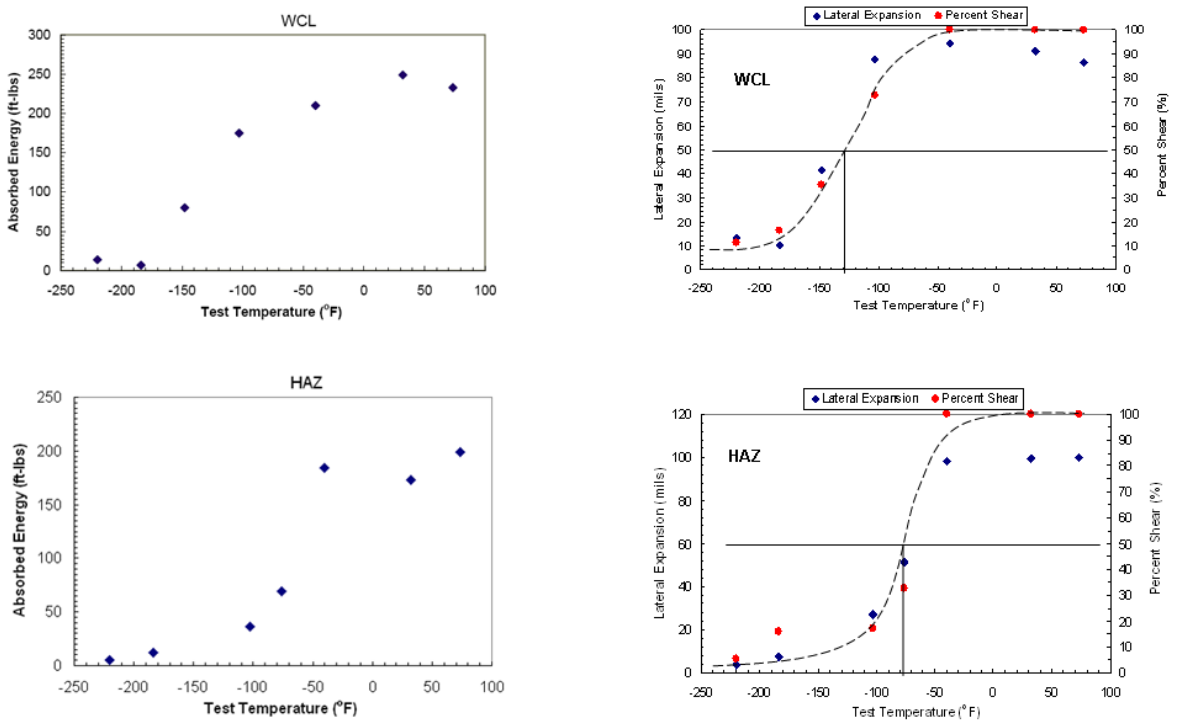


Figure 43. X80 Toughness Results – 11-mm Root Face. Absorbed Energy for the WCL and HAZ notch locations on the left. Lateral Expansion and Percent Shear on the right.

Results from tensile and weld soundness tests on the X80 joints welded with a 4-mm root face are shown in Figure 44. The tensile specimens all yielded in the base material with a 0.2% yield strength above 93 ksi. No defects were found during the weld soundness tests. Tensile and weld soundness data were not obtained for the X80 welds made on 6- and 11-mm root faces.

CROSS WELD TENSION TEST RESULTS - ASTM E8

Technician: Steve O'Mara **Test Date:** October 13, 2009
Test Frame: H1938 UK18 **Loading Rate:** 0.05 (in/min) 1.27 (mm/min)
Orientation: Cross Weld **Test Temperature:** Room Temperature

Spec. ID	Width (in.)	Thickness (in.)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	0.2% Yield Strength (ksi)	0.2% Yield Strength (MPa)	Elongation (%)	%RA (%)	Failure Location
T1	0.921	0.316	108.9	751.0	95.4	657.9	14.2	59.2	Base
T2	0.921	0.316	110.6	762.8	98	675.9	14.5	57.2	Base
T3	0.921	0.317	108.6	749.0	93.9	647.6	15.3	57.3	Base

BEND TEST RECORD - ASTM E290

Technician: Steve O'Mara **Test Date:** October 13, 2009

Spec. ID	Thickness (in.)	Orientation	Mandrel Diameter (in.)	Results	Validity
SB1	0.362	Side	3.5	No visual defects	Pass
SB2	0.362	Side	3.5	No visual defects	Pass
SB3	0.365	Side	3.5	No visual defects	Pass

NICK-BREAK TEST RESULTS - AWS B4.0

Project Number: 50453GTH-09 **Test Date:** October 13, 2009
Job No: 2010-138158 **Technician:** Steve O'Mara
Customer: Ian Harris

Specimen Identification	Observations	Validity
NB-1	No visual defects	Pass
NB-2	No visual defects	Pass
NB-3	No visual defects	Pass

Figure 44. X80 Tensile and Weld Soundness Results – 4-mm Root Face. Tensile results, side bend results, and Nick-Break results were all acceptable

The hardness results from the X100 weld trials (4-mm root face) are shown in Figure 45. The maximum hardness near the root of the weld, after adding a hot pass, was 266 HVN. Prior to adding the hot pass the maximum hardness was 315 HVN (Figure 46).

