REPORT

April 28, 2006
EWI Project No. 47961GTH
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Innovative Welding Processes for Small to Medium Diameter Gas Transmission Pipelines

Task 1 Report
Development of Innovative Root Pass Welding Processes

Submitted to:

U.S. Department of Transportation
Research and Special Programs Administration
Washington, D.C.

EWI®

MATERIALS JOINING TECHNOLOGY

Task 1 Report

Project No. 47961GTH
U.S. Dot OTA No. DTRS56-05-T-0001

on

Innovative Welding Processes for Small to Medium Diameter Gas Transmission Pipelines
Task 1 – Development of Innovative Root Pass Welding Processes

to

U.S. Department of Transportation
Research and Special Programs Administration
Washington, D.C.

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Executive Summary

Pipelines will be an integral part of our energy distribution systems for the foreseeable future. It is predicted that natural gas consumption will double over the next 20 years. Operators are currently considering the installation of many tens of billions of dollars of pipeline infrastructure. In a number of cases, the cost of exporting the product will have a dominating influence on the viability of the upstream production facilities. These facilities will progress only if the industry can substantially reduce capital expenditure and improve design for pipeline integrity. Whether the application is an onshore gas transmission line or a deepwater pipeline, there is a need to constantly improve the productivity, quality, integrity, and reliability of pipeline girth welds to reduce construction costs. There is also a need for improved technologies suitable for the higher strength steels currently being developed.

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 setup the weld preparation are also important. On large-diameter tie-ins, and small- to medium-diameter pipelines, root side access is generally not provided due to cost constraints and equipment limitations. There is a technology gap to deploy high-strength materials on single-sided pipeline welding applications.

This project was aimed at developing innovative welding processes and technologies for single-sided pipeline girth welding. 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. Advanced automation techniques will be used to improve weld quality, process control, seam tracking, and robustness.

The project is broken down into the following tasks:

- Task 1 – Development of Innovative Root Pass Welding Processes
- Task 2 – Property Testing of Preferred Root Pass Welding Techniques
- Task 3 – Improved Root Pass Techniques
- Task 4 – Process Control Systems for Pipeline Girth Welding
- Task 5 – Real-Time Quality Monitoring for the Detection of Welding Defects
- Task 6 – Preferred Process/Technique Demonstration
- Task 7 – Productivity/Economic Analysis
- Task 8 – Final Report.

This report addresses the technical approach achieved in Task 1 – Development of Innovative Root Pass Welding Processes.

Based on the work reported here for GMAW procedure development on X80 pipe material, and laser or hybrid laser/GMAW work on X100, the following conclusions can be stated:

1. The GMAW process showing the most promise for high-speed mechanized root pass welding was the rotating electrode GMAW (GMAW-RE), known as Spin Arc.

2. Welding procedures were developed for welding in the 5G position using the "double-down" technique, but using only a single torch for the development work.

3. A welding speed of 0.7 m/min was the maximum speed at which robust root pass welds could be made on X80 pipe without centerline solidification cracking using ER70S-6 or ER80S-D2 wires. Welding parameters were as follows:

   - Flat position – Weld SA-115
     - Travel speed: 27.6 in./min (0.7 m/min)
     - Wire feed speed: 350 in./min
     - Welding current: 177 A
     - Arc voltage: 22.8 V
     - Wire feed speed/travel speed ratio: 12.7
     - Throat thickness: 4.5 mm.

   - Vertical-down position – Weld SA-129
     - Travel speed: 31.5 in./min (0.8 m/min)
     - Wire feed speed: 448 in./min
     - Welding current: 209 A
     - Arc voltage: 22.0 V
     - Wire feed speed/travel speed ratio: 14.2
     - Throat thickness: 4.2 mm – weld had buried solidification crack.

4. Welding speeds up to 1.5 m/min were used in the vertical-down position, but the combination of pipe metallurgy, elongated teardrop weld pool shape, and the requirements of achieving full penetration with a reasonable throat thickness, consistently resulted in centerline solidification cracking.

5. The persistent cracking found with ER70S-6 and ER80S-D2 wires in the vertical-down position was solved using the ER90S-G Union NiMo80 wire with an average root pass welding speed of 0.95 m/min.

- Flat position – Weld SA-134
    - Travel speed: 27.6 in./min (0.7 m/min)
    - Wire feed speed: 397 in./min
    - Welding current: 210 A
    - Arc voltage: 21.5 V
    - Wire feed speed/travel speed ratio: 14.4
    - Throat thickness: 5.6 mm.

- Vertical-down position – Welding SA-137
    - Travel speed: 46.3 in./min (1.2 m/min)
    - Wire feed speed: 552 in./min
    - Welding current: 254 A
    - Arc voltage: 22.1 V
    - Wire feed speed/travel speed ratio: 11.
    - Throat thickness: 4.3 mm.

Alternative parameters developed to use a single travel speed and maintain a more even throat thickness can be summarized as follow:

- Flat position – Weld SA-155
    - Travel speed: 27.6 in./min (0.7 m/min)
    - Wire feed speed: 496 in./min
    - Welding current: 213 A
    - Arc voltage: 17.8 V
    - Wire feed speed/travel speed ratio: 18.0
    - Throat thickness: 5.6 mm.

- Vertical-down position – Weld SA-164
  - Travel speed: 27.6 in./min (0.7 m/min)
  - Wire feed speed: 460 in./min
  - Welding current: 198 A
  - Arc voltage: 21.1 V
  - Wire feed speed/travel speed ratio: 16.7
  - Throat thickness: 5.0 mm.

Trials were conducted with this wire to develop tolerance to root face mismatch and the results showed the procedure to be tolerant to 1.5 mm of mismatch with good penetration and root face profile, in both the flat and vertical-down positions.

6. For hybrid laser beam welding (LBW)/GMAW the speeds achieved easily exceed the objective of 1.5 m/min, and in fact it is possible to achieve 4 m/min welding speed with only 4-kW laser power. The productivity (and cost) of the overall welding system depends on the precise combination of laser power, arc power, and root throat thickness. This issue was investigated and reported in Task 7.

7. For laser and hybrid LBW/GMAW root passes it was decided that a weld root face of 6 mm should be used as basis for the GMAW fill weld to be made under Task 2, since this would provide a significant volume of laser melted weld metal, which could be evaluated during mechanical property testing.

Based on the work and conclusions above, the GMAW-RE technique is recommended as the best for further work toward field deployment for root passes with GMAW in terms of economic as well as technical grounds based on the high cost of the 8-kW fiber laser system.

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Legal Notice

1.0 Introduction

Pipelines will be an integral part of our energy distribution systems for the foreseeable future. It is predicted that natural gas consumption will double over the next 20 years. Operators are currently considering the installation of many tens of billions of dollars of pipeline infrastructure. In a number of cases, the cost of exporting the product will have a dominating influence on the viability of the upstream production facilities. These facilities will progress only if the industry can substantially reduce capital expenditure and improve design for pipeline integrity. Whether the application is an onshore gas transmission line or a deepwater pipeline, there is a need to constantly improve the productivity, quality, integrity, and reliability of pipeline girth welds to reduce construction costs. There is also a need for improved technologies suitable for the higher strength steels currently being developed. Furthermore, advanced welding technologies are currently only deployed on large diameter pipelines where the costs of internal backing clamps or internal root welding machines can be justified. The vast majority of small- to medium-diameter pipelines (24 in. and less) are welded manually, which may be more cost-effective at present, but does not always provide the highest integrity pipeline and raises specific metallurgical concerns on pipelines exceeding the strength levels of Grade X70, or employing corrosion-resistant alloy materials.

2.0 Objectives

This project was aimed at developing innovative welding processes and technologies for single-sided pipeline girth welding. 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. Advanced automation techniques will be used to improve weld quality, process control, seam tracking, and robustness.

3.0 Technical Background

3.1 Current State-of-the-Art in Pipeline Welding

Increasing demand for gas will require major investment in new long-distance gas-transmission pipelines with significant expansion of existing infrastructure using shorter sections of small- and medium-diameter pipelines to extend and loop existing lines and increase capacity. Tie-in welds can also be very frequent due to ditch, river, road, and rail crossings, as well as other topographical features and these are often the weak link in a system. Tie-in welding may represent 50% of the welding costs of some pipelines. Small- to medium-diameter and tie-in welds are typically performed using cellulosic welding techniques which are generally not suitable for pipelines over Grade X70. A prerequisite for these applications is single-sided welding since internal welding machines and alignment tools are not practical. These will need to be constructed as economically as possible, but the trends toward higher operating pressures and higher strength steels require improved pipeline integrity through overmatching weld metals and better quality processes.

This report addresses Task 1 – Development of Innovative Root Pass Welding Processes, using various newer forms of GMAW with solid wire consumables.

3.2 Welding Process Importance to Advance Pipeline Safety

High-strength pipeline materials, over X70, offer cost savings but are more sensitive to process variation to assure properties. The ideal welding process produces welds with good bead shape and fusion, matching or over-matching material properties, and is cost effective. There should be no cracks or flaws in the weld deposit. Cracking susceptibility increases as the hydrogen content, stress, and hardness of the microstructure increase. For high-strength pipelines, manual welding processes cannot meet the required combination of properties, diffusible hydrogen, and weld integrity to assure cracking resistance. Low hydrogen automated welding processes are preferred to control microstructure to optimize strength and toughness on 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 setup the weld preparation are also important. On large diameter tie-ins, and small- to medium-diameter pipelines, root side access is generally not provided due to cost constraints and equipment limitations. There is a technology gap to deploy high-strength materials on single-sided pipeline welding applications.

3.3 Developments in Pipeline Welding

Innovative arc welding techniques have been the preferred process for new pipeline welding applications. For fill pass welding, this includes high-speed welding procedures with single or tandem torches, and more recently dual tandem torches; i.e., the Cranfield Automated Pipeline System (CAPS). For root pass welding, the only known case for mechanized single-sided welding is in offshore applications using pulse short circuit (PSC)-GMAW. Unfortunately, these offshore applications have to be performed at slow travel speeds since the process requires significant operator oversight and have been reported to have poor tolerance to fit-up mismatch and gap causing significant repair and lost earnings. In addition, these welds do not meet emerging fatigue properties. Offshore pipeline contractors have a strong need for a robust single-sided welding process, especially for deepwater application where fatigue requirements are being imposed for bead contour and quality.

Only advanced processes coupled with automation techniques have the potential to improve the robustness, quality, productivity, and integrity of single-sided pipeline root passes, and assure resistance to flaws through the use of in-process monitoring and adaptive control techniques. These processes include rotating electrode GMAW (GMAW-RE), pulsed short circuit GMAW (PSC-GMAW), PSC-GMAW with wire feed modulation (such as controlled short Circuit™ (CSC-GMAW) or Cold Metal Transfer™ (CMT-GMAW), variable polarity GMAW (GMAW-VP) using fuzzy logic short circuit transfer, and hybrid laser beam welding/GMAW (LBW/GMAW). These processes have been targeted toward root pass welding on narrow-groove joint preparations with or without gas backing. All these processes are designed to improve metal transfer and minimize spatter, and are preferred for downhill fixed-position pipeline welding since the metal droplets from the welding electrode are transferred to the welding pool by surface tension permitting welding in all positions.

Cranfield has received over $2M of funding to develop laser-GMAW for root pass applications using a new generation of laser technology and has purchased an 8-kW laser for this purpose. This program has benefited from these results and additional welds made on program materials. BP is funding Cranfield University to develop high-integrity mechanized root pass techniques for corrosion-resistant alloy pipelines for onshore and deepwater applications. Results from their research will be provided to this program.

The purpose of the work conducted at Cranfield University was to develop processes and procedures for laser and laser/arc hybrid welding of pipe root runs, in order to achieve high-quality root runs at high welding speeds. The aim was to achieve a welding speed of 1.5 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 minutes. Hence, there is there is little incentive to reduce the welding time below about 1 minute. 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 at least achieve a welding speed of 1.5 m/min.

4.0 Technical Approach

The project is broken down into the following tasks:

- Task 1 – Development of Innovative Root Pass Welding Processes
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- Task 6 – Preferred Process/Technique Demonstration
- Task 7 – Productivity/Economic Analysis
- Task 8 – Final Report.

This report addresses the technical approach and results achieved in Task 1 – Development of Innovative Root Pass Welding Processes.

4.1 Task 1 – Development of Innovative Root Pass Welding Processes

New GMAW power source technologies have led to the development of new innovative welding processes that could improve root pass welding, especially from a single side with no backing or root side intervention. This task considered single-sided root pass welding processes in the light of the work completed in the EWI GSP Project No. 46380CPQ, "Novel Arc Processes for Improved Pipeline Welding", such as:

- PSC-GMAW with wire feed modulation (WFM) – eliminated in the GSP and not used in the present work as a result.

- GMAW-VP with fuzzy logic short circuit transfer – eliminated later in the GSP – limited trials in this work.

- GMAW-RE with constant voltage short circuit transfer and PSC-transfer – lead candidate process for the root pass in the GSP, and thus the process studied in detail in this work.

- Hybrid LBW/GMAW welding was performed by Cranfield University.

This task evaluated the different root pass welding processes and the joint design developed by Serimer-Dasa for mechanized pipeline welding (Figures 1 and 2). All test welds (with the exception of GMAW-VP) were performed on X80 pipe with parameters initially developed on X80 "plate" coupons cut from pipe (Figure 3) and mounted on a simple fixture (Figure 4). The parameters were then deployed in the 5G position on pipe butt joints to suit cross-country pipeline applications. The preferred process will be evaluated with advanced techniques in Task 3 to improve robustness and quality. The X80 pipe was 36-in. diameter with a wall thickness of 0.656 in. and the composition is shown in Table 1.