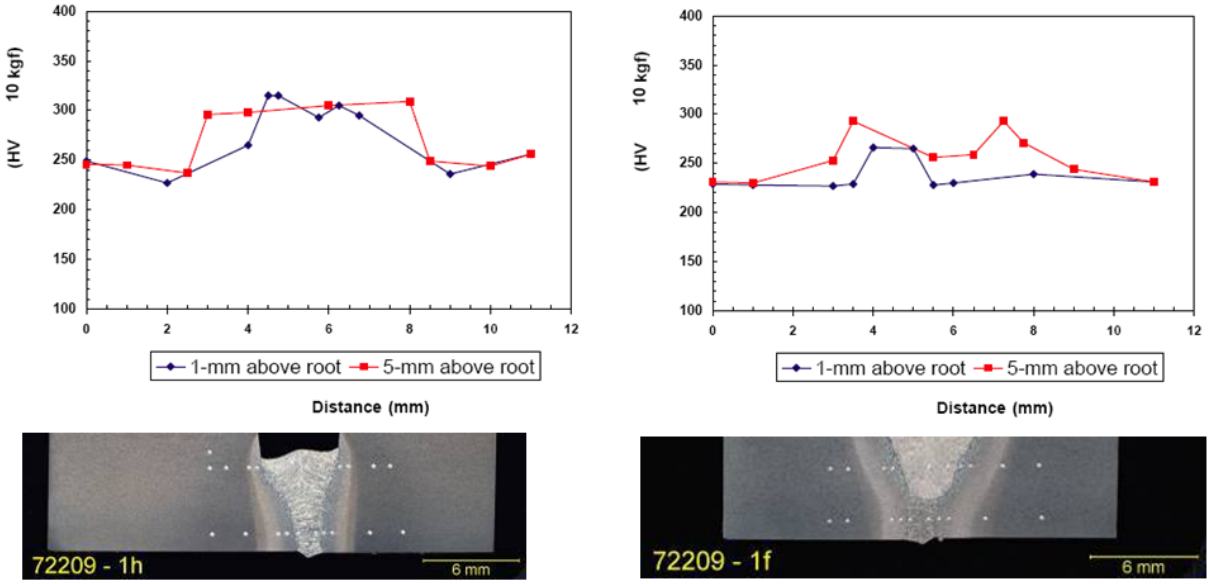
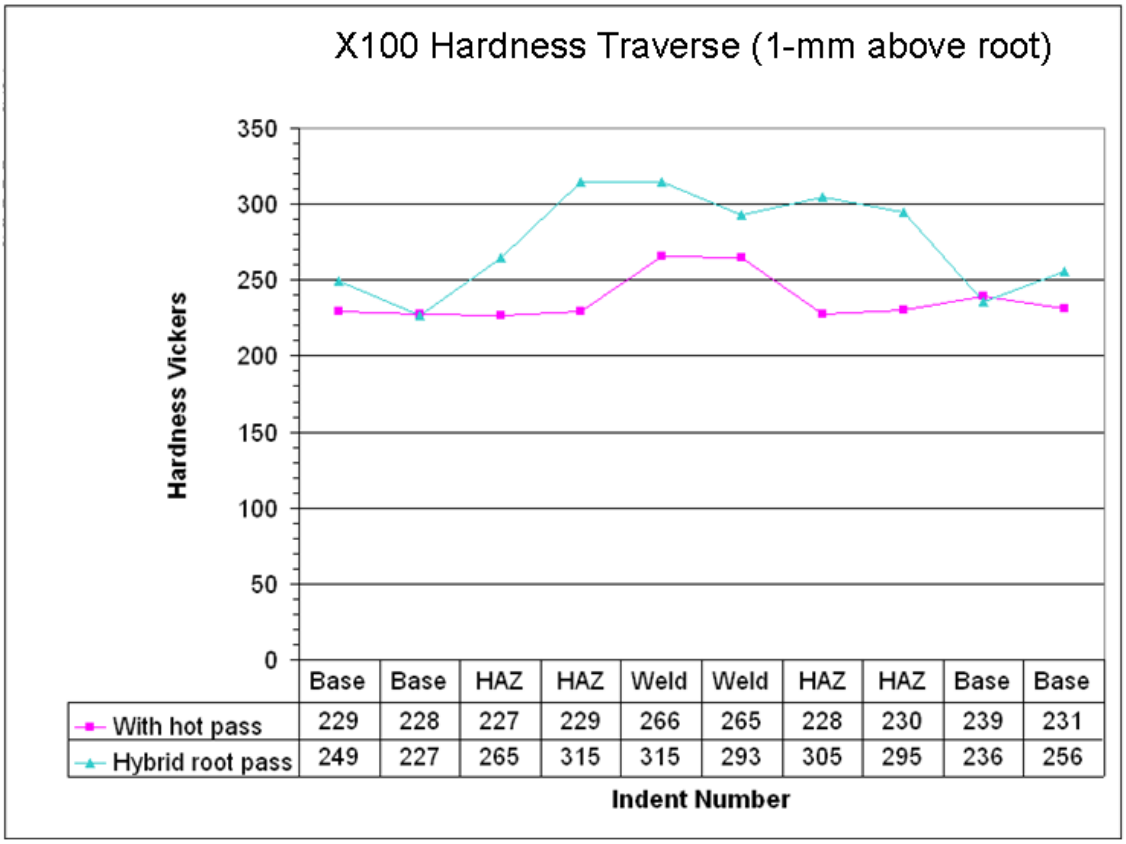


Figure 45. X100 Hardness Profile – 4-mm Root Face. As welded HLAW root pass on left, with hot pass on right



	Base	Base	HAZ	HAZ	Weld	Weld	HAZ	HAZ	Base	Base
With hot pass	229	228	227	229	266	265	228	230	239	231
Hybrid root pass	249	227	265	315	315	293	305	295	236	256

Figure 46. X100 Hardness Profile – 4-mm Root Face. Graph shows the effect of tempering from the hot pass

Results from tensile and weld soundness tests on the X100 joints welded with a 4-mm root face are shown in Figure 47. The tensile specimens all failed in the base material with an ultimate strength above 117-ksi. No defects were found during the weld soundness tests.

ULTIMATE TENSILE STRESS TEST RESULTS - API 1104

Specimen Identification	Specimen Orientation	Specimen Width (in)	Specimen Thick (in)	Test Temperature (°C)	Test Temperature (°F)	Ultimate Load (N)	Ultimate Load (lbf)	Ultimate Strength (MPa)	Ultimate Strength (psi)	Displacment at Maximum Load (mm)	Displacment at Maximum Load (in.)	Failure Location
T-1	Transverse	1.001	0.233	23	73	122679	27480	812.6	117822.1	6.99	0.275	Base
T-2	Transverse	1.004	0.234	23	73	124063	27790	815.8	118287.5	7.95	0.313	Base
T-3	Transverse	0.996	0.233	23	73	122768	27500	817.2	118499.8	8.15	0.321	Base

BEND TEST RECORD - API 1104

Spec. ID	Thickness (in.)	Orientation	Mandrel Diameter (in.)	Results	Validity
FB-1	0.233	Face	3.5	No visual defects	Pass
FB-2	0.233	Face	3.5	No visual defects	Pass
FB-3	0.233	Face	3.5	No visual defects	Pass
RB-1	0.234	Root	3.5	No visual defects	Pass
RB-2	0.233	Root	3.5	Pin hole < 1/8"	Pass
RB-3	0.235	Root	3.5	No visual defects	Pass

NICK-BREAK TEST RESULTS - API 1104

Specimen Identification	Observations	Validity
NB-1	No visual defects	Pass
NB-2	No visual defects	Pass
NB-3	No visual defects	Pass

Figure 47. X100 Tensile and Weld Soundness Results – 4-mm Root Face. Tensile results, side bend results, and Nick-Break results were all acceptable

5.0 Discussion

5.1 Task 1 – Development of the Hybrid Laser Arc Welding Processes

An important finding from the initial trials was the sensitivity of the HLAW process to variations in root face thickness. While 4-mm was the target root face thickness for the test grooves, fluctuations in pipe wall thickness caused certain areas to be more than 5-mm thick. Because the Nd:YAG power supply was already set to its maximum output of 4-kW, additional laser power was not available to penetrate through the thicker root face in a stable manner. This variation in root face thickness may have been a primary cause for the inconsistent weld root profiles seen in Figure 6.