A solid steel wire welding consumable to AWS A5.18 ER70S-6 was used for GMAW-VP. The wire diameter was 1.6 mm (1/16 in.). For Spin Arc (GMAW-RE), a 1.0-mm (0.040-in.)-diameter Lincoln SupraMIG wire to AWS A5.18 ER70S-6 was used. The chemical analysis is shown in Table 2. Based on the results achieved, a 1.0-mm (0.040-in.)-diameter low-alloy steel wire to AWS A5.28 ER80S-D2 and a 1.0-mm (0.040-in.)-diameter low-alloy steel Bohler Thyssen Union NiMo80 wire to AWS A5.28 ER90S-G were also used. The chemical analyses of the latter two wires are shown in Table 3.

The shielding gases used for Spin Arc trials were Ar-50%CO_2, Ar-25%CO_2, and Ar-10%CO_2. For GMAW-VP welding trials a 100% CO_2 shielding gas was used.

4.1.1 GMAW-VP

A Motoman/Kobelco 350 power source (Figure 5) and a Serimer-Dasa STX track-mounted pipeline welding tractor (Figure 6) were used in the work on GMAW-VP. The system was controlled through a laptop-based GUI connected to a Serimer-Dasa controller (Figure 7). The controller provided the following motion controls:

- Welding travel speed
- Torch position L/R and up/down.

The GMAW-VP work was conducted on 16-in.-diameter carbon steel pipe as the 36-in.-diameter X80 pipe was not available at the time and the process had already been shown to have less potential than the GMAW-RE technique. Argon gas backing was used (Figure 8).

4.1.2 Spin Arc GMAW

The controller for Spin Arc welding is embedded in the robot controller for a robotic arc welding system and cannot presently be operated separately. As such, a robotic welding system was loaned to EWI by Panasonic Factory Automation. The system components are shown in Figure 9 and set up for pipe welding in Figure 10.

The Spin Arc uses a rotating gas diffuser and contact tip assembly which is driven by a dedicated motor to produce the rotary motion of the assembly and thus the electrode wire (Figure 11). The spin diameter is fixed and a number of kits are available to develop 2-, 3- and 4-mm spin diameters. For this work, the 4-mm spin kit was used, generating a 4-mm-diameter motion at the wire tip. The spin frequency is controllable in the range 0 to 100 Hz. A tapered contact tip (Figure 12) was used to enable joint access and spin motion in the narrow-groove joint preparation without sidewall contact. A short contact tip-to-workpiece distance (CTWD) and electrical stickout were used with the tapered contact tip extending beyond the gas nozzle (Figure 13).

The power source can be run in constant voltage GMAW (GMAW-CV) mode or pulsed mode ("Dip Pulse" is the Panasonic trade name for the latter). In either case, the metal transfer mode is short circuit, appropriate for control of root pass welding. The Dip Pulse mode is effective in controlling the arc re-ignition to minimize spatter generation.

4.1.3 Laser and Hybrid Laser/GMAW

The laser equipment consisted of the following:

- IPG ytterbium fiber laser
- YLR 8000
- 1070-nm wavelength
- 20-m long work fibree
- 300-μm diameter
- Precitec welding head
- 250-mm focal length
- 15.8-mm radius beam quality.

The arc welding equipment used was a Lincoln Powerwave 455M/STT GMAW-P welding power source with associated wire feeder, welding torch, and water cooler.

Laser hybrid welding was conducted on plate in the flat position, with the laser at right angles to the surface. Welds were made with the laser leading and with the arc welding torch at an angle of 19 degrees to the axis of the laser beam. The schematic arrangement of the laser and welding arc is shown in Figure 14 and the weld preparation used for most tests is shown in Figure 15.

Three main series of tests were conducted: evaluation of weld penetration for bead-on-plate welds, study of a range of parameter variations on 6-mm thick plate, and laser root welds on X100 steel pipe material. The main parameters studied were:

- Laser power: 4 to 6.75 kW
- Focus point: plate surface ±0.2 mm
- Arc power: 5 to 7.5 kW
- Wire feed speed: 10 to 15 m/min
- CTWD: 12 to 17 mm
- Bevel angle: 12, 18, 45 degrees
- Root face: 0, 1, 2, 6, 8 mm
- Laser/arc distance: 2 to 5 mm
- Laser/torch angle: 19 degrees
- Consumable: Oerlikon Carbofil NiMo1 – 1-mm diameter
- Plate thickness: 6 mm
- Shielding gas: Trimix (82.5%Ar, 12.5%CO_2, 5%He), 100% Ar.

5.0 Results

This report addresses the results achieved in Task 1 – Development of Innovative Root Pass Welding Processes. The results are divided between GMAW-VP and GMAW-RE. Preliminary results using the 8-kW fiber laser for hybrid LBW/GMAW of pipe root passes have recently become available and are reported here also.

5.1 GMAW-VP Parameter Development Trials

Work was conducted with a Serimer-Dasa STX pipeline welding tractor, on a pipe track (Figure 8). The joint profile and access are illustrated in Figure 2.

The set-up and general conditions used for welding 16-in. pipe with argon gas backing were as follows:

- Closed root joint
- 1-mm root face
- Aim – Full penetration with 2- to 3-mm backface bead width and low-penetration bead convexity (high toe angle).

Using the results from the GSP as a baseline, Welds V5, V6, and V8 showed the most promise for girth welding and are summarized below.

- Weld V5 (Figures 16 and 17) was made with the following parameters:

    - Travel speed 1.3 m/min on a closed root (0- to 10- degree position)
    - 3-mm throat
    - 90%Ar-10%CO_2 shielding gas
    - 330-in./min wire feed speed
    - 20% direct current electrode negative (DCEN)
    - 23.5 V.

Weld V6 (Figure 18) was made with the same parameters (0- to 20- degree position). Weld V8 (Figure 19) was made with similar parameters (0- to 50-degree position).

The results showed that a 3-mm weld throat could be achieved with a 1-mm root face at a travel speed of 1.3 m/min when a closed root was used.

Results for parametric development using GMAW-VP in this project are shown in Table 3. The same joint preparation and root face (1 mm) were used as before, and also on 16-in.-diameter carbon steel pipe. The best results were achieved in the flat position at 1.6-m/min travel speed, (Weld VP-02, Figure 20) and at 1.8 m/min in the vertical-down position (Weld VP-09, Figure 21). A higher wire feed speed of 400 in./min and higher DCEN percentage of 40 and 30% were used in the flat and vertical-down positions, respectively. The weld throat thickness was 3 mm in both cases.

5.2 GMAW-RE (Spin Arc) Parameter Development Trials

Baseline parameters for this development work were the best results from the cost-matched EWI GSP 46380CPQ, "Novel Arc Welding Processes for Improved Pipeline Welding". These parameters are shown in Table 4.

The resulting welds from these parameters are shown in Figures 22 through 27. For Weld W13, the weld consistency and general appearance is shown from the outside diameter (OD) (Figures 22 and 23), from the inside diameter (ID) (Figures 24 and 25), and from macrosections (Figures 26 and 27). The lack of sidewall fusion defect shown in these figures resulted in development of the parameters for Weld W21. The internal and external appearance and macrosection for Weld W21 are shown in Figures 28 through 30, respectively. The weld macrosections were removed from the vertical-down portion of the weld in both Welds W13 and W21.

In the development work reported here, a total of 130 welds were made between pipe sections prepared as plate butt welds and pipe girth weld sections. Welds were typically 6- to 8-in. long in each case. All the welding parameters evaluated and comments on the results are recorded in Table 5. The sections of development effort are described separately below, and summarized in Table 6, Sections 6a-6l. This table correlates to those reported in the May and August 2005 Quarterly Reports for this project.

Work in the GSP had shown the benefit of using a thinner root face to achieve full penetration and higher travel speed using GMAW-VP. This approach was tried for the root face in GMAW-RE as well, but the results were not as good (Table 6, Sec. 6a, and Figure Y). Burn-through was experienced in the majority of cases, so the next step was to increase the root face thickness. A summary of the parameter ranges is shown in Table 6, Sec. 6a. Illustrative weld penetration bead profiles are shown in Figure 31.

Less or no penetration and burn-through were observed. The shielding gas composition was changed to 90%Ar/10%CO_2. A summary of the parameter ranges is shown in Table 6, Sec. 6b. Illustrative weld penetration bead profiles are shown in Figure 32.

Mixed results of burn-through and intermittent lack of penetration were observed. Gas composition was changed to 75%Ar/25%CO_2 in an effort to broaden the penetration profile somewhat compared to use of 90%Ar/10%CO_2. A summary of the parameter ranges is shown in Table 6, Sec. 6c. Illustrative weld penetration bead profiles are shown in Figure 33.

Mixed results of good penetration, inadequate penetration, and some burn-through were observed. The welding parameter that gave good results (Weld SA-33) were used more at a later stage. The next step was to perform trials with a root face thickness of 2.0 mm with varying TSs. A summary of the parameter ranges is shown in Table 6, Sec. 6d. Illustrative weld penetration bead profiles are shown in Figure 34, while macrosections of Welds SA-22 and SA-33 are shown in Figures 35 and 36, respectively.

Good results were found at a travel speed of 59.1 ipm in four cases, had one weld with burn-through – consistency of the weld parameters not proven. A summary of the parameter ranges is shown in Table 6, Sec. 6e. Illustrative weld penetration bead profiles are shown in Figure 37, and a macrosection of Weld SA-51 is shown in Figure 38.

The next step was to return to parameters of Weld SA-33 for further development and consistency trials to compare with the results noted above. Select the root face to machine on the pipe butt joints on this basis.

The root face thickness was reduced to 1.70 mm to overcome the lack of penetration problem. Development work in this stage was performed in the flat position on X80 plate cut from pipe using CV mode GMAW. A summary of the parameter ranges is shown in Table 6, Sec. 6f. The result of this work was generally lack of penetration and some instances of burnthrough were observed. Illustrative weld penetration bead profiles are shown in Figure 39.

The gas composition was then changed to 90%Ar/10%CO_2 using pulse parameters; i.e., the Dip Pulse mode. Changing to welding in the pulse mode was done to achieve more consistent metal transfer, providing better and more uniform weld penetration. The work was performed on X80 plates in the flat position. A summary of the parameter ranges is shown in Table 6, Sec. 6g. Illustrative weld penetration bead profiles are shown in Figure 40. The results were a combination of little to good penetration. Macrosections revealed centerline cracking (Figure 41, Weld SA-79).

The next step was to change the welding parameters to restrict wire feed speed/travel speed ratio and achieve a depth-to-width ratio closer to 1:1. The procedure development was performed with a 50%Ar/50%CO_2 gas composition to produce a wider bead penetration profile, helping to control the depth-to-width ratio in order to resolve the centerline cracking problem. The work was performed on X80 plates in the flat position. A summary of the parameter ranges is shown in Table 6, Sec. 6h. Illustrative weld penetration bead profiles are shown in Figure 42. The results were that robust welding parameters were established for horizontal welding. Macrosections of Welds SA-93 and SA-94 showed centerline solidification cracks (Figures 43 through 46).

The next step was to start working on the vertical-down position welding parameters. From this point forward, welding was performed on pipe girth welds only (Figures 47 through 49). The work performed confirmed the use of parameters established on plate transferred to welding on to pipe butt joints. Trials started with welding between 0 to 20 degrees and then progressed toward working on vertical-down parameters in the 80- to 100-degree segment of the pipe. A summary of the parameter ranges are shown in Table 6, Sec. 6i. Illustrative weld penetration bead profiles are shown in Figure 50. The results were mixed; good penetration, inadequate penetration, and crater cracks were observed (Figures 51 and 52 for Weld SA-95).

The next step was to perform trials with a drag torch angle instead of a push angle (as performed in previous tasks) to better control the weld pool and bead shape in the vertical-down position. A summary of the parameter ranges are shown in Table 6, Sec. 6j. Illustrative weld penetration bead profiles are shown in Figures 53 and 54.

The results were a combination of good penetration and crater cracking. The welding procedure for Weld SA-115 was selected for the final procedure for girth welding in the horizontal position. The weld penetration bead profile is shown in Figure 55, and the weld profiles are illustrated in Figures 56 and 57. No evidence of cracking was seen in this weld.

The next step was to use a higher strength consumable with varying torch angles and revised welding parameters.

5.2.1 Use of Alternative Welding Consumables to Eliminate Cracking in the Vertical-Down Position

Trials were performed in the vertical-down position using the welding parameters developed to this point in an effort to eliminate cracking. As the welding concept was single-sided welding without backing or internal clamping, no clamping had been used to this point. Pipe clamps were used to provide some transverse restraint, and the higher strength. ER80S-D2 wire, to AWS A5.28: 2005, and with 68-ksi (min) yield strength (YS) and 80-ksi (min) ultimate tensile strength (UTS), was used to provide somewhat higher hot strength in the solidifying weld metal compared with the ER70S-6 consumable. 250°F preheat was used, with the results obtained using the ER70S-6 electrode wire being used as a baseline for comparison.

The following combinations were tried in an effort to eliminate cracking:

- ER70S-6 – with 250°F preheat (but no clamping)
- ER70S-6 – with clamping (but no preheat)
- ER70S-6 – with clamping and 250°F preheat.
- ER80S-D2 – without clamping or preheat
- ER80S-D2 – with 250°F preheat (but no clamping)
- ER80S-D2 – with clamping (but no preheat)
- ER80S-D2 – with clamping and 250°F preheat.

None of these trials were able to eliminate cracking in the vertical-down position.

The work was performed on pipe with use of a higher strength consumable in an effort to overcome the centerline cracking problem. A summary of the parameter ranges are shown in Table 6, Sec. 6k. Illustrative weld penetration bead profiles are shown in Figure 58.

The results were that centerline cracking was still observed (Figures 59 and 60).

The next step was to reduce the travel speed. The work was performed on pipe with use of a higher strength consumable and lower travel speed in an effort to overcome the centerline cracking. A summary of the parameter ranges are shown in Table 6, Sec. 6l. Illustrative weld penetration bead profiles are shown in Figure 61, with macrosections shown in Figures 62 and 63. The results were that centerline cracking was still observed.