Along with the variation in root face thickness, it was noted that the focal position of the hybrid welding head was varying as the bug travelled around the pipe. At the 12-o'clock position, the focal position of the HLAW process was set to the appropriate 200-mm. As the bug was moved

to the three o'clock, and then six o'clock position, the focal position would increase by as much as 4 mm. This was a result of the modified P450 bug not being rigid enough to prevent the HLAW head (and all required process cables) from pulling away from the joint as it moved around the pipe. Because the GMAW torch and laser focusing optics were coupled to the same axis (Z-axis), the 4-mm increase in focal position had an impact on the beam-to-wire spacing of the process. As the focal position increased, the beam-to-wire spacing would decrease. This variation in beam-to-wire spacing and focal position is another potential explanation for the inconsistent weld root profiles seen in Figure 6.

Investigations into the P450 bug and Fronius power supply revealed that there were two options for maintaining a stable GMAW process. One option, used for the welds during Task 1, was to allow the Fronius power supply to use its adaptive welding capabilities to maintain a target arc length by varying the pulsed GMAW waveform. This method allowed for the welding head to drift away from the joint during the welding process.

A second option, used in later trials and demonstrations, was to disengage the Fronius adaptive welding feed-back and use the CRC-Evans P450 Arc Voltage Control (AVC) feature. This feature allowed the operator to set a target voltage (arc length) and an allowable deviation to that voltage. If the system detected a change to the target voltage that was outside of the allowable deviation, the Z-axis of the welding head would adjust to regulate the voltage. For example, if the welding head drifted away from the weld joint, a corresponding increase in voltage was detected and the P450 corrected itself by driving the Z-axis back toward the joint. This method of controlling the GMAW stability was much better for overall HLAW stability. It reduced the changes in focal position and beam-to-wire spacing to an acceptable level.

The T-GMAW defects seen in Figure 7 resulted from a combination of low heat input, high travel speed, and narrow groove joint design. A higher level of effort and additional equipment (narrow-groove T-GMAW torch) would have been required to develop T-GMAW parameters that resulted in acceptable welds in this joint configuration. Other research had already shown that T-GMAW was a viable option for narrow-groove pipe welding. As HLAW, not T-GMAW, was the main focus of this project, EWI decided not to pursue further development efforts using this technology.

5.2 Task 2 – Property Testing of Preferred Welding Processes

Based on results from preliminary higher-speed HLAW trials (110- to 120 IPM), a 3-mm root face was chosen as the preferred joint condition for initial mechanical property testing. The welds produced on a 4.5-mm root face did not show the same consistency obtained on the 3-mm root face. Although stable, full-penetration laser welds could be made at those travel speeds on the 4.5-mm root face, the addition of the GMAW process caused full penetration to be lost along the length of the hybrid weld. This phenomenon was not seen when welding the 3-mm root face. Welding on joints with thicker root faces at slightly lower travel speeds is further discussed in Task 9.

The industry standards for maximum allowable hardness in sour service (248 HVN) and non-sour service (350 HVN) were used to evaluate the HLAW hardness results. In all cases (X80 and X100), the hardness was below the non-sour service target. Both the as-welded root pass and the root pass tempered by a hot pass fell below the maximum allowable 350 HVN.

The parameters and consumables used during this task did not produce a weld that was under the maximum allowable hardness level for sour service. However, the average maximum hardness after adding the hot pass was only 15 HVN (X80) and 23 HVN (X100) above the target of 248 HVN. Alternative filler materials, higher preheat, or higher heat-input welding parameters could be used to further reduce the hardness.

Many of the tensile and bend test failures that occurred during this task could be attributed to the poor quality of the GMAW hot pass. A large amount of porosity was discovered upon destructive testing of those welds. An inadequate or turbulent flow of shielding gas into the narrow groove could have caused the porosity. The small mandrel radius used for the bend tests was also a contributing factor in the large number of weld failures experienced during this task. As mentioned previously, a 1.75-in. mandrel/plunger radius was specified in API Standard 1104 for all root, face, and side bends. For this task a 0.75-in. mandrel radius was used, which caused much greater strain on the welds than is required per API Standard 1104. Perhaps of more interest is that six of the eight root bends that were performed during this task still passed, suggesting that the quality of the HLAW root pass was superior to the GMAW hot pass (due to the porosity). Only the two root bends on X100 material welded with a low heat input failed.

The toughness of the X80 welds met requirements for the weld metal and HAZ with a 4-mm root face on the joint preparation. This was true both for conventional service in the lower 48 and arctic service, since the welds achieved -73°C (-100°F) at the weld centerline and -62°C (-80°F) in the HAZ.

Additional discussion pertaining to hardness and toughness is covered in Section 5.9.

5.3 Task 3 – Use of Integrated Data Acquisition and Laser Sensors for Hybrid Welding

The important issue discovered in the sensory portion of this work was the difficulty in gaining accurate seam tracking, as this is integral for production-type welding. The key contributor to lack of success was the gravitational shift in the bug as the welding moved from the 12 o'clock position down to the 6 o'clock position. The extra weight of the laser welding elements exceeded the limit for the bug and band system. This resulted in the bug, and all associated parts, to shift with respect to the joint as its position changed along the circumference of the pipe.

To overcome the issue of gravitational bug shift, a compensation factor was added to the seam tracking algorithm. This factor essentially provided a shift opposite to the bug motion, with respect to position along the circumference of the pipe. However, in modeling this shift, it was found that the repeatability was less than the accuracy needed to track the joint. In addition, the bug shifts were not solely horizontal (with respect to the pipe surface). The shifts also contained a vertical

component, which affected the laser sensor positioning. This variation added another source of error because it affected the calibration factors which correlate pixel count to distance on the pipe.

To resolve this issue, future versions of the HLAW pipeline welders must have the payload capacity to accurately manipulate the bug with little shift. This is crucial to the end success of the tool as seam tracking is a necessity for the production of quality welds.

5.4 Task 4 – Field Deployment and Operator Training

Although the demonstration welds were successful in proving the feasibility of HLAW pipeline welding in the field, the prototype bug and band system used to make these welds had several issues that prevented it from being a production-ready tool. Perhaps the most important issue was the lack of horizontal seam tracking, as discussed in Section 5.3. The P450 (as designed and built for normal GMAW operation) uses an oscillation motor to weave the GMAW torch inside the weld groove. This oscillation was used to track the joint and make real-time adjustments to the torch location. In order to install the laser focusing optics necessary for HLAW, the oscillation motor had to be removed. This prevented the horizontal seam tracking capabilities of the P450 from being used during hybrid welding.

A second issue was the weight of the HLAW processing head and the large umbilical that supplied power, cooling water, control, and the laser. The P450 was most likely not designed to rigidly hold the amount of weight being attached to it (especially at travel speeds of 80 to 120 IPM). Although the vertical tracking feature of the P450 helped to counter the effect of gravity, a more rigid design would be beneficial for future development.