The procedure in Weld SA-129 (Figures 64 through 66) was selected for further development in the vertical-down position, although this weld also exhibited centerline cracking.

The GMAW-RE procedures developed to this point can be summarized as follows:

- Flat position – Weld SA-115
    - Travel speed: 27.6 in./min (0.7 m/min)
    - Wire feed speed: 350 in./min
    - Welding current: 177 A
    - Arc voltage: 22.8 V
    - Wire feed speed/travel speed ratio: 12.7

- Vertical-down position – Weld SA-129
    - Travel speed: 31.5 in./min (0.8 m/min)
    - Wire feed speed: 448 in./min
    - Welding current: 209 A
    - Arc voltage: 22.0 V
    - Wire feed speed/travel speed ratio: 14.2

To overcome the persistent centerline hot cracking problem in the vertical-down position, a higher strength Union NiMo80 wire from Bohler Thyssen was subsequently used. This low alloy steel wire was developed for welding X80 pipe and conforms to AWS A5.28: 2005 ER90S-G. It has a YS equivalent to ER90S-D2 (78 ksi) although no minimum is specified, and a UTS of 90 ksi (min).

Two welding speeds were employed in the vertical-down position to overcome this issue, 0.8 and 1.2 m/min. The best results were achieved at 1.2 m/min, Weld SA-137 (Figures 67 and 68).

At this point in development work the final configuration of welding equipment was being used. This consisted of the addition of a "slave" tractor and track used to mount the wire feeder (Figure 69).

Alternative parameters, developed to use a single travel speed and maintain a more even throat thickness, can be summarized as follow.

- Flat position – Weld SA-155
    - Travel speed: 27.6 in./min (0.7 m/min)
    - Wire feed speed: 496 in./min
    - Welding current: 213 A
    - Arc voltage: 17.8 V
    - Wire feed speed/travel speed ratio: 18.
    - Throat thickness: 5.6 mm.

- Vertical-down position – Weld SA-164
    - Travel speed: 27.6 in./min (0.7 m/min)
    - Wire feed speed: 460 in./min
    - Welding current: 198 A
    - Arc voltage: 21.1 V
    - Wire feed speed/travel speed ratio: 16.7
    - Throat thickness: 5.0 mm.

The fusion profiles and penetration bead widths are illustrated in Figures 70 and 71. Good fusion characteristics were exhibited including improved bead surface profile for deposition of the "hot" pass.

Trials were conducted with this wire to assess tolerance to root face mismatch and the results showed the procedure to be tolerant to 1.5 mm of mismatch with good penetration and root face profile, in both the flat and vertical-down positions (Figures 72 through 75). This meets the industry requirement for tolerance to high/low mismatch in the root.

5.3 Hybrid Fiber Laser/GMAW

Root pass welding trials were conducted at Cranfield University using a fiber laser system rated at 8 kW. This is one of the highest power fiber lasers available, although at least one 12-kW fiber laser has been used in Germany recently.

The joint preparation used was modified from the Serimer-Dasa joint preparation used for the GMAW process variants since the 8-kW laser can penetrate at least 10 mm of steel in a single pass. A root pass with a throat thickness of 6 mm was produced at a travel speed of 4 m/min (160 in./min).

Initial bead-on-plate laser welds were conducted on 19.5-mm-thick pipe material, to characterize laser performance. The results are shown in Figures 76 and 77. These results are similar to those obtained in Nd:YAG laser welding.

The main series of test was conducted on 6-mm thick carbon steel (BS EN10025, Grade S275). The objective of this series of tests was to determine the range of welding parameters necessary to make acceptable welds with a range of weld preparations. The majority of tests were conducted with a 12-degree bevel angle and a 1-mm root face. Tests were also conducted with zero root face and with an 18-degree bevel angle.

Figures 78 and 79 show the weld profiles produced with a laser power of 6.25 kW, a 12-degree bevel angle and a 1-mm root face. It is apparent that satisfactory welds can be made at this laser power at speeds in the range 2.5 mm/min and 4 m/min. The reduced heat-affected zone (HAZ) width is apparent for weld the higher travel speed. These travel speeds are in excess of those required for high productivity welding of small and intermediate diameter pipe, and it is apparent that a good root profile has been achieved in both cases. The root profile achieved is dependant on the combination of welding parameters used: Figures 80 through 82 show the effects on root profile of a gradual increase in laser power for fixed arc welding parameters.

The distance between the laser beam and the filler wire impingement point is critical in achieving a successful weld. If the distance is too small, the arc and filler metal disrupts the formation of the keyhole. However, if the distance is too large, the arc plasma operates separately from the laser plasma, and the positive synergic operation of the laser and arc is lost. The optimum distance in this series of experiments was determined to be about 2 mm. Figure

83 shows the effect of increasing the spacing to 5 mm, when full penetration has not been achieved under conditions otherwise similar to Figure 82.

CTWD must also be optimized for satisfactory welds. Figures 84 and 85 show that satisfactory welds can be achieved for variations in CTWD over a small range.

Figures 86 and 87 show the effect of changing the root face to zero, indicating that very high travel speeds can be achieved at reduced laser power, although in this case the root profile is not fully satisfactory. Figure 88 shows a weld made with an 18-degree bevel angle and laser power reduced to 4.5 kW. A satisfactory root bead has resulted, although in this case there has been some instability in the arc welding conditions, thought to have been cause by an elevated welding voltage.

The final series of welds was conducted using laser welding (i.e., not hybrid LBW/GMAW) on 19.5-mm-thick X100 steel, with the weld preparation shown in Figure 89. The root weld and completed GMAW tandem fill are shown in Figure 90. The throat root weld was in excess of 6 mm before the GMAW fill, and it is evident that the first GMAW fill pass has re-melted about half of the laser root weld throat thickness. The results of mechanical property tests on these welds are given in the Task 2 report for this project.

6.0 Discussion

Work in the GSP using 16-in.-diameter, 0.5-in.-wall carbon steel pipe was used as the baseline for the development work in this project on X80 pipe. The pipe used here was 36-in. diameter with a 0.650-in. wall, thus both higher strength and higher joint restraint in terms of the stress state in the joint region. The requirements for the joints are broadly similar in each case in terms of the desired productivity and physical profile of the root pass welds, as follows:

1. Full penetration
2. High travel speed
3. High throat thickness
4. No copper backing
5. No argon/gas backing.

Obvious limitations include avoidance of lack of fusion, lack of penetration, and burnthrough. The desire for high productivity and high (greater than 2.5 mm) throat thickness introduce competing factors regarding weld pool shape. In the case of carbon steel, the pipe metallurgy allows high welding speed with a teardrop weld and acute angle trailing edge to be used.

However, the metallurgy and resulting increase in hot cracking susceptibility of the X80 pipe introduced limitations on welding speed based on weld pool shape and centerline hot cracking.

For X80 procedure development with GMAW the limitations or boundary conditions were as follows:

1. Lack of sidewall fusion
2. Lack of root penetration
3. Burnthrough
4. Teardrop shape weld pool at high speed promoting tendency to hot crack
5. High weld depth-to-width ratio promoted the tendency to hot crack, but cracks were also formed at a depth-to-width of 1:1 in the vertical-down position.

6.1 GMAW-VP

The GMAW-VP technique has welding power limitations that result in lower welding speeds and the requirement to use a joint gap to achieve consistent full penetration. The productivity limitations resulted in this technique being eliminated from further development effort after establishing parameters for flat and vertical-down positions for pipe girth welds. A useful exercise was the interpolation of parameters from the flat and vertical-down positions to establish working parameters for the 45-degree area in between. This worked well and parameters for this position were established fairly straightforwardly. This boded well for similar interpolation using the GMAW-RE technique.

Although travel speeds of 1.3 m/min were achieved for the GMAW-VP root pass on a closed root girth weld, feedback from industrial sponsors of the GSP was that the root face of 1 mm was too small based on the likelihood of damage in handling the pipe by crane and impacting the joint preparation on the section of pipe to which it was to be butted prior to fit-up in the pipe trench. A root face of 1.6 mm ±0.2 mm, yielding a minimum of 1.4 mm was considered appropriate.

Interested parties at the Department of Transportation (DoT) project kick-off meeting had agreed that a 1.0-mm root face, albeit small, could be considered with more careful pipe handling and fit-up. It was considered likely that more careful handling could be achieved for offshore fabrication, but unlikely for cross-country pipelines.

6.2 GMAW-RE

Fill ratio based on wire feed speed/travel speed resulted in a depth-to-width ratio of 2.5-3:1 and resulted in extensive subsurface centerline hot cracking in the weld determined through macrosections of the welds. The welding parameters were adjusted to give a wire feed speed/travel speed ratio in the range of 9-12. Cracking was consistently caused at ratios above this, in the range 13-7, and also at a wire feed speed/travel speed ratio of 6.

However, reducing the weld depth-to-width ratio to a nominally ideal 1:1 still resulted in hot cracking (Figures 60 and 66 for Welds SA-125 and SA-129, respectively) in the vertical-down position. Typical root pass throat thickness was 4.6 mm. This is about double the typical root pass throat thickness of 2 mm achieved with existing shielded metal arc welding (SMAW) practice.

Although ER70S-6 is often used for pipe root passes in industry, an ER80S-D2 wire was used in an attempt to use a higher hot strength in the weld metal to overcome the hot cracking tendency. The phenomenon was such that ER80S-D2 did not significantly reduce the hot cracking in high-speed root passes. Preheat and clamping of the pipe with standard pipe clamps in an attempt to alter the transverse residual stresses was not successful either.

Transverse residual stresses in the joint were such that hot cracks were developed to such an extent that in one case the solidification resulted in centerline planar defects having oxidized surfaces. In other words, the metal solidified before a true weld was formed. One practical difficulty was that in many cases the cracks were not surface breaking and allowed misinterpretation in terms of visual inspection during procedure development. Two macrosections were taken at the 1/3 and 2/3 weld distance for the later welds to pick up these buried cracks. The macrosections showed cracking to extend 80-90% of the through-thickness dimension of the weld throat.

To overcome the cracking problem in the vertical-down position, a higher strength Union NiMo80 wire from Bohler Thyssen was used. This low alloy steel wire conforms to AWS A5.28 ER90S-G. This wire was recommended by project stakeholders as it has been found to be one of the best for fill passes in X80 pipeline girth welds. However, it was also stated that cracks were common when it was used for root pass using copper backing shoes, knowing that in this project unbacked joints were required.

The persistent cracking found with ER70S-6 and ER80S-D2 wires was solved using the ER90S-G Union NiMo80 wire. Welding speed of 0.8 to 1.2 m/min for a single torch equates to 1.6 to 2.4 m/min for a double-down welding approach with one torch on each side of the joint. This compares favorably to the 1.4- to 4.0-m/min travel speed using laser or laser/GMAW with one torch when the comparative capital costs of the respective systems are considered. The system cost for an 8-kW fiber laser is about $1M; whereas, the cost for a dual-torch GMAW-RE system is less than $100K.

Further trials will be conducted with the ER90S-G wire to determine the robustness of the developed procedures, including mismatch and misalignment tolerances. This work will be reported in the project final report.

6.3 Hybrid Fiber Laser/GMAW

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 laser alone is $1M. This should be compared to a single torch GMAW system at a cost of about $25K.

Part of the work scope of this project is the productivity and cost analysis task, Task 7 – Productivity/Economic Analysis. The costs and productivity of the GMAW-RE and hybrid LBW/GMAW will be analyzed and reported in Task 7.

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

- 18-degree preparation angle, 0-mm root face – welding speed of 4 m/min at 4-kW laser power, and 5-kW arc power.
- 12-degree preparation angle, 1-mm root face – welding speed of 4 m/min at 5-kW laser power, and 7.4-kW arc power.
- 45-degree preparation angle, 6-mm root face – welding speed of 1.5 m/min at 7.6-kW laser power.
- 45-degree preparation angle, 8-mm root face – welding speed of 1.4 m/min at 7.8-kW laser power.

The speeds achieved easily exceed the objective of 1.5 m/min, and in fact it is possible to achieve 4-m/min welding speed with only 4-kW laser power. The productivity (and cost) of the overall welding system depends on the precise combination of laser power, arc power, and root throat thickness. This issue is under investigation and will be reported in Task 7.

It was decided that a high weld root face of 6 mm should be used as basis for the GMAW fill weld to be made under Task 2, since this would provide a significant volume of laser melted weld metal, which could be evaluated during mechanical property testing.

7.0 Conclusions

Based on the work reported here for GMAW procedure development on X80 pipe material, and laser or hybrid laser/GMAW work on X100, the following conclusions can be stated:

1. The GMAW process showing the most promise for high speed mechanized root pass welding was the GMAW-RE, known as Spin Arc.

2. Welding procedures were developed for welding in the 5G position using the double-down technique, but using only a single torch for the development work.

3. A welding speed of 0.7 m/min was the maximum speed at which robust root pass welds could be made on X80 pipe without centerline solidification cracking using ER70S-6 or ER80S-D2 wires. Welding parameters were as follows:

   - Flat position – Weld SA-115
     - Travel speed: 27.6 in./min (0.7 m/min)
     - Wire feed speed: 350 in./min
     - Welding current: 177 A
     - Arc voltage: 22.8 V
     - Wire feed speed/travel speed ratio: 12.7
     - Throat thickness: 4.5 mm.

   - Vertical-down position – Weld SA-129
     - Travel speed: 31.5 in./min (0.8 m/min)
     - Wire feed speed: 448 in./min
     - Welding current: 209 A
     - Arc voltage: 22.0 V
     - Wire feed speed/travel speed ratio: 14.2
     - Throat thickness: 4.2 mm – weld had buried solidification crack.