5.5 Task 5 – Productivity Analysis

The HLAW process was successfully demonstrated for welding full girth joints at 80 in/min (2.0 m/min.) with a single bug using the double-down technique. This translated to roughly 160 in/min (4.0 m/min.) of joint completion rate as two bugs are typically used simultaneously in cross country linepipe girth welding. This travel speed pushes the bottleneck in pipeline time on the right-of-way to the hot pass station. For the hot pass more stations can be added or dual T-GMAW-P can be used to increase productivity at this point as well. The use of an 11-mm root face was shown to produce a 12-mm throat in the root pass weld. From discussions with a major company in offshore pipe contracting, this met the economic breakpoint of 12 mm indicated for selection of the process for offshore fabrication. This weld, on X80 pipe, had a DBTT of -61°C (-78°F) in the HAZ and met the 350 HVN requirement for conventional service.

5.6 Task 6 – Progress Meetings, Pipeline Conference, Annual Panel Peer Review, and Reporting

Disseminating the information from the project at conferences, progress meetings and demonstrations, along with the partners in the cost-matched JIP, led directly to the development of equipment by a leading offshore contractor for pipeline construction. This equipment will be made available for both proprietary and cooperative research projects.

5.7 Task 7 – Study of Beam-to-Wire Spacing, Travel Speed, and Solidification Morphology

The solidification morphology of welds made in the 1G position at 80 IPM changed from hybrid to tandem at a beam-to-wire spacing between 5 and 6 mm (Figure 21). All welds made with spacing at or below 5 mm resulted in a desirable top and backside profile and displayed a hybrid solidification mode. Although the weld made using a 4-mm spacing solidified as a hybrid weld, it did not look as stable as the other welds made with spacing at or below 5 mm. An unfavorable interaction between the laser keyhole and GMAW pool might have been occurring at this distance. Additional trials and the use of high-speed video imaging would be required to analyze the different interactions at various beam-to-wire spacing.

Welds made with spacing at or greater than 6-mm did not result in consistent top or backside profiles and solidified in the tandem mode (Figure 22). The exact cause of the backside instability is not fully understood. Autogenous laser welds made at the same travel speed and laser power did not result in backside instability (although root concavity was observed). Only when the GMAW was added did the humping and instability occur.

The solidification morphology of welds made in the 1G position at 100 IPM changed from hybrid to tandem at a shorter beam-to-wire spacing. A transition could be seen in the cross-sections at spacings between 3 and 4 mm (Figure 23). At higher travel speeds, the heat-input of the laser welding process was lower, causing faster cooling rates and a smaller process window for obtaining 'hybrid' solidification.

Trials completed in the 3G and 4G position showed that out-of-position welding did not have a process window as large as the 1G welding. Slower travel speeds, smaller laser spot size (400-µm), and shorter beam-to-wire distances were required to produce welds of acceptable quality in the vertical and overhead positions. Based on these results, all welds made in later trials used the smaller spot size and maximum spacing of 2 mm.

5.8 Task 8 – Start-Stop Development with Hybrid Laser GMAW System

The use of laser power ramping on the start overlap allowed for the hybrid weld to transition from partial penetration to full penetration through a thinner amount of solid material. The initial burst of 3 kW penetrated approximately 3 mm of the bottom weld, leaving about 4 mm of solid material. Trials for the start of the bottom weld showed that 4 mm of solid material could be fully penetrated by 5 kW of laser power and not produce a discontinuity on the backside. The same proved to be true on the top weld when the laser power was increased from 3 kW to 8.5 kW (Figure 33). In a production environment, the laser could be programmed to ramp back down to a lower power once the overlap region was complete.

The use of laser ramping on the stop overlap allowed for the hybrid weld to remain stable at the high travel speed while only partially penetrating through the first weld. This created a depth-to-width ratio at the stop location that was much less prone to solidification cracking. The ramping down of the laser power combined with the stop sequence resulted in stop/stop overlaps without cracks and an acceptable backside profile.

Although acceptable start and stop overlaps were produced as a result of these trials, repeatability was poor due to a lack of system integration. It was crucial that all of the processes and equipment used to produce a hybrid weld were properly integrated. The ability to ramp the laser power (both up and down) was also crucial. Ramping of the power allowed for smooth transitions from full-penetration welding to partial-penetration welding (and vice-versa).

5.9 Task 9 – HLAW Process Evaluation for Meeting Toughness Requirements

Results from the hardness test on the X80 and X100 welds showed that tempering from a hot/fill pass could reduce the hardness of the hybrid root pass when thin root faces were used (4 to 6 mm). Hardness reductions were most notable when the 4-mm root face was used on X80 material (sour service hardness requirements were nearly met after the hot-pass was added). An alternative filler material, higher heat-input hybrid process, or 'hotter' hot pass would likely bring the hardness down to acceptable sour service levels in the case of a 4-mm root face. All welds that were produced during this task were under the maximum allowable hardness for non-sour service.

Results from cross-weld tensile and weld soundness tests for the X80 and X100 welds were better and more consistent than results from preliminary testing in Task 2. All tensile specimens failed in the base material. No defects or failures were seen in the bend tests or nick-break tests. This can be attributed to a better quality GMAW hot pass (no noticeable porosity) and the larger mandrel diameter used for the bend tests.

The impact toughness of the X80 welds was quite good, with typical values for all welds tested being above 70 ft-lb at -60°C (-76°F). Because there was no mixing of filler metal into the root of the weld made using an 11-mm root face, the weld behaved similarly to an autogenous laser weld, with toughness values far exceeding those of the other welds.

Discussions with industry on sour service requirements and arctic conditions have clarified that X80 pipe is not being considered for sour service based on the hardness of the base material being close to the 248 HVN requirement. As such, X65 pipe was the material of choice for this application. Preliminary work here has shown that, for arctic service, X80 pipe can be welded to meet the 350 HVN hardness limit and -62°C (-80°F) DBTT requirement with up to 12-mm weld throat thickness.

6.0 Conclusions

This project aimed to develop the HLAW process for on-shore pipeline girth welding and to demonstrate the system under field conditions. Special emphasis was placed on understanding the mechanical properties of HLA welds made on X80 and X100 material. Other areas of focus included weld overlaps and general HLAW process phenomena. These objectives were successfully achieved. In the course of this work, nine tasks were undertaken as follows:

Task 1 – Development of the Hybrid Laser Arc Welding Processes
Task 2 – Property Testing of Preferred Welding Processes
Task 3 – Use of Integrated Data Acquisition and Laser Sensors for Hybrid Welding
Task 4 – Field Deployment and Operator Training
Task 5 – Productivity Analysis
Task 6 – Progress Meetings, Pipeline Conference, Annual Panel Peer Review, and Reporting
Task 7 – Study of Beam-to-Wire Spacing, Travel Speed, and Solidification Morphology
Task 8 – Start-Stop Development with Hybrid Laser GMAW System
Task 9 – HLAW Process Evaluation for Meeting Toughness Requirements

Specific conclusions follow:

(1) The HLAW process is capable of producing root passes in an outdoor environment simulating a welding tent, and was successfully demonstrated to 40 participants in two separate demonstrations.

(2) The HLAW process, using up to 8.5 kW of laser power, and 80 in/min. of travel speed, was shown to be capable of producing good integrity unbacked pipe girth root-pass welds and good tie-in in the start/start and stop/stop regions.