4. Welding speeds up to 1.5 m/min were used in the vertical-down position, but the combination of pipe metallurgy, elongated teardrop weld pool shape, and the

requirements of achieving full penetration with a reasonable throat thickness, consistently resulted in centerline solidification cracking.

5. The persistent cracking found with ER70S-6 and ER80S-D2 wires in the vertical-down position was solved using the ER90S-G Union NiMo80 wire with an average root pass welding speed of 0.95 m/min.

- Flat position – Weld SA-134
    - Travel speed: 27.6 in./min (0.7 m/min)
    - Wire feed speed: 397 in./min
    - Welding current: 210 A
    - Arc voltage: 21.5 V
    - Wire feed speed/travel speed ratio: 14.4
    - Throat thickness: 5.6 mm.

- Vertical-down position – Weld SA-137
    - Travel speed: 46.3 in./min (1.2 m/min)
    - Wire feed speed: 552 in./min
    - Welding current: 254 A
    - Arc voltage: 22.1 V
    - Wire feed speed/travel speed ratio: 11.9
    - Throat thickness: 4.3 mm.

Alternative parameters developed to use a single travel speed and maintain a more even throat thickness can be summarized as follow:

- Flat position – Weld SA-155
    - Travel speed: 27.6 in./min (0.7 m/min)
    - Wire feed speed: 496 in./min
    - Welding current: 213 A
    - Arc voltage: 17.8 V
    - Wire feed speed/travel speed ratio: 18.0
    - Throat thickness: 5.6 mm.

- Vertical-down position – Weld SA-164
    - Travel speed: 27.6 in./min (0.7 m/min)
    - Wire feed speed: 460 in./min
    - Welding current: 198 A

- o Arc voltage: 21.1 V
- o Wire feed speed/travel speed ratio: 16.7
- o Throat thickness: 5.0 mm.

Trials were conducted with this wire to develop tolerance to root face mismatch and the results showed the procedure to be tolerant to 1.5 mm of mismatch with good penetration and root face profile, in both the flat and vertical-down positions.

1. For hybrid LBW/GMAW the speeds achieved easily exceed the objective of 1.5 m/min, and in fact it is possible to achieve 4-m/min welding speed with only 4-kW laser power. The productivity (and cost) of the overall welding system depends on the precise combination of laser power, arc power, and root throat thickness. This issue is under investigation and will be reported in Task 7.

2. For laser and hybrid LBW/GMAW root passes it was decided that a weld root face of 6 mm should be used as basis for the GMAW fill weld to be made under Task 2, since this would provide a significant volume of laser melted weld metal, which could be evaluated during mechanical property testing.

8.0 Recommendations

Based on the work and conclusions above, the GMAW-RE technique is recommended as the best for further work toward field deployment for root passes with GMAW in terms of economic as well as technical grounds based on the high cost of the 8-kW fiber laser system.

Table 1. Chemical Analysis of X80 Pipe

Lab Services

Chemical Analysis Results

Project Number: 47961GTH-01
Job Number: 2005-94173
Customer: Pratik Patel
Material: X80
Pipe Number: 39006C
Heat Number: B4E612C19

Sample Number: 36 inch pipe
Report Number: 130339
Date Reported: May 15, 2005
Specification:

Element	36 inch pipe	Method
Aluminum	0.013	Optical Emission Spectoscopy
Boron	<0.001	Optical Emission Spectoscopy
Carbon	0.055	Leco Furnace
Cobalt	<0.01	Optical Emission Spectoscopy
Chromium	0.038	Optical Emission Spectoscopy
Copper	0.25	Optical Emission Spectoscopy
Manganese	1.77	Optical Emission Spectoscopy
Molybdenum	0.30	Optical Emission Spectoscopy
Niobium	0.055	Optical Emission Spectoscopy
Nickel	0.27	Optical Emission Spectoscopy
Phosphorus	0.022	Optical Emission Spectoscopy
Sulfur	<0.001	Leco Furnace
Silicon	0.12	Optical Emission Spectoscopy
Titanium	<0.01	Optical Emission Spectoscopy
Tungsten	<0.01	Optical Emission Spectoscopy
Vanadium	<0.01	Optical Emission Spectoscopy
Zirconium	<0.01	Optical Emission Spectoscopy

Conducted By NSL Analytical Services, Cleveland, OH Reviewed By ______________________

Title: Project Manager

Table 2. Chemical Analysis of SupraMIG GMAW Electrode Wire

Lab Services

Chemical Analysis Results

Project Number: 47961GTH-01 **Sample Number: Wire**

Job Number: 2005-94173 **Report Number:** 130519

Customer: Pratik Patel **Date Reported:** May 16, 2005

Trade Name: Lincoln Supra-MIG **Specification:**

Lot Number: 603 B

Designation: EN 440 G3SIL

Element	Wire	Method
Aluminum	0.002	ICP/MS
Boron	<0.001	ICP/MS
Carbon	0.091	Leco Furnace
Chromium	0.015	ICP/MS
Copper	0.014	ICP/MS
Manganese	1.47	ICP/MS
Molybdenum	0.004	ICP/MS
Niobium	<0.001	ICP/MS
Nickel	0.007	ICP/MS
Phosphorus	0.007	ICP/MS
Sulfur	0.006	Leco Furnace
Silicon	<0.005	ICP/MS
Titanium	0.002	ICP/MS
Tungsten	<0.001	ICP/MS
Vanadium	<0.001	ICP/MS
Zirconium	<0.001	ICP/MS

Conducted By NSL Analytical Services, Cleveland, OH Reviewed By ____________________

Title: Project Manager

Table 3. Chemical Analyses of ER80S-D2 and Union NiMo80 ER90S-G GMAW Electrode Wires

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

Chemical Analysis Results

Project Number: 47961 GTH-06
Job Number: 2006-99010
Customer: Ian Harris
Material: Welding Wire

Sample Number: **see below**
Report Number: 138066
Date Reported: November 15, 2005
Specification:

Element	ER80S-D2, %	ER90S-G, %	Test Method
Aluminum	0.001	0.006	ICP/MS
Boron	<0.001	<0.001	ICP/MS
Carbon	0.094	0.074	Leco Furnace
Chromium	0.058	0.034	ICP/MS
Copper	0.063	0.034	ICP/MS
Manganese	1.81	1.48	ICP
Molybdenum	0.43	0.35	ICP/MS
Niobium	<0.001	<0.001	ICP/MS
Nickel	0.089	1.20	ICP/MS
Phosphorus	0.011	0.010	ICP/MS
Sulfur	0.011	0.007	Leco Furnace
Silicon	0.66	0.70	ICP/MS
Titanium	0.006	0.057	ICP/MS
Vanadium	0.005	0.002	ICP/MS
Tungsten	<0.001	0.001	ICP/MS
Zirconium	<0.001	<0.001	ICP/MS

Conducted By NSL Analytical Services, Cleveland, OH Reviewed By ____________
Title: Senior Engineer

Table 4. Results of Welding Procedure Development for GMAW-VP

Weld No.	Date	Position from Top (Degree)	Set WFS (ipm)	Set Voltage (Trim)	Set% EN	Set Travel Speed (cm/min)	Torch Travel (Push/Drag)	Torch Travel Angle (Degree)	Comments	Meas. WFS (ipm)	Meas. Voltage (V)	Meas. Current (A)	Travel Speed at Root	Ratio WFS/TS
VP01	2/9/05	0-20	400	3.0	40%	160	Drag	8.5	Good bead face contour. Light penetration. Data acq. Not set to print out often enough.	No data	No data	No data	50.5	8.8
VP02	2/10/05	0-20 - Macro VP02 @ ~18°	400	3.0	40%	160	Drag	8.5	Good penetration about 2-mm width.	443	24.6	226	50.5	8.8
VP03	2/10/05	0-40	400	3.0	30%	160	Drag	8.5	Burnthrough, a couple of small holes.	432	24.8	233	50.5	8.6
VP04	2/10/05	0-40	525	3.0	40%	180	Drag	8.5	Relative to VP02 we increase WFS and TS proportionally. Result: little burnthrough.	528	26.4	266	56.8	9.3
VP05	2/10/05	0-40	525	3.0	50%	180	Drag	8.5	More EN. Result: "maxed out" current and got burn back of the tip at end.	525	25.5	266	56.8	9.2
VP06	2/10/05	0-40	480	3.0	40%	170	Drag	8.5	One burnthrough hole. Bead became off-center at 10-20 degrees and this is evident as no penetration in that region.	475	25.1	253	53.6	8.9
VP07	2/10/05	0-40	480	3.0	40%	170		0.0	A few small burnthrough holes. Not a significant difference with this change of torch angle.	473	25.1	261	53.6	8.8
VP08	2/11/05	50-90	400	3.0	40%	170	Drag	20.0	Little or no penetration. Bead is flat except over tack (~1 in. long). Try less EN.	406	24.5	216	53.6	7.6
VP09	2/11/05	50-90 - Macro VP09 @ ~74°	400	3.0	30%	170	Drag	20.0	A little more penetration than VP08. Good looking weld profile for OD.	412	25.3	221	53.6	7.7
VP10	2/11/05	50-90	400	3.0	40%	160	Drag	20.0	Good looking weld profile for OD, but very little intermittent penetration.	430	24.6	222	50.5	8.5
VP11	2/11/05	50-90	400	3.0	30%	160	Drag	20.0	Insufficient penetration. Next, increase WFS and travel proportionally.	410	24.9	226	50.5	8.1
VP12	2/11/05	50-90	450	3.0	30%	180	Drag	20.0	Reasonable OD profile with some unevenness at toes. Good penetration in ID, especially on first 4 in. After 4 in., Begins ~0.015-in. mismatch and penetration is not as strong or consistent.	457	25.7	260	56.8	8.0
VP13	2/18/05	50-90 -- Macro VP13 @ ~66°	450	3.0	30%	180	Drag	20.0	Good penetration most of the way. Some short spots where penetration anarrows, but mostly 2- to 3-mm width on root side. Bead from OD side looks ok, maybe a little off-center. Like this for the 50-90 degree position.	456	25.5	242	56.8	8.0
VP14	2/18/05	50-90	500	3.0	30%	200	Drag	20.0	Good penetration. On OD, first 3 in. the bead favors one side then other like wire cast is changing. A wire spool carried along on the bug (or a idler carriage) would be nice for a short conduit that is always the same orient with respect to the torch.	497	26.1	257	63.1	7.9

Table 5. Baseline Results for GMAW-RE from Cost-Matched GSP No. 46380CPQ

		Position from Top (Degree)	Set Current (A)	Set Voltage (V)	Travel Speed (m/min)	Torch Travel (Push/Drag)	Torch Travel Angle (Degree)	WFS [Calculated (in./min)]	Est. Actual Voltage (Calculated)	Comments	Travel Speed (ipm)	Ratio WFS/TS
						Weld No. 13						
Approach		0	155	25.5	1.00	Push	5.0	390.3	22.4	0-30 degree. Almost enough penetration. Intermittent spots penetrating	39.3700787	9.91235
Constant push angle. Program different parameters for different positions on the pipe. Faster, more wire on downhill, slower, less wire on overhead.		10	155	25.5	1.00	Push	5.0	390.3	22.4		39.3700787	9.91235
		20	155	25.5	1.00	Push	5.0	390.3	22.4		39.3700787	9.91235
		30	180	26.5	1.40	Push	5.0	510.5	23.2		55.1181102	9.26192857
		40	180	26.5	1.40	Push	5.0	510.5	23.2	30-90 degree. Good, but excessive at 30 degree where sudden change in current.	55.1181102	9.26192857
		50	180	26.5	1.40	Push	5.0	510.5	23.2		55.1181102	9.26192857
		60	180	26.5	1.40	Push	5.0	510.5	23.2		55.1181102	9.26192857
		70	180	26.5	1.40	Push	5.0	510.5	23.2		55.1181102	9.26192857
		80	180	26.5	1.40	Push	5.0	510.5	23.2		55.1181102	9.26192857
Date of Weld		90	165	25.5	1.10	Push	5.0	438.4	22.4	90-120 degree. Penetration through this range is minimal, looks rough.	43.3070866	10.1219
Robot Program Name	46380-004	100	165	25.5	1.10	Push	5.0	438.4	22.4		43.3070866	10.1219
Joint Design	A	110	165	25.5	1.10	Push	5.0	438.4	22.4		43.3070866	10.1219
Shielding Gas	Ar/CO_2 50-50	120	155	25.0	1.00	Push	5.0	390.3	21.9	120-180 degree. First 10 degree of this range ok, then penetration becomes excessive, but no burnthrough.	39.3700787	9.91235
		130	155	25.0	1.00	Push	5.0	390.3	21.9		39.3700787	9.91235
		140	155	25.0	1.00	Push	5.0	390.3	21.9		39.3700787	9.91235
Spin Diameter (mm)	2	150	155	25.0	1.00	Push	5.0	390.3	21.9		39.3700787	9.91235
Spin Frequency (Hz)	5	160	155	25.0	1.00	Push	5.0	390.3	21.9		39.3700787	9.91235
		170	155	25.0	1.00	Push	5.0	390.3	21.9		39.3700787	9.91235
		180	155	25.0	1.00	Push	5.0	390.3	21.9		39.3700787	9.91235
Results/Conclusions:												

Table 5. (Continued)

		Position from Top (Degree)	Set Current (A)	Set Voltage (A)	Travel Speed (m/min)	Torch Travel (Push/Drag)	Torch Travel Angle (Degree)	WFS [Calculated (in./min)]	Est. Actual Voltage (Calculated)	Comments	Travel Speed (ipm)	Ratio WFS/TS
Weld No. 21												
Approach		0	162	25.7	1.11	Drag	30.0	423.9	22.5		43.7007874	9.70051171
More drag angle through the flat portion.		10	162	25.7	1.11	Drag	30.0	423.9	22.5		43.7007874	9.70051171
		20	161	25.8	1.12	Drag	30.0	419.1	22.6		44.0944882	9.50481607
		30	166	25.9	1.18	Drag	25.0	443.2	22.7		46.4566929	9.53920678
		40	173	26.0	1.26	Drag	20.0	476.8	22.8		49.6062992	9.6122873
		50	181	26.4	1.37	Drag	20.0	515.3	23.1		53.9370079	9.55392263
		60	183	26.6	1.40	Drag	20.0	524.9	23.3		55.1181102	9.52373
		70	183	26.6	1.40	Drag	20.0	524.9	23.3		55.1181102	9.52373
		80	183	26.6	1.40	Drag	20.0	524.9	23.3		55.1181102	9.52373
Date of Weld	7/12/2004	90	178	26.3	1.33	Drag	20.0	500.9	23.0		52.3622047	9.5656782
Robot Program Name	46380-07	100	172	25.9	1.25	Drag	20.0	472.0	22.7		49.2125984	9.5914464
Joint Design	A	110	168	25.5	1.19	Drag	20.0	452.8	22.4		46.8503937	9.66437983
Shielding Gas	Ar/CO_2 50-50	120	162	25.4	1.11	Drag	20.0	423.9	22.3		43.7007874	9.70051171
		130	160	24.7	1.08	Drag	10.0	414.3	21.7		42.519685	9.74372222
		140	158	24.2	1.06	Drag	0.0	404.7	21.3		41.7322835	9.69704906
Spin Diameter (mm)	2	150	158	24.2	1.06	Drag	0.0	404.7	21.3		41.7322835	9.69704906
Spin Frequency (Hz)	50	160	158	24.2	1.06	Drag	0.0	404.7	21.3		41.7322835	9.69704906
		170	158	24.2	1.06	Drag	0.0	404.7	21.3		41.7322835	9.69704906
		180	158	24.2	1.06	Drag	0.0	404.7	21.3		41.7322835	9.69704906
Results/Conclusions:	This was a pretty good weld. See how it repeats on the other half on the pipe.											

Table 6. Welding Trials for Procedure Development on 36-in.-Diameter X80 Pipe

Weld No.	Date	Weld Position (degr)	Process	Wire Electrode	Root Shield	Arc Shield Gas	Preheat (degr F)	Torch Travel (Push/ Drag)	Torch Travel Angle (degr)	Avg. Measured Root Face (mm)	Root Gap (mm)	Root Mismatch (mm)	Robot Setting "AMP"	Robot Setting "VOLT"	Robot Setting "S" (m/min)	Spin Freq. (Hz)	Comment	MEAS. WFS (ipm)	MEAS. Voltage (V)	MEAS. Current (A)	Trav. Speed @ Root (ipm)	Ratio WFS/TS	Heat Input kJ/in.	Heat Input kJ/mm
SA01	3/30/05	0	GMAW	.040 ER70S-6	none	50%50%	75	Push	8	1.25	0	0	190	24.7	1.00	50	Burn-through, intermittent holes	387	23.4	190	39.4	9.8	6.78	0.27
SA02	3/30/05	0	GMAW	.040 ER70S-6	none	50%50%	75	Push	8	1.20	0	0	190	24.7	1.20	50	Burn-through, intermittent holes	391	23.2	197	47.2	8.3	5.80	0.23
SA03	3/30/05	0	GMAW	.040 ER70S-6	none	50%50%	75	Push	8	1.21	0	0	190	24.7	1.50	50	Burn-through, intermittent holes. Next try incr spin freq.	392	22.8	211	59.1	6.6	4.89	0.19
SA04	3/31/05	0	GMAW	.040 ER70S-6	none	50%50%	75	Push	8	1.26	0	0	190	24.7	1.00	80	Melt through, a little more spatter.	388	22.6	203	39.4	9.9	6.99	0.28
SA05	3/31/05	0	GMAW	.040 ER70S-6	none	50%50%	75	Push	8	1.27	0	0	190	24.7	1.00	100	Better, only one burn-through hole. A little more spatter high up on side walls. Under root inspection shows that penetration varied greatly. After recovery from the burn-through hole, it lost penetration.	389	22.9	217	39.4	9.9	7.57	0.30
SA06	3/31/05	0	GMAW	.040 ER70S-6	none	50%50%	75	Push	8	1.20	0	0	190	24.7	1.20	100	No burn-through holes, but minimal penetration. Some skips where weld necked down.	390	23.0	208	47.2	8.3	6.08	0.24
SA07	3/31/05	0	GMAW	.040 ER70S-6	none	50%50%	75	Push	8	1.14	0	0	190	24.7	0.90	80	Melt through.	390	22.9	202	35.4	11.0	7.83	0.31
SA08	3/31/05	0	GMAW	.040 ER70S-6	none	50%50%	75	Push	8	1.13	0	0	190	24.7	1.10	100	Melt through.	391	22.9	216	43.3	9.0	6.85	0.27
SA09	3/31/05	0	GMAW	.040 ER70S-6	none	50%50%	75	Push	8	1.12	0	0	183	24.0	0.90	100	Melt through.	349	22.2	199	35.4	9.8	7.48	0.29
SA10	4/1/05	0	GMAW	.040 ER70S-6	none	50%50%	75	Push	8	1.08	0	0	183	24.0	1.00	50	Melt through.	350	22.2	197	39.4	8.9	6.67	0.26
SA11	4/1/05	0	GMAW	.040 ER70S-6	none	50%50%	75	Push	8	1.08	0	0	183	24.0	1.20	50	Melt through.	348	22.2	197	47.2	7.4	5.55	0.22
SA12	4/11/05	0	GMAW	.040 ER70S-6	Argon	50%50%	75	Push	8	1.08	0	0	190	24.7	1.00	100	Similar to SA-05. 2 burn-thru holes.	386	22.9	213	39.4	9.8	7.43	0.29
SA13	4/11/05	0	GMAW	.040 ER70S-6	Argon	50%50%	75	Push	8	1.68	0	0	190	24.7	1.00	100	No burn-through. Not penetrated.	388	22.8	216	39.4	9.9	7.51	0.30
SA14	4/11/05	0	GMAW	.040 ER70S-6	none	50%50%	75	Push	8	1.63	0	0	190	24.7	1.00	100	No burn-through. Not penetrated.	388	22.8	216	39.4	9.9	7.51	0.30
SA15	4/11/05	0	GMAW	.040 ER70S-6	none	50%50%	75	Push	8	1.54	0	0	190	24.7	1.00	50	No burn-through. Some intermittent penetration.	390	22.9	218	39.4	9.9	7.61	0.30
SA16	4/11/05	0	GMAW	.040 ER70S-6	none	50%50%	75	Push	8	1.53	0	0	190	24.7	1.00	50	Longer repeat of SA15 on a new plate set. This time, many burn-through holes.	391	22.6	219	39.4	9.9	7.54	0.30
SA17	4/11/05	0	GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.60	0	0	190	24.7	1.00	50	90/10 Ar/CO2 shielding gas. Not penetrated, but very stable outcome and bead profile on the face.	391	22.1	231	39.4	9.9	7.78	0.31
SA18	4/11/05	0	GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.55	0	0	200	23.5	1.00	50	No burn-through. Good, mostly penetrated root, some skips in penetration. Penetration tends to diminish towards end of weld.	432	21.9	234	39.4	11.0	7.81	0.31
SA19	4/11/05	0	GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.50	0	0	215	23.5	1.00	50	One burn-through hole near beginning. Good penetration most of the way, but penetration goes away in last inch of weld.	491	22.8	254	39.4	12.5	8.83	0.35
SA20	4/12/05	0	GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.57	0	0	210	23.0	1.00	50	Lots of burn-through holes. Why?	475	Data not recorded	Data not recorded	39.4	12.1		
SA21	4/12/05	0	GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.63	0	0	210	24.0	1.00	50	Is a little higher voltag better? Still lots of burn-through holes.	475	23.4	258	39.4	12.1	9.20	0.36
SA22	4/12/05	0	GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.09	0	0	183	24.0	0.80	50	Nice bead, nice penetration. Some skips in the penetration.	351	21.6	208	31.5	11.1	8.56	0.34
SA23	4/12/05	0	GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.03	0	0	190	24.5	0.80	50	A few burn-through holes.	392	22.1	219	31.5	12.4	9.22	0.36
SA24	4/25/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.57	0	0	200	23.5	1.00	50	Burn-through	437	22.5	225	39.4	11.1	7.72	0.30
SA25	4/25/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.57	0	0	205	23.5	1.05	50	Burn-through (worse than SA-24)	452	23.2	235	41.3	10.9	7.91	0.31
SA26	4/25/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.56	0	0	195	23.0	0.95	50	No burn-through. Good penetration.	407	21.6	227	37.4	10.9	7.87	0.31
SA27	4/25/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.57	0	0	195	23.0	0.95	50	No burn-through. Not much penetration. Punched through in one small place.	406	21.6	226	37.4	10.9	7.83	0.31
SA28	4/25/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.84	0	0	183	24.0	0.85	50	No burn-through. Very light intermittent penetration. Most of weld unpenetrated	348	22.0	208	33.5	10.4	8.20	0.32
SA29	4/25/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.80	0	0	190	24.5	0.85	50	No burn-through. About 50% of weld penetrated to an underbead width of ~2.5 mm. Not penetrated at start and end of weld.	387	22.5	220	33.5	11.6	8.88	0.35
SA30	4/25/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.72	0	0	195	24.5	0.85	50	No burn-through. Most of weld good penetration (2-3 mm underbead width). With some short sections where root not totally fused.	417	22.9	225	33.5	12.5	9.24	0.36
SA31	4/25/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.68	0	0	200	23.5	0.85	50	Burn-through. Inconsistent penetration.	439	22.3	229	33.5	13.1	9.16	0.36
SA32	4/25/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.69	0	0	190	24.0	0.70	50	No burn-through. Good consistent penetration. Underbead width of 2-3 mm.	388	22.3	219	27.6	14.1	10.63	0.42
SA33	4/25/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.68	0	0	195	24.0	0.70	50	No burn-through. Good consistent penetration. Underbead width of 3-4.5 mm.	415	22.4	226	27.6	15.1	11.02	0.43
SA34	4/25/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.64	0	0	195	23.0	0.70	50	No burn-through. Ran consistent for entire weld. Good consistent penetration. Underbead width of 3-4 mm.	417	21.6	225	27.6	15.1	10.58	0.42
								Push																
SA35	4/27/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.58	0	0	190	24.5	0.80	50	No burn-through. Some penetration through middle of weld.	387	22.6	218	31.5	12.3	9.39	0.37
SA36	4/27/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.57	0	0	195	24.5	0.80	50	No burn-through. Good, mostly penetrated.	408	22.9	224	31.5	13.0	9.77	0.38
SA37	4/27/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.51	0	0	200	23.5	0.80	50	2 burn-through holes in entire weld.	430	22.4	225	31.5	13.7	9.60	0.38
SA38	4/27/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.46	0	0	195	24.5	0.75	50	Burn-through. Lots of spatter.	409	22.8	222	29.5	13.9	10.29	0.40
SA39	4/27/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.50	0	0	190	24.0	0.75	50	Through half of the weld good penetration. Then sudden melt-through which it never recovered from.	386	22.2	216	29.5	13.1	9.74	0.38
SA40	4/27/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.44	0	0	183	24.0	0.75	50	No burn-through. Intermittent penetration.	346	21.9	206	29.5	11.7	9.17	0.36
SA41	4/27/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.45	0	0	195	23.5	0.80	50	Burn-through. It started out ok, burned a hole, thenrecovered a while, then burned through continuously. Lower voltage helped reduce spatter.	407	22.1	215	31.5	12.9	9.05	0.36
SA42	4/27/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.57	0	0	192	23.2	0.80	50	One burn-through hole. Good penetration up to that hole.	386	21.3	221	31.5	12.3	8.97	0.35
SA43	4/27/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.60	0	0	187	23.0	0.75	50	No burn-through. Inconsistent penetration.	367	20.9	210	29.5	12.4	8.92	0.35
SA44	4/29/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	2.01	0	0	215	23.5	1.00	50	Burn-through. At first, some good penetration, then melt-through.	493	23.2	251	39.4	12.5	8.87	0.35
SA45	4/29/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.99	0	0	210	23.5	1.00	50	Burn-through (but not as soon as SA44 did). At first, no penetration, then sudden melt-through.	478	23.4	243	39.4	12.1	8.67	0.34
SA46	4/29/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.97	0	0	200	23.0	1.00	50	No burn-through. No penetration.	432	21.8	233	39.4	11.0	7.74	0.30
SA47	4/29/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	2.01	0	0	210	23.5	1.50	70	No burn-through. No penetration. Spatter.	473	23.3	254	59.1	8.0	6.01	0.24
SA48	4/29/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	2.01	0	0	220	23.0	1.50	70	No burn-through. A little intermittent penetration.	500	23.0	261	59.1	8.5	6.10	0.24
SA49	4/29/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.97	0	0	225	23.0	1.50	70	Good penetration. Front face of bead a bit narrow. This voltage may be too low for this WFS.	538	22.8	270	59.1	9.1	6.25	0.25
SA50	4/29/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	2.02	0	0	225	23.5	1.50	70	2 burn-through holes in entire weld. This voltage was better.	536	23.2	266	59.1	9.1	6.27	0.25
SA51	4/29/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	2.02	0	0	225	23.5	1.50	70	No burn-through. Good penetration most of the way.	538	23.2	264	59.1	9.1	6.22	0.24
SA52	4/29/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	2.09	0	0	210	23.5	0.80	70	No burn-through. Good penetration . Spatter.	474	23.3	247	31.5	15.0	10.96	0.43
SA53	4/29/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	2.04	0	0	210	23.5	0.80	70	2 burn-through holes in entire weld.	474	23.3	247	31.5	15.0	10.96	0.43

Table 6. (Continued)