(3) The HLAW process was successfully demonstrated for welding full girth joints at 80 in/min. (2.0 m/min.) with a single welding bug using the double-down technique. This translated to roughly 160 in/min. (4.0 m/min.) of joint completion rate as two bugs are typically used simultaneously in cross country linepipe girth welding.

(4) For conventional service, a weld throat thickness of 12 mm could be produced in the root pass in X80 pipe while meeting the root hardness requirement of less than 350 HVN and achieving a DBTT of -61°C (-78°F). This met economic productivity requirements for deployment of HLAW in both onshore and offshore conventional service.

(5) Using the 11-mm root face, a 19-mm wall pipe joint could be completed with three passes (root, hot, and fill/cap pass), and still meet hardness and Charpy impact requirements for conventional service.

(6) Welds met nominal requirements for tensile, nick-break, and bend testing to API 1104.

7.0 Future Work

Additional work is required to meet sour service requirements. X65 pipe is now the material of choice for sour service environments. Preliminary work here has shown that, for arctic service, X80 pipe can be welded to meet the 350 HVN hardness limit and -62°C (-80°F) DBTT requirement with up to 12-mm weld throat thickness. Significantly more work will be required to develop complete welding solutions based on the encouraging results of the preliminary work reported here.

While the use of power ramping and weld sequencing for the GMAW-P and laser portions of the HLAW process was demonstrated, it was manually sequenced. Further work will be required to integrate these into an automatic process control sequence for both practical deployment and field robustness of a pipe welding operation.

8.0 References

[1] EWI Project 47961GTH, “Innovative Welding Processes for Small to Medium Diameter Gas Transmission Pipelines”, (U.S. DOT OTA No. DTRS56-05-T-0001).

[2] EWI Project 46380CPQ, “Novel Arc Welding Processes for Improved Pipeline Welding”.

[3] EWI Joint Industry Project (JIP), EWI Project 49191CPQ, “Fiber Laser Based Hybrid Automated Pipe Girth Welding”.

[4] EWI Project 50453GTH Task 1 through Task 6 agreement between EWI and the DOT, “Hybrid Laser/Gas Metal Arc Welding (HLAW) of High Strength Steel Gas Transmission Pipelines”.

[5] EWI Project 50453GTH Task 7 through Task 9. The final three tasks were agreed upon as part of a contract modification brought about by positive results from the original tasks and the cost-shared JIP.

[6] API Standard 1104 – “Welding Pipelines and Related Facilities”, American Petroleum Institute.

[7] Harris, I. D., and Norfolk, M., “Hybrid Laser/Gas Metal arc Welding (GMAW) of High Strength Steel Gas Transmission Pipelines”, Proceedings of the 2008 7th International Pipeline Conference, IPC2008 September 29 - October 3, 2008, Calgary, Alberta, Canada. Volume 3, Paper No. IPC2008-64129 (pp. 61-66).

[8] Harris, I. D. and Norfolk, M., “Hybrid Laser/Gas Metal Arc Welding (GMAW) of High Strength Steel Gas Transmission Pipelines”, Rio Pipeline 2009 Conference and Exposition, Rio de Janeiro, Brazil, September 22-24, 2009. Paper No. IBP1255-09.

Appendix

Productivity Analysis

50453GTH Task 5 – Productivity Analysis

6.25.09.

Throughout the research project, the potential productivity benefits of the hybrid Laser/GMAW process (Figures 1 and 2) were analyzed and compared to competitive techniques to ensure that the greatest potential benefit was achieved. Data developed in the past GSP (EWI Project 46380CPQ) (Ref 1) and DOT project (EWI Project 47961GTH) (Ref. 2) for GMAW and hybrid laser arc welding (HLAW) root passes was employed and compared to the external-only welding approach developed in this project. Experience gained in conducting another GSP (EWI Project 49191CPQ) (Ref 3) was also applied as it was cost-matched to the current project (EWI Project 50453GTH) (Ref 4).

1.0 Introduction

Low-hydrogen automated welding processes are preferred to control microstructure to optimize strength and toughness on linepipe with strength of X70 and above. The overall productivity of a pipeline construction spread is usually controlled by the cycle time of the root-pass welding operations. Internal welding machines have historically assured good root-pass quality on high-strength pipelines. While welding speed is important, the costs of equipment and the time to align and set up the weld preparation are also important.

Root-pass welding techniques were emphasized since they have the greatest potential to improve pipeline integrity and facilitate the use of new and existing gas metal arc welding (GMAW) fill pass techniques.

2.0 Prior Work

The Pipeline Cost Calculator "PRCI Productivity and Economic Estimation Tool for Mechanized GMAW Welding of Pipelines" developed by BP for PRCI was used to calculate costs for single-torch GMAW, tandem GMAW, and hybrid laser beam welding (LBW/GMAW) for three pipe sizes.

The Cost Calculator really only applies to GMAW procedures for root passes and fill passes, so is only partially useful for analyzing costs of various pipeline welding root pass and fill pass technologies. However, it is useful for giving some indication of relative costs among different welding processes.

The cost calculator was used for four cases as noted below:

1. A baseline case for 52-in. pipe using internal root pass welding and dual-tandem GMAW fill.

2. A 24-in.-diameter pipeline using copper shoes for GMAW root pass (double down) and dual-tandem GMAW fill.

3. The LBW/GMAW external root pass case for 36in X80 pipe (single orbital head) with dual tandem GMAW fill.

4. The rotating electrode GMAW (GMAW-RE) external root pass case for 36-in. X80 pipe (double down) and dual-tandem GMAW fill.

The results from the prior GSP (EWI Project 46380CPQ) are presented in Appendix A. Attention is drawn to a comparison of the data for the "joints per day" (JPD) average productivity (70% of theoretical maximum). This number was multiplied by a normalizing factor, n, chosen to take into account the joint volume required to complete each joint for the different pipe diameters, based on the 36-in. pipe diameter, and expressed as JPDn. Based on this comparison, the following joint completion rates were derived.

1. Baseline case for 52-in. pipe (internal root)	99 JPD	148 JPDn
2. 24-in.-diameter pipeline (copper shoes)	81 JPD	61 JPDn
3. LBW/GMAW root pass for 24-in. pipe (external root)	112 JPD	84 JPDn
4. GMAW-RE root pass for 36-in. pipe (external root)	74 JPD	74 JPDn

These numbers show internal root pass welding to be the most productive, appreciating that external root pass welding is required for smaller pipe sizes. For small pipe sizes the normalized results show both LBW/GMAW and GMAW-RE to be more productive than external roots on copper shoes. Of course, these "raw numbers" need to be put in perspective of the overall cost of capital equipment cost differentials, especially for the LBW/GMAW case.

The cost calculator was not available for this work – BP was not a sponsor of the GSP – to which the DOT project was cost-matched.