Weld No.	Date	Weld Position (degr)	Process	Wire Electrode	Root Shield	Arc Shield Gas	Preheat (degr F)	Torch Travel (Push/Drag)	Torch Travel Angle (degr)	Avg. Measured Root Face (mm)	Root Gap (mm)	Root Mismatch (mm)	Robot Setting "AMP"	Robot Setting "VOLT"	Robot Setting "S" (m/min)	Spin Freq.(Hz)	Comment	MEAS. WFS (ipm)	MEAS. Voltage (V)	MEAS. Current (A)	Trav. Speed @ Root (ipm)	Ratio WFS/TS	Heat Input kJ/in.	Heat Input kJ/mm
SA54	5/3/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	2.01	0	0	225	23.5	1.50	70	Repeat of SA51. During weld there was one short burn-through. The burn-through recovered and filled in (no hole). For the rest of the weld penetration is not consistent. Start of weld little penetration.	539	23.0	271	59.1	9.1	6.33	0.25
SA55	5/3/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	2.03	0	0	225	23.5	1.50	70	Another repeat of SA51. Very little intermittent penetration.	538	23.3	269	59.1	9.1	6.37	0.25
SA56	5/3/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	2.05	0	0	195	23.0	0.70	50	Very little intermittent penetration.	416	21.9	222	27.6	15.1	10.58	0.42
SA57	5/3/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	2.04	0	0	200	23.0	0.70	50	Intermittent penetration. (more than SA56)	442	22.1	232	27.6	16.0	11.16	0.44
SA58	5/3/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	2.00	0	0	210	23.0	0.70	50	Minimal intermittent penetration.	474	22.8	246	27.6	17.2	12.21	0.48
SA59	5/3/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	2.08	0	0	210	23.0	0.75	50	Burn-through.	472	23.0	236	29.5	16.0	11.03	0.43
SA60	5/3/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	2.09	0	0	215	23.5	0.70	50	Burn-through.	488	23.5	244	27.6	17.7	12.48	0.49
SA61	5/3/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	2.09	0	0	210	23.0	0.75	70	Burn-through.	473	22.9	243	29.5	16.0	11.31	0.45
SA62	5/3/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	2.08	0	0	200	23.0	0.70	50	Repeat of SA57. Arc ran mostly unstable stubbing. Don't pay much attention to the penetration of this weld.	438	22.2	222	27.6	15.9	10.73	0.42
SA63	5/4/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.32	0	0	190	24.0	0.70	50	Repeat of SA32, but this root face is thinner. As expected this burned through. This was intermittent burn-through from which it could recover.	386	22.3	215	27.6	14.0	10.44	0.41
SA64	5/3/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.33	0	0	183	23.5	0.70	50	Again, burn-through.	346	21.5	199	27.6	12.6	9.31	0.37
SA65	5/4/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.32	0	0	183	23.5	0.70	70	Again, burn-through.	346	21.5	200	27.6	12.6	9.36	0.37
SA66	5/4/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Drag	20	2.06	0	0	198	23.5	1.11	50	No burn-through. Only a small amount of penetration at the end of the weld.	431	22.5	234	43.7	9.9	7.23	0.28
SA67	5/4/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	2.08	0	0	198	23.5	1.11	50	No burn-through. Very similar. No penetration until the end of the weld.	426	22.5	228	43.7	9.7	7.04	0.28
SA68(A)	5/4/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	5	2.07	0	0	205	20.5	0.90	50	Stubbing from voltage too low.	457	21.9	no data	35.4	12.9		
SA68(B)	5/4/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	5	2.07	0	0	205	22.0	0.90	50	No penetration (this was a very short weld)	459	21.9	242	35.4	13.0	8.97	0.35
SA69	5/4/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	5	1.16	0	0	205	22.0	0.90	50	Try same parameters on thinner root face. Result is severe burn-through.	458	22.4	219	35.4	12.9	8.31	0.33
SA70	5/12/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.72	0	0	195	23.0	0.70	50	No burn-through. Mostly good penetration. A little lack of penetration at start, the several shorts skips in penetration. Arc sounded like it may have caused the skips due to instability in the short circuiting transfer. Maybe reduced voltage would help.	412	21.8	224	27.6	14.9	10.63	0.42
SA71	5/12/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.72	0	0	195	22.5	0.70	50	Little penetration. Arc was sometimes unstable, wire stubbing.	409	21.1	220	27.6	14.8	10.11	0.40
SA72	5/12/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.71	0	0	195	23.5	0.70	50	2 burn-through holes from which it recovered.	413	21.9	224	27.6	15.0	10.68	0.42
SA73	5/12/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.73	0	0	195	23.0	0.70	50	No burn-through. Some skips in the penetration of the root.	409	21.5	223	27.6	14.8	10.44	0.41
SA74	5/12/05	0	GMAW	.040 ER70S-6	none	75%25%	75	Push	8	1.73	0	0	195	23.0	0.65	50	One burn-through hole. Looked like bead got hotter the further it welded. Still inconsistent.	408	21.6	225	25.6	15.9	11.39	0.45
SA75	5/12/05	0	P-GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.73	0	0	190	24.0	0.70	50	Set up machine for pulsed welding. Changed to 90/10 shielding gas. Arc was very short a lot of spatter. Most of the weld not penetrated, but some sudden strong penetration at the end of the weld. In pulsed mode, same machine settings give different wire feed.	486	17.2	223	27.6	17.6	8.35	0.33
SA76	5/13/05	0	P-GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.71	0	0	185	26.0	0.70	50	Good. Penetration good all the way, even near the end of weld where it burned through, but filled in.	478	19.9	221	27.6	17.3	9.57	0.38
SA77	5/13/05	0	P-GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.71	0	0	185	26.0	1.00	50	No burn-through. Penetrated most of the way. Lost penetration near end of weld. Underbead is narrower than SA76.	477	20.0	221	39.4	12.1	6.74	0.27
SA78	5/13/05	0	P-GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.72	0	0	185	26.0	0.80	50	Good. Penetration good all the way. Underbead width is less than SA76 but wider than SA77.	476	19.9	221	31.5	15.1	8.38	0.33
SA79	5/13/05	0	P-GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.73	0	0	185	26.0	0.70	50	Good. Penetration good all the way. No burn-through.	477	19.9	221	27.6	17.3	9.57	0.38
SA80	5/13/05	0	P-GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.14	0	0	185	26.0	0.70	50	Burn through as expected. But with pulse, arc stays stable throughout the weld even when melting through. This is a good point in favor of pulsed.	477	19.9	213	27.6	17.3	9.23	0.36
SA81	5/17/05	0	P-GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.70	0	0	225	29.0	1.30	50	Lots of penetration, root side undercut, face side is ropey. Some burn-through holes. Try a faster travel speed.	583	22.5	259	51.2	11.4	6.83	0.27
SA82	5/17/05	0	P-GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.68	0	0	225	29.0	1.50	50	One burn-through hole at the end. Penetration is not consistent (intermittent through most of the weld, then strong excessive penetration at the end).	582	22.5	259	59.1	9.9	5.92	0.23
SA83	5/17/05	0	P-GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.70	0	0	225	29.0	1.40	50	Penetration most of the way. Some burn-through holes especially at the end. Too much penetration near the end of weld.	581	22.6	256	55.1	10.5	6.30	0.25
SA84	5/17/05	0	P-GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.69	0	0	195	27.0	1.00	50	Penetration all of the way., but underbead width is narrow. Some narrowing and skips in penetration.	496	21.0	226	39.4	12.6	7.23	0.28
SA85	5/17/05	0	P-GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.72	0	0	205	27.5	1.00	50	Try more current (WFS). Looks similar to SA-81, but no burn-through. Underbead shaped poorly with undercut. Face of bead is ropey.	524	21.7	235	39.4	13.3	7.77	0.31
SA86	5/17/05	0	P-GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.72	0	0	200	27.0	1.00	50	Looks similar to SA-84, but a little more penetration. Penetration is inconsistent, little penetration near the end of weld.	505	21.4	231	39.4	12.8	7.53	0.30
SA87	5/17/05	0	P-GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.73	0	0	205	27.0	1.00	80	Worse than SA-85. Burn-through, a lot of penetration.	524	20.9	238	39.4	13.3	7.58	0.30
SA88	5/17/05	0	P-GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.73	0	0	205	27.0	1.00	40	Better than SA-85. Good penetration most of the way with excessive penetration and burn-through at the end of weld.	524	20.8	237	39.4	13.3	7.51	0.30
SA89	5/17/05	0	P-GMAW	.040 ER70S-6	none	90%10%	75	Push	8	1.72	0	0	205	27.0	1.00	40	Repeat of SA-88. Result similar to SA-88, but a little penetration and melt-through.	524	21.0	234	39.4	13.3	7.49	0.29
								Push																
SA90	5/17/05	0	P-GMAW		none	90%10%		Push	8	1.73	0	0	205	27.0	1.00	30	More burn-through than SA-88 or SA-89.	524	21.0	237	39.4	13.3	7.58	0.30
SA91	5/23/05	0	P-GMAW	.040 ER70S-6	none	50%50%	75	Push	8	1.58	0	0	145	24.5	0.70	50	While running, arc was inconsistent. First half of weld was fairly good, then the arc began spattering more. The face of the weld looks different, more ropey, uneven, in the second half. Penetration is fair in the first half of weld but then disappears. I'm not sure whether the loss of penetration was caused by the bad arc transfer or the arc caused the llack of penetration.	315	21.0	156	27.6	11.4	7.13	0.28
SA92	5/23/05	0	P-GMAW	.040 ER70S-6	none	50%50%	75	Push	8	1.57	0	0	145	25.5	0.70	50	Increased arc voltage helped it run more stable. Penetration virtually the same as SA-91 , some good penetration and some lost penetration.	315	22.2	156	27.6	11.4	7.54	0.30
SA93	5/23/05	0	P-GMAW	.040 ER70S-6	none	50%50%	75	Push	8	1.57	0	0	160	27.0	0.70	50	One burn-through hole. Bead face is very nice... Some spatter. Good penetration, about 3-4 mm underbead width	339	23.2	169	27.6	12.3	8.54	0.34
SA94	5/23/05	0	P-GMAW	.040 ER70S-6	none	50%50%	75	Push	8	1.52	0	0	160	27.0	0.75	50	One burn-through hole near beginning, then it ran consistent with good penetration the rest of the way. Penetration similar to SA-93.	341	23.6	165	29.5	11.5	7.91	0.31

Table 6. (Continued)

Weld No.	Date	Weld Position (degr)	Process	Wire Electrode	Root Shield	Arc Shield Gas	Preheat (degr F)	Torch Travel (Push/Drag)	Torch Travel Angle (degr)	Avg. Measured Root Face (mm)	Root Gap (mm)	Root Mismatch (mm)	Robot Setting "AMP"	Robot Setting "VOLT"	Robot Setting "S" (m/min)	Spin Freq.(Hz)	Comment	MEAS. WFS (ipm)	MEAS. Voltage (V)	MEAS. Current (A)	Trav. Speed @ Root (ipm)	Ratio WFS/TS	Heat Input kJ/in.	Heat Input kJ/mm
SA95	6/6/05	0 ---> 20	P-GMAW	.040 ER70S-6	none	50%50%	75	Push	8		0	0	160	27.0	0.70	50	Beginning of weld good penetration. At <10 degrees down, penetration went away. During welding I could see that the pool caught up with the arc. We may be able to increase parameters early in the weld as downhill begins quite soon.	353	22.7	176	27.6	12.8	8.70	0.34
SA96	6/6/05	80 ---> 90	P-GMAW	.040 ER70S-6	none	50%50%	75	Push	8		0	0	205	28.0	1.30	50	Light penetration. At halfway point of the segment, it tracked up and out of the joint so I stopped the welding. Tracking went astray possibly because low voltage or wire angled into joint poorly.	522	20.8	239	51.2	10.2	5.83	0.23
SA97	6/6/05	80 ---> 100	P-GMAW	.040 ER70S-6	none	50%50%	75	Push	8		0	0	210	29.0	1.40	50	Tracking ok. Front side a lot of spatter. Root side good penetration but could have more. Root has negative penetration (suck-back)	527	22.1	239	55.1	9.6	5.75	0.23
SA98	6/6/05	80 ---> 100	P-GMAW	.040 ER70S-6	none	50%50%	75	Push	8		0	0	220	30.0	1.40	50	Result similar to SA-97. Still a lot of spatter. Good penetration, but suck-back.	542	23.0	246	55.1	9.8	6.16	0.24
SA99	6/6/05	80 ---> 100	P-GMAW	.040 ER70S-6	none	50%50%	75	Push	8		0	0	220	33.0	1.40	50	More suck-back and intermittently penetrating a little then a lot. Tracking good. Still bad spatter.	542	26.0	255	55.1	9.8	7.22	0.28
SA100	6/6/05	80 ---> 100	P-GMAW	.040 ER70S-6	none	50%50%	75	Push	8		0	0	220	28.0	1.40	50	Less suck-back, but a lot of spatter. Intermittent skips in penetration.	541	21.3	242	55.1	9.8	5.61	0.22
SA101	6/6/05	80 ---> 100	P-GMAW	.040 ER70S-6	none	50%50%	75	Push	8		0	0	205	28.0	1.20	50	Some popping sounds and instability in the arc. Root looks like less suck-back, but it is jagged and inconsistent.	520	21.3	236	47.2	11.0	6.38	0.25
SA102	6/6/05	80 ---> 100	P-GMAW	.040 ER70S-6	none	50%50%	75	Push	8		0	0	230	28.0	1.60	50	Popping and instability and a lot of spatter. Light penetration.	606	20.3	262	63.0	9.6	5.07	0.20
SA103	6/6/05	80 ---> 100	P-GMAW	.040 ER70S-6	none	50%50%	75	Push	8		0	0	170	28.0	1.00	50	Much more stable bead, but very little penetration.	393	21.2	189	39.4	10.0	6.11	0.24
SA104	6/6/05	80 ---> 100	P-GMAW	.040 ER70S-6	none	50%50%	75	Push	8		0	0	180	28.0	1.00	50	This is the best vert-down trial up to this point. Fairly stable, some spatter. Root has good penetration a little suck-back. This may have some gap opening up. Crater is cracked.	434	21.8	208	39.4	11.0	6.91	0.27
SA105	6/7/05	80 ---> 100	P-GMAW	.040 ER70S-6	none	50%50%	75	Push	8		0	0	185	28.5	1.00	50	Some popping sounds and instability in the arc, a lot of spatter. Penetration is ok.	476	21.6	223	39.4	12.1	7.34	0.29
SA106	6/7/05	80 ---> 100	P-GMAW	.040 ER70S-6	none	50%50%	75	Drag	15		0	0	185	28.5	1.00	50	Good. Drag angle dramatically helped the stability. Good penetration, consistent. Still need some positive reinforcement in the root. Crater is cracked.	476	21.4	227	39.4	12.1	7.40	0.29
SA107	6/7/05	80 ---> 100	P-GMAW	.040 ER70S-6	none	50%50%	75	Drag	15		0	0	210	29.0	1.30	50	Good. Stable, good penetration which is mostly flat.	526	22.1	246	51.2	10.3	6.37	0.25
SA108	6/7/05	80 ---> 100	P-GMAW	.040 ER70S-6	none	50%50%	75	Drag	15		0	0	225	29.5	1.45	50	Good. Still stable, a little more spatter.	575	21.7	262	57.1	10.1	5.98	0.24
SA109	6/7/05	80 ---> 100	P-GMAW	.040 ER70S-6	none	50%50%	75	Drag	15		<0.1	0	225	29.5	1.45	50	Similar result to SA-108.	576	21.9	259	57.1	10.1	5.96	0.23
SA110	6/7/05	0 ---> 20	P-GMAW	.040 ER70S-6	none	50%50%	75	Drag	8		0	0	160	27.0	0.70	50	Weak intermittent penetration. As down-hill increases, penetration goes away	350	22.8	175	27.6	12.7	8.69	0.34
SA-111	6/15/05	80 ---> 100	P-GMAW	.040 ER70S-6	none	50%50%	75	Drag	15	1.56	0	0	225	29.5	1.30	50	Good penetration. Crater has crack.	573	22.0	258	51.2	11.2	6.65	0.26
SA112	6/15/05	80 ---> 100	P-GMAW	.040 ER70S-6	none	50%50%	75	Drag	15	1.57	0	0	225	29.5	1.30	50	Axial clamping. Good penetration. Crater has crack	573	22.0	258	51.2	11.2	6.65	0.26
SA113	6/15/05	80 ---> 100	P-GMAW	.040 ER70S-6	none	50%50%	255	Drag	15	1.61	0	0	225	29.5	1.30	50	Good penetration which is wider with preheat. Crater has crack.	571	21.8	260	51.2	11.2	6.64	0.26
SA114	6/15/05	80 ---> 100	P-GMAW	.040 ER70S-6	none	50%50%	245	Drag	15	1.62	0	0	225	29.5	1.30	50	Axial clamping. Good penetration which is wider with preheat. Crater has crack.	573	22.1	258	51.2	11.2	6.68	0.26
SA115	6/15/05	0 ---> 20	P-GMAW	.040 ER70S-6	none	50%50%	250	Drag	8	1.57	0	0	160	27.0	0.70	50	A repeat of SA-95 with preheat. Good penetration. Mostly consistent but penetration goes away at the very end. Penetration lasted longer and was better than SA-95 hopefully due to the preheat. No visible cracking.	350	22.8	177	27.6	12.7	8.79	0.35
SA116	6/28/05	80 ---> 100	P-GMAW	.040 ER80S-D2	none	50%50%	75	Drag	15	1.61	0	0	225	29.5	1.30	50	Good penetration. Crater has crack.	583	22.2	254	51.2	11.4	6.61	0.26
SA117	6/28/05	80 ---> 100	P-GMAW	.040 ER80S-D2	none	50%50%	75	Drag	15	1.56	0	0	225	29.5	1.30	50	Axial clamping. Good penetration. Crater has crack	583	21.8	258	51.2	11.4	6.59	0.26
SA118	6/28/05	80 ---> 100	P-GMAW	.040 ER80S-D2	none	50%50%	250	Drag	15	1.56	0	0	225	29.5	1.30	50	Good penetration which is wider with preheat. Crater has crack.	583	22.2	252	51.2	11.4	6.56	0.26
SA119	6/28/05	80 ---> 100	P-GMAW	.040 ER80S-D2	none	50%50%	250	Drag	15	1.58	0	0	225	29.5	1.30	50	Axial clamping. Good penetration which is wider with preheat. Crater has crack.	585	22.4	255	51.2	11.4	6.70	0.26
SA120	6/28/05	80 ---> 100	P-GMAW	.040 ER80S-D2	none	50%50%	250	Drag	30	1.58	0	0	225	29.5	1.30	50	Better arc with less spatter with the 30 degree drag angle.	587	22.0	261	51.2	11.5	6.73	0.27
SA121	6/28/05	80 ---> 100	P-GMAW	.040 ER80S-D2	none	50%50%	250	Drag	30	1.62	0	0	215	29.5	1.20	50	This seemed to be the best vertical down parameters so far for arc characteristics and reduction of spatter. Can still see cracking.	547	22.8	248	47.2	11.6	7.18	0.28
SA122	6/28/05	80 ---> 100	GMAW	.040 ER80S-D2	none	50%50%	250	Drag	15	1.59	0	0	225	23.5	1.20	50	These CV parameters were unstable.	547	23.0	264	47.2	11.6	7.71	0.30
SA123	6/29/05	80 ---> 100	GMAW	.040 ER80S-D2	none	50%50%	250	Drag	15	1.57	0	0	220	23.0	1.30	50	Unsable, stubbing sometimes. End of weld stabilized ok, but still has suck-back and cracked.	507	23.0	253	51.2	9.9	6.82	0.27
SA124	6/29/05	80 ---> 100	GMAW	.040 ER80S-D2	Argon	50%50%	250	Drag	30	1.58	0	0	215	29.5	1.20	50	I intended to repeat SA-121 with back shielding, but mistakenly left the setup in CV mode. Spray transfer, and root was unpenetrated.	491	29.4	283	47.2	10.4	10.57	0.42
SA125	6/29/05	80 ---> 100	P-GMAW	.040 ER80S-D2	Argon	50%50%	250	Drag	30	1.62	0	0	215	29.5	1.20	50	Repeat of SA-121 but with argon back-shielding. Back-shielding coverage wasn't too good. It helped some, suck-back not as bad compared to SA-121.	548	22.4	251	47.2	11.6	7.14	0.28
SA126	6/29/05	0 ---> 20	P-GMAW	.040 ER80S-D2	none	50%50%	250	Push	8	1.57	0	0	160	27.0	0.70	50	Repeat of SA-95 with preheat & using ER80S-D2 wire. Lighter penetration than expected with preheat. Penetration quickly goes away. No visible cracking.	356	22.8	173	27.6	12.9	8.59	0.34
SA127	7/8/05	80 ---> 100	P-GMAW	.040 ER80S-D2	none	50%50%	240	Drag	15	1.66	0	0	160	27.0	0.70	50	Mostly unpenetrated. Some small spots of penetration. No cracking visible in the crater.	357	22.6	178	27.6	13.0	8.76	0.34
SA128	7/8/05	80 ---> 100	P-GMAW	.040 ER80S-D2	none	50%50%	250	Drag	30	1.69	0	0	160	27.0	0.70	50	No penetration. No visible crack in crater.	355	22.6	179	27.6	12.9	8.81	0.35
SA129	7/8/05	80 ---> 100	P-GMAW	.040 ER80S-D2	none	50%50%	250	Drag	30	1.67	0	0	175	28.0	0.80	50	Good consistent penetration. Some suck-back. Crater is cracked.	448	22.0	209	31.5	14.2	8.76	0.34
SA130	7/8/05	80 ---> 100	P-GMAW	.040 ER80S-D2	none	50%50%	250	Drag	15	1.70	0	0	175	28.0	0.80	50	Not much penetration. Crater has crack. More spattery than 30 degree travel angle.	459	22.4	199	31.5	14.6	8.49	0.33

Table 6. (Continued)