The productivity and economic trade-offs for faster welding speeds on pipeline girth welds need to be weighed against the costs of weekly or monthly equipment rental required for each welding station on a pipe-lay operation. For example:

- Trenching
- Crane to put next pipe in the trench
- Crane to put welding tent on the next joint
- The cost of welding contractor personnel and equipment based on the number of welding stations
- Any other equipment needed for such things as nondestructive evaluation (NDE) vehicle.

The benchmark is the typical total weekly or monthly equipment cost for a pipe spread using X80 pipe based on manual welding of the root and single-torch GMAW mechanized welding of the hot, fill, and cap passes using a double-down technique. X80 pipe from the Cheyenne Project was used in the prior work, so the number of welding stations and associated equipment rental costs for that project are a useful benchmark as well.

3.0 Results for Current DOT Project

A useful summary of laser welding costs, comparing CO_2, Nd:YAG, fiber, and disc lasers was presented at ICALEO 2004. (Ref 5).

The current cost for IPG fiber lasers is as follows:

- 4-kW nominal power: $350,000
- 10-kW nominal power: $900,000

Laser costs are coming down somewhat for newer technology such as fiber lasers, but not at a significant rate in real terms.

Other items that will be required (Figures 3 and 4), include the following:

- Laser optics package (collimator and optics, no spares): $9,000
- Armored fiber optic delivery cable for fiber laser: $15,000
- Hybrid welding head: $60,000

Additional items which should be considered include:

- **Size of Equipment** – The amount of space the equipment takes up can be an issue. The fiber laser is about 1/10th the size of a Nd:YAG laser and chiller combination is a plus.

- **Power Consumption** – The fiber laser is 25% electrically efficient compared to only 3% for a Nd:YAG laser.

- **Utilities** – The fiber laser only needs 480 V at 80 A (or less) which may be available already.

- **Cost of Diodes** – There is an expected life of 25,000 hr. for the diodes in a fiber laser. There is a cost savings in materials and in labor for the change-out compared with typical maintenance costs for other laser systems (Ref. 5).

- **Laser Safety Enclosure** – The enclosure must assure eye safety for passing/proximate personnel. Laser-safe glass (for the 1.03/1.06-μm beam wavelength) must be used. The cost differential between a standard welding tent and a laser-safe enclosure must be considered.

Further development of hybrid laser/GMAW to weld out of position for 5G girth welding was conducted. Using a thinner root face (the laser can penetrate 12 mm steel) of 4-5 mm, hardness and toughness properties for X80 can be met using the hot pass to temper the hardness of the root pass HAZ (Figures 5 and 6). Using the wire feed in GMAW, a throat thickness of 6 mm can be easily achieved for the root pass at high travel speed up to 3 m/min. Because the welding speed was doubled from 1.5 m/min to 3 m/min, the equivalent JPDn for a 10 kW fiber laser/GMAW-P hybrid system is as follows:

- LBW/GMAW root pass for 24-in. pipe (external root) 224 JPD 168 JPDn

The JPDn is noticeable in that, at 168 JPDn, it is about 15 percent higher than that for welding with the internal root pass (148 JPDn) calculated in the prior work discussed above. Thus, based on the current level of development, the single-sided approach using hybrid laser arc welding is the most productive technique on paper. Naturally this needs to be developed and tested for pipeline girth welding on a right-of-way.

4.0 Discussion

High-speed pipe root pass welding increases the rate at which subsequent, hot, fill, and cap passes need to be completed to keep up with the root pass process.

The aim was to achieve a welding speed of 2.5 m/min or better, so that the overall rate of pipeline welding is not restricted by the welding speed for the root pass. A fixed time is necessary to attach, align, and clamp a new section of pipe for welding, typically 2 to 3 min. Hence, there is little incentive to reduce the welding time below about 1 min. However, there is a very strong incentive to be able to make the pipe root weld from the outside of the pipe with mechanized welding, without using a copper backing bar inside the pipe, and to achieve a welding speed of at least 1.5 m/min.

The results are very significant in terms of their potential application to pipeline welding. Very high welding speeds of 3 m/min were achieved on a X80 pipe 36-in. in diameter.

To put these results in perspective, the time taken for a complete root run with one laser in a 24-in.-diameter pipe would be 45 sec at 2.5 m/min and 38 sec at 3 m/min. These values easily exceed those required to achieve optimum performance. As the time necessary to attach, align, and clamp a new section of pipe for welding is typically 2 to 3 min., any welding speed in excess of 1.5 m/min will provide high productivity. The corresponding time for GMAW-RE using two torches in a double-down configuration at the 1.9 m/min root pass completion rate (two torches at 0.95 m/min average speed) is 60 sec. for a 24-in. pipe.

This also allowed the weld to be completed in 19.5-mm pipe material in only four passes using the tandem GMAW process. The overall deposition rate of the process was high at 10.8 kg/hr (23.7 lb/hr).

Laser hybrid root welds can be made with excellent weld quality and surface profile, together with very high productivity in X80 and X100 pipe material. Welds can be made with a 3-mm root throat thickness at 3 m/min and with a 4-mm throat thickness at 2.5 m/min. These welding speeds easily exceed the requirement for high productivity root welding, corresponding to a total root welding time of 58 sec. and 87 sec., respectively, for a single laser head welding the root of a 36-in. pipe. Using two GMAW-RE heads for double-down welding at an average travel speed for each of 0.95 m/min would equate to a root pass welding time of 113 sec. for a 36-in.-diameter pipe.

While the throat thickness and travel speed achieved with the hybrid fiber laser/GMAW equipment is impressive, it must be borne in mind that the capital equipment cost of the

system is about $1M. This should be compared to two single-torch GMAW systems at a cost of about $50K.

The main outcome of the hybrid laser/GMAW work was that satisfactory laser and laser hybrid root welds can be made for a range of root face dimensions and welding conditions as follows:

The speeds achieved easily exceeded the objective of 1.5 m/min for the single torch GMAW solution. It is possible to achieve 3-m/min welding speed with only 4-kW laser power on a 3 mm root face. The productivity (and cost) of the overall welding system depends on the precise combination of laser power, arc power, and root throat thickness.

The use of laser root passes was shown to produce acceptable mechanical properties in X100 pipe material and X80 pipe. A 3-mm root face and a 4.4 -m/min root pass completion rate (travel speed of 2.2 m/min) is recommended since two heads would be used to make the root pass at 2.2-m/min travel speed with a two-torch double-down procedure currently employed.

As a thinner, rather than a thicker root pass is required so that the root can be tempered by the hot pass to achieve the desired root toughness in X80 and X100 linepipe, a lower laser power of 4-5 kW is most appropriate (Figures 5 and 6), even when a 10 kW laser is available. As such, the ability to use a single laser with a beam splitter would allow two weld heads to be employed in a conventional manner for double-down welding. Thus, effectively, the root pass completion rate could be as high a 6 m/min, completing a 36-in pipe root in 29 seconds!

A welding speed of 1.5 m/min for a single torch equates to 3 m/min for a double-down welding approach with one torch on each side of the joint. The 2.2- to 3.0-m/min travel speed using laser/GMAW with one torch compares favorably to this, especially if a high power laser with a beam splitter is used for two heads to achieve 4.4- to 6 m/min root completion rate. When the comparative capital costs of the respective systems are considered, the system cost for a 10-kW fiber laser is about $900K whereas the cost for a dual-torch GMAW-RE system is less than $120K.

5.0 Summary - Conclusions

1. For hybrid laser arc welding the speeds achieved easily exceed the objective of the two past projects of 1.5 m/min, and in fact it is possible to achieve 3-m/min welding speed with only 5-kW laser power and a 5 mm root face, when used in a

hybrid configuration with 5 kW of GMAW arc power. The productivity (and cost) of the overall welding system depends on the precise combination of laser power, arc power, and root throat thickness. For high strength (X80 and X100) linepipe, the best process robustness is achieved at 2.2 m/min using 5-8 kW of laser power and 5 kW of arc power on a 3 mm root face to assure API 1104 property requirements can be met consistently.

2. The economic case for using a 10-kW fiber laser and associated equipment versus the case for two GMAW-RE torches for the root pass needs to be considered. While the 6- to 8-mm throat thickness and travel speed achieved with the hybrid fiber laser/GMAW equipment is impressive, it must be borne in mind that the capital equipment cost of the laser/GMAW system is around $1M. This should be compared to a single torch GMAW system at a cost of about $50K for two systems which can produce a throat thickness for the root pass of 4 to 5.5 mm.

3. Ultimately the cost effectiveness of a mechanized pipe welding system depends on the pipe material and wall thickness, and the length of the pipeline in addition to the other items discussed here. There is not a single solution for all cases. Ultimately the ability to finish a project ahead of schedule with the concomitant cost savings for equipment rental and labor may be an overriding factor in determining which form of process and mechanization is the most cost effective.

6.0 Commercialization

The welding process developed in this project can provide a robust method for girth welding of medium to large diameter pipelines in the field. The system has already been successfully demonstrated in a simulated field environment (Figures 7 through 9), using a diesel powered generator to supply power for the laser and GMAW elements of the system. FAA and FDA approvals were also secured for the demonstrations outside the EWI building, which is on the flight path to the Columbus Metropolitan Airport. The system development is based on the field-tested commercial CRC-Evans product P450 bug and band. The process is available for further prototype development and commercialization as CRC-Evans makes and leases welding systems and intends to commercialize and deploy the process. CRC-Evans supplies onshore pipeline activities as well as deepwater installation contractors.

The following areas for future work are considered worthwhile:

1. Further development of the prototype hybrid laser/GMAW system for field welding out of position for 5G girth welding.

2. Further development of the prototype hybrid laser/GMAW system for field welding out of position for 2G girth welding.

3. Testing the system on a pipeline right-of-way for girth welding.

4. Further development of the pipeline cost calculator allowing the use of laser and laser/GMAW welding procedures for root passes and fill passes.

7.0 References

1. Harris, I. D., EWI Project 46380CPQ Group Sponsor Project (GSP) titled 'Novel Arc Welding Processes for Improved Pipeline Welding'

2. Harris, I.D., EWI Project No. 47961GTH, 'Innovative Welding Processes for Small to Medium Diameter Gas Transmission Pipelines', Task 7 Report 'Productivity and Economic Analysis'. April 2006. OPS R&D Project No. 154, DoT Transaction Agreement No. DTRS56-05-T-0001

3. Harris, I. D., EWI Project 49191CPQ 'Group Sponsor Project (GSP) titled 'Fiber Laser Based Hybrid Automated Pipe Girth Welding'

4. Harris, I. D., EWI Project 50453GTH, 'Hybrid Laser/Gas Metal Arc Welding (GMAW) of High Strength Steel Gas Transmission Pipelines' OPS R&D Project No. 219, DoT Transaction Agreement No. DTPH56-07-T-000003

5. Ream, S., 'Laser Welding Efficiency and Costs: CO_2, YAG, Fiber, and Disc', Proceedings of the 23rd International Congress on Applications of Lasers and Electro-Optics (ICALEO), San Francisco, CA (Oct. 4-7, 2004).

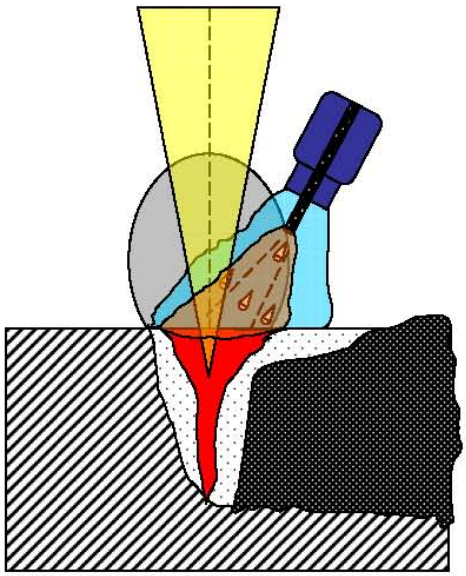


Figure 1. Focused laser beam and GMAW elements for hybrid LBW/GMAW

Figure 2. Commercial P450 bug and band pipe girth welding system with prototype hybrid welding head.

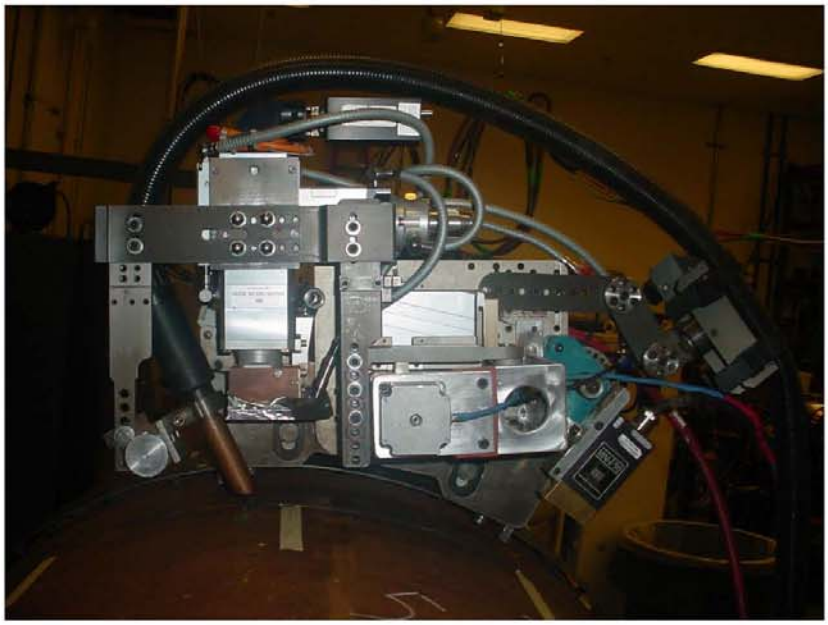


Figure 3. 10 kW capable hybrid girth welding head

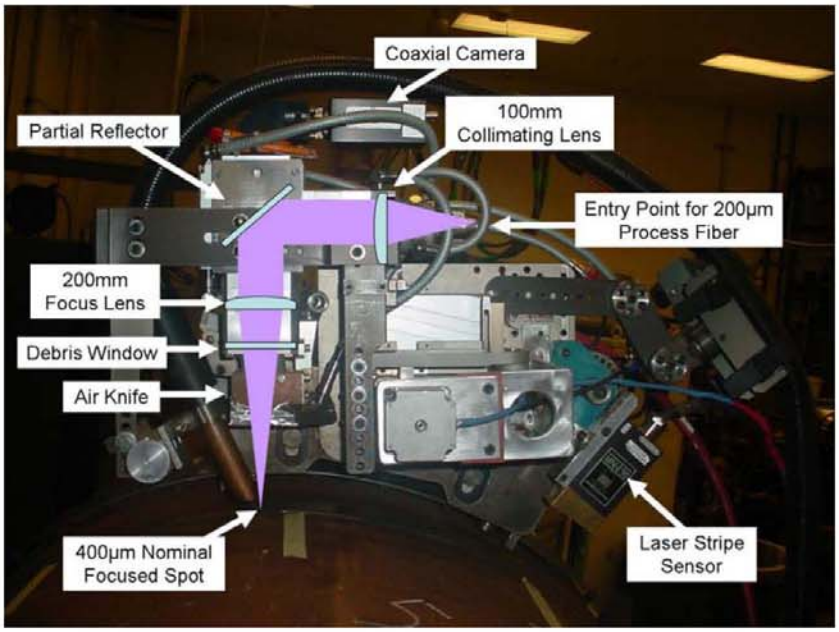
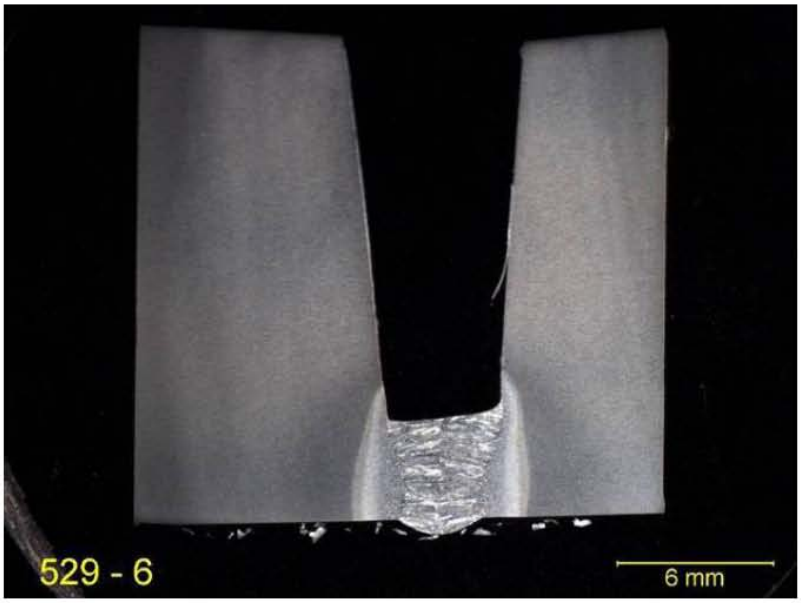


Figure 4. 10 kW capable hybrid girth welding head with component identification



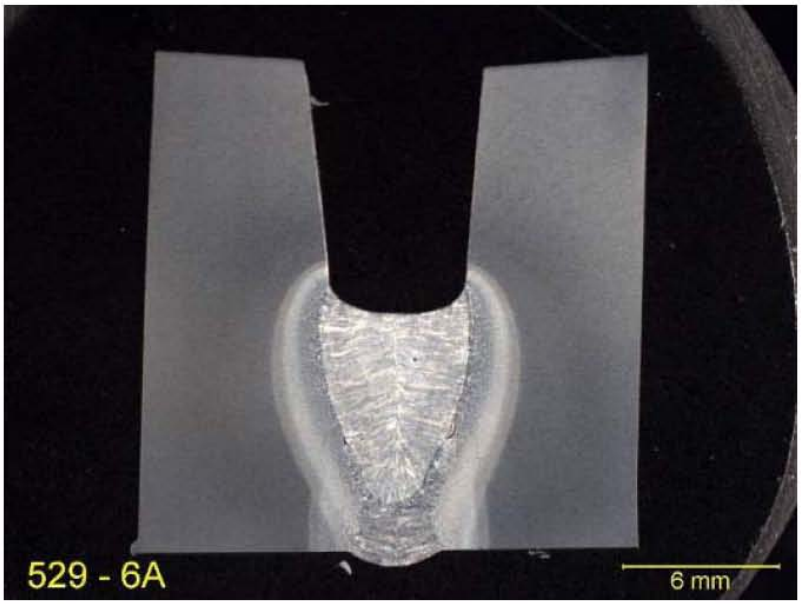


Figure 5. Typical macrosections of root pass (top) and root and hot pass (bottom)

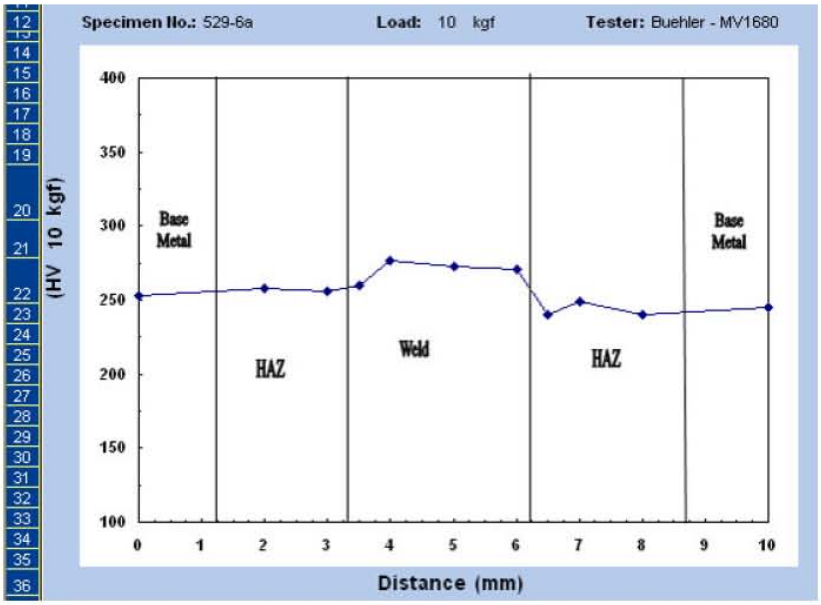


Figure 6. Typical cross weld hardness profile of X80 linepipe with root and hot pass

Figure 7. Welding tent and externally sullied electrical power from a diesel generator.

Figure 8. Welding set-up for hybrid LBW/GMAW girth welding demonstration

Figure 9. Welding set-up for hybrid LBW/GMAW girth welding demonstration