Weld No.	Date	Weld Position (degr)	Process	Wire Electrode	Root Shield	Arc Shield Gas	Preheat (degr F)	Torch Travel (Push/ Drag)	Torch Travel Angle (degr)	Avg. Measured Root Face (mm)	Root Gap (mm)	Root Mismatch (mm)	Remote Setting "AMP"	Remote Setting "VOLT"	Travel Setting (m/min)	Spin Freq. (Hz)	Comment	MEAS. WFS (ipm)	MEAS. Voltage (V)	MEAS. Current (A)	Trav. Speed @ Root (ipm)	Ratio WFS/TS	Heat Input kJ/in.	Heat Input kJ/mm
WELDS MADE USING SERIMER SATURNAX5 BUG (NOT PANASONIC ROBOT). PANASONIC HM500, AIR COOLED SPIN TORCH, NO TRACKING																								
SA131	11/30/05	0 ---> 20	P-GMAW	.040 NiMo80	none	50%50%	250	Push	8	1.66	0	0	dial	dial	0.76	50	Approach is to repeat SA-95, SA-126 using the NiMo80 wire	351	22.7	196	29.9	11.7	8.92	0.35
SA132	11/30/05	0 ---> 20	P-GMAW	.040 NiMo80	none	50%50%	250	Push	8	1.69	0	0	dial	dial	0.70	50	Slow down travel some.	351	22.6	195	27.6	12.7	9.59	0.38
SA133	11/30/05	0 ---> 20	P-GMAW	.040 NiMo80	none	50%50%	250	Push	8	1.65	0	0	dial	dial	0.70	50	Increase current some.	404	21.7	204	27.6	14.7	9.64	0.38
SA134	11/30/05	0 ---> 20	P-GMAW	.040 NiMo80	none	50%50%	250	Push	8	1.65	0	0	dial	dial	0.70	30	Reduce spin frequency.	397	21.5	210	27.6	14.4	9.83	0.39
SA135	12/1/05	80 ---> 100	P-GMAW	.040 NiMo80	none	50%50%	250	Drag	30	1.66	0	0	dial	dial	0.80	30	Approach is to repeat SA-129 using the NiMo80 wire.	460	22.9	232	31.5	14.6	10.12	0.40
SA136	12/1/05	80 ---> 100	P-GMAW	.040 NiMo80	none	50%50%	250	Drag	30	1.72	0	0	dial	dial	1.20	30	Approach is to repeat SA-121 (faster) using the NiMo80 wire.	553	22.3	252	42.8	12.9	7.88	0.31
SA137	12/1/05	80 ---> 100	P-GMAW	.040 NiMo80	none	50%50%	250	Drag	30	1.68	0	0	dial	dial	1.30	30	Travel faster based on speed measured on SA-136.	552	22.1	254	46.3	11.9	7.27	0.29
NOTE: ON WELDS SA-131 THROUGH SA-137 THE HM500 POWER SUPPLY HAD (+) LEAD CONNECTED TO THE "MIG / PULSE (AL)" TERMINAL.																								
I CHANGED THE (+) LEAD TO THE TERMINAL "PULSE (STEEL)"																								
SA138	1/16/06	0 ---> 20	P-GMAW	.040 NiMo80	none	50%50%	70	Push	8	1.64	0	0	dial	dial	0.70	30	Repeat SA-95, SA-126 using the NiMo80 wire and Panasonic power supply + lead connected to "pulse steel". Result was no penetration, possibly because didn't pre-heat.	351	23.3	183	25.5	13.7	10.02	0.39
SA139	1/16/06	0 ---> 20	P-GMAW	.040 NiMo80	none	50%50%	260	Push	8	1.67	0	0	dial	dial	0.73	30	Repeat with pre-heat. Result was a quick hole just after the start, then some penetration that went away mid way through the weld.	354	22.9	192	26.5	13.4	9.95	0.39
SA140	1/17/06	0 ---> 20	P-GMAW	.040 ER70S-6	none	50%50%	260	Push	8	1.68	0	0	dial	dial	0.73	30	Can we repeat SA-95 (ER70S-6 wire) using thhe current setup and get the penetration? Result: this time got penetration. It seems the wire has most to do with not being able to penetrate.	360	22.5	193	26.5	13.6	9.83	0.39
SA141	2/13/06	0 ---> 20	P-GMAW	.040 NiMo80	none	50%50%	260		0	1.54	0	0	dial	dial	0.73	30	NiMo wire at 0 torch angle to try to get more penetration. Arc very spattery. Got some penetration at the start similar to SA-95. Intermittent penetration after first 2 inches.	349	24.0	182	26.6	13.1	9.85	0.39
SA142	2/13/06	0 ---> 20	P-GMAW	.040 NiMo80	none	50%50%	260		0	1.59	0	0	dial	dial	0.73	30	New bottle of gas. Same settings a SA-141. Arc just as spattery. Penetration is light and spotty with none at the start. It doesn't seen like the gas was a problem.	356	23.6	183	26.6	13.4	9.74	0.38
SA143	2/13/06	0 ---> 20	P-GMAW	.040 NiMo80	none	50%50%	260		0	1.56	0	0	dial	dial	0.73	30	Try higher wfs and voltage. WFS pre set to a higher setting. Voltage increased during the weld. Result: A hole burned through at 1" into weld. Penetration most of the way except the end. Wher voltage was turned up, face side has undercut and root side penetration is flat with no reinforcement.	411	27.3	205	26.6	15.4	12.62	0.50
SA144	2/13/06	0 ---> 20	P-GMAW	.040 NiMo80	none	50%50%	260		0	1.57	0	0	dial	dial	0.73	30	27 V definitely too high although it helpe it run more stable and with less spatter. Try a voltage in between. Result: Good penetration, but 3 holes burned through.	399	24.7	196	26.6	15.0	10.92	0.43
SA145	2/13/06	0 ---> 20	P-GMAW	.040 NiMo80	none	50%50%	260		0	1.60	0	0	dial	dial	0.73	30	A wfs between SA-142 and SA-144. Result: Prior to this weld, there was a weld which failed to travel, leaving a large mound of metal. SA-145 had no penetration possibly because it started too close to the mound of metal.	380	25.5	188	26.6	14.3	10.81	0.43
SA146	2/15/06	0 ---> 20	P-GMAW	.040 NiMo80	none	50%50%	260		0	1.60	0	0	dial	dial	0.70	30	A wfs between SA-142 and SA-144. (but started on clean joint). Result: Too much penetration. Burned a series of 4 equally spaced holes. Current and wfs were higher than trying for.	413	24.9	201	26.8	15.4	11.21	0.44
SA147	2/15/06	0 ---> 20	P-GMAW	.040 NiMo80	none	50%50%	260		0	1.57	0	0	dial	dial	0.70	30	Try again for a wfs between SA-142 and SA-144. Result: Too much penetration. Burned a 2 holes. Current and wfs were still higher than trying for.	393	25.2	199	26.8	14.7	11.23	0.44
SA148	2/17/06	0 ---> 20	P-GMAW	.040 NiMo80	none	50%50%	260		0	1.57	0	0	dial	dial	0.70	30	Try again for a wfs between SA-142 and SA-144. Result: Penetration with no holes for the first 3" of weld then the penetration goes away. This is the closest we have gotten to matching SA-95.	371	25.5	187	26.8	13.8	10.68	0.42
SA149	2/17/06	0 ---> 20	P-GMAW	.040 NiMo80	none	50%50%	260		0	1.57	0	0	dial	dial	0.80	30	Try nominal 400 ipm wfs and travel .80 m/minute. Result: Penetration at start then a hole then penetration went away. Less consistent than SA-148.	425	24.3	206	30.6	13.9	9.81	0.39
BEGIN KEEPING TRACK OF THE PULSE PARAMETER SETTINGS ON THE PANASONIC HM500																								
"MATERIAL", "DIAMETER", "PULSE CONTROL", "INDIVIDUAL/UNITARY" SWITCHES, "FINE ADJ. FREQUENCY" DIAL																								
"PULSE CURRENT", "BASE CURRENT", "PULSE RISING", "PULSE FALLING", "CURRENT", "VOLTAGE", "PULSE FREQ", "WIRE FEED SPEED" DIGITAL INDICATORS																								
SA150	2/21/06	0 ---> 20	P-GMAW	.040 NiMo80	none	90%10%	250		0	1.58	0	0	374	23.4	0.72	30	Try 90/10 gas to see it we get more stable, less spatter. Result: Bead not good, it didn't deposit at the bottom of the joint. 23V too high with this gas. No penetration. Very stable, spatter-free	378	23.3	191	27.6	13.7	9.69	0.38
SA151	2/21/06	0 ---> 20	P-GMAW	.040 NiMo80	none	90%10%	250		0	1.59	0	0	374	23.4	0.72	30	Try 90/10 gas to see it we get more stable, less spatter. Lower voltage. Result: Bead face good, ran stable, spatter-free but no penetration.	378	20.5	175	27.6	13.7	7.81	0.31
SA152	2/24/06	0 ---> 20	P-GMAW	.040 NiMo80	none	90%10%	250		0	1.60	0	0	413	22.0	0.72	30	Turn up current (WFS). Result: Bead face good, ran stable, spatter-free but no penetration.	420	22.0	186	27.6	15.2	8.91	0.35
SA153	2/28/06	0 ---> 20	P-GMAW	.040 NiMo80	none	90%10%	250		0	1.59	0	0	460	21.0	0.72	30	Turn up current (WFS) more. Result: A few short spots where penetration broke through.	471	17.9	207	27.6	17.1	8.07	0.32
SA154	2/28/06	0 ---> 20	P-GMAW	.040 NiMo80	none	90%10%	250		0	1.55	0	0	491	21.6	0.72	30	Turn up current (WFS) more. Result: Penetration most of the way with a few skips in penetration. Penetration width ~2.5 mm and it is convex (not sucked back). Arc and travel not coordinated well making a buildup at beginning. Is this affecting the penetration at the start?	495	18.1	222	27.6	18.0	8.75	0.34
SA155	3/1/06	0 ---> 20	P-GMAW	.040 NiMo80	none	90%10%	250		0	1.59	0	0	491	21.6	0.72	30	Same parameters but try a running start. Result: at start not penetrated then good strong penetration for 2-1/4". Then penetration went away for remainder. This weld had CTWD increasing which could account for losing the penetration.	496	17.8	213	27.6	18.0	8.25	0.32
SA156	3/9/06	0 ---> 20	P-GMAW	.040 NiMo80	none	90%10%	250		0		0	0	522	22.0	0.55	50	More current & higher spin rate to spread out wider at root. Travel was mistakenly set at .55 m/min. Result: Travel and arc start was better coordinated and it didn't leave buildup at beginning. About 1/4" at beginning not penetrated, then strong penetration most of the way except a few short skips of penetration. Very stable and face of weld looks very good.	525	18.6	224	21.1	24.9	11.87	0.47
SA157	3/9/06	0 ---> 20	P-GMAW	.040 NiMo80	none	90%10%	250		0		0	0	542	22.0	0.72	50	More current & higher spin rate to spread out wider at root. Travel set where intended. Result: A little more spatter and arc was a little "bouncy". Needs a little more voltage at this wfs. Despite the higher current, penetration was less than SA-156. penetration poking through in some places, but most is not fully penetrated.	545	18.1	232	27.6	19.8	9.14	0.36

Table 6. (Continued)

SWITCH TO 75%Ar-25%CO2 SHIELDING GAS AS A COMPROMISE BETWEEN THE STABILITY OF 90/10 AND THE PENETRATION PROFILE OF 50/50.																								
SA158	3/14/06	0 ---> 20	P-GMAW	.040 NiMo80	none	75%25%	250		0		0	0	460	22.6	0.72	30	Try 75/25 gas to see if we can be more stable than 50/50 , but get penetration. Result: Good penetration all the way with no burn-through. Arc was fairly stable with some fine spatter.	465	21.8	191	27.6	16.9	9.07	0.36
SA159	3/14/06	0 ---> 20	P-GMAW	.040 NiMo80	none	75%25%	250		0		0	0	460	22.6	0.72	30	See if SA-158 is repeatable. Result: Good penetration up to the point it encountered a small hole which was pre-existing in the joint. After it passed the hole, penetration disappeared.	465	21.4	198	27.6	16.9	9.22	0.36
SA160	3/14/06	0 ---> 20	P-GMAW	.040 NiMo80	none	50%50%	250		0		0	0	413	23.6	0.72	30	Try 50/50 gas with the latest pulse parameters to see if it might be more stable than before. Result: Unstable. The arc was bouncing up and down and the DAQ shows this. Lots of spatter. Some penetration. Abandon 50/50 shielding.	415	29.0	183	27.6	15.1	11.55	0.45
SA161	3/14/06	0 ---> 20	P-GMAW	.040 NiMo80	none	75%25%	250		0		0	0	460	23.2	0.72	30	Improve on SA-158 by optimizing the voltage. Higher voltage. Result: Ran less stable tha SA-158. Arc bounced up and down an had popping sounds. Penetration was inconsistent; none at the start then good penetration through mid-weld then lost penetration at the end.	465	22.5	199	27.6	16.9	9.75	0.38
SA162	3/15/06	0 ---> 20	P-GMAW	.040 NiMo80	none	75%25%	250		0		0	0	460	22.2	0.72	30	Improve on SA-158 by optimizing the voltage. Lower voltage. Result: Stable, but no penetration. How can parameters so close to same as SA_158 not penetrate? Maybe joint is slightly thicker. Maybe process is that sensitive to voltage. When voltage setpoint is dropped to a certain level, there is a lot more short-circuit drastically lowering the amount of heat.	465	20.4	198	27.6	16.9	8.79	0.35
SA163	3/15/06	0 ---> 20	P-GMAW	.040 NiMo80	none	75%25%	250		0		0	0	460	22.6	0.72	30	See if SA-158 is repeatable. Result: Good penetration up to the point it encountered a small hole which was pre-existing in the joint. After it passed the hole, penetration disappeared.	465	21.2	196	27.6	16.9	9.05	0.36
SA164	3/30/06	80 ---> 100	P-GMAW	.040 NiMo80	none	75%25%	250	Drag	30		0	0	460	22.6	0.72	30	Try parameters of SA-158 in vert-down position. Result: Some penetration in the beginning of the weld. This is where the root face is thin due to the prep on pipe half #10. Penetration disappeared where the root face resumes normal thickness.	460	21.1	198	27.6	16.7	9.10	0.36

Table 7. Groupings of Welds in Terms of Development Effort

Parameter Range Ref. No.	No. of Welds Made	Avg. Root Face Thickness (mm)	Shielding Gas Comp. (Ar/CO_2) %	Welding Current (A)	Arc Voltage (V)	Wire Feed Speed (in./min)	Travel Speed (in./min)	Photo Reference Nos.
6a	12	1.08-1.27	50/50	197-213	22.6-23.0	350-391	35-47	SA-07, SA-08
6b	4	1.53-1.68	50/50	216-219	22.6-22.8	380-391	39.4	SA-14, SA-15, SA-16
6c	5	1.50-1.63	90/10	234-258	21.9-23.4	391-491	31.5-39.4	SA-17, SA-17 WELD FACE, SA-18
6d	20	1.57-1.72	75/25	208-226	20.9-22.9	348-452	27.6-41.3	SA-23, SA-29, SA-32, SA-33, SA-34, SA-39
6e	26	1.97-2.09	75/25	199-271	21.5-23.5	346-539	27.6-59.1	SA-47, SA-48, SA-49, SA-50, SA-51
6f	5	1.71	75/25	220-225	21.1-21.9	408-413	25.6-27.6	SA-72, SA-73
6g	16	1.71	90/10	213-259	17.2-22.6	476-583	27.6-59.1	SA-79, SA-84
6h	4	1.65	50/50	156-169	21.0-23.6	315-341	27.6-29.5	SA-93
6i	11	1.65	50/50	176-255	20.3-26.0	353-606	27.6-63.0	SA-100, SA-105
6j	10	1.61	50/50	175-262	21.4-22.8	350-576	27.6-57.1	SA-108, SA-110, SA-115
6k	10	1.60	50/50	248/283	21.8-29.4	491-587	47.2-51.2	SA-116, SA-125
6l	5	1.65	50/50	173/209	22.0-22.8	355-459	27.6-31.5	SA-126, SA-129,

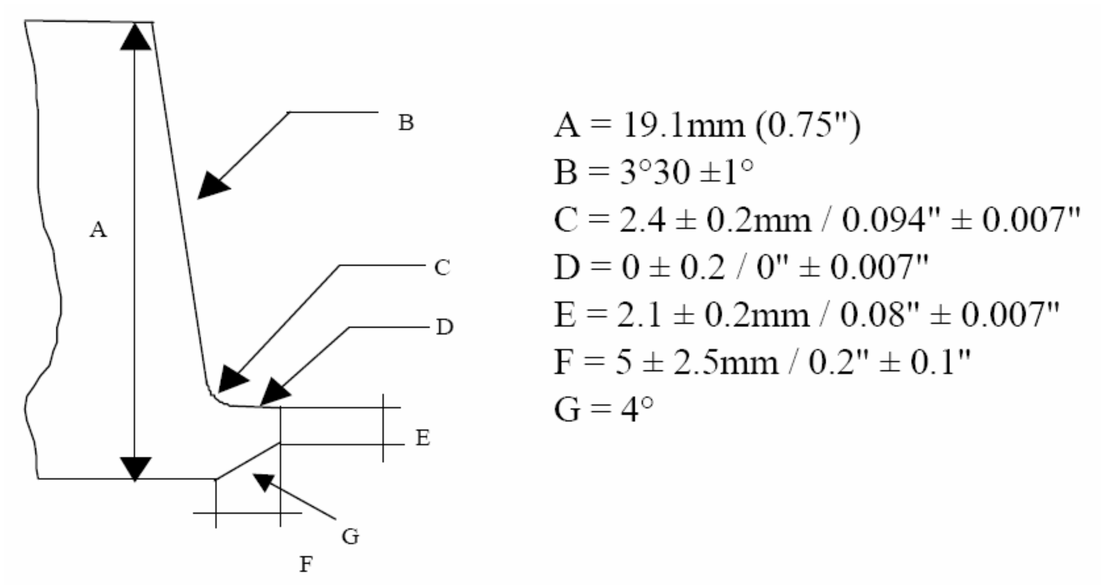


Figure 1. Joint Preparation Details

Figure 2. Side View of Narrow Gap Pipe Joint to Convey Joint Profile and Torch Access

Figure 3. Tacking Fixture Loaded with X80 Pipe Sections for Plate-Type Welding Procedure Development

Figure 4. Tacking Fixture for X80 Plate Butt Joints

Figure 5. Motoman/Kobelco PC 350 GMAW-VP Power Source Front Panel

Figure 6. Serimer Dasa STX Pipeline Welding Tractor and Track on 16-in.-Diameter Carbon Steel Pipe

(a) Controller

(b) Laptop-based GUI

Figure 7. Controlling the Serimer Dasa STX Pipeline Welding Tractor

Figure 8. **General View of the Pipeline Tractor and Track Mounted on a Development Pipe Girth Weld Test Piece** (Gas backing was used here, but discontinued for work on GMAW-RE.)

Figure 9. **Components of the Spin Arc Robotic Welding System**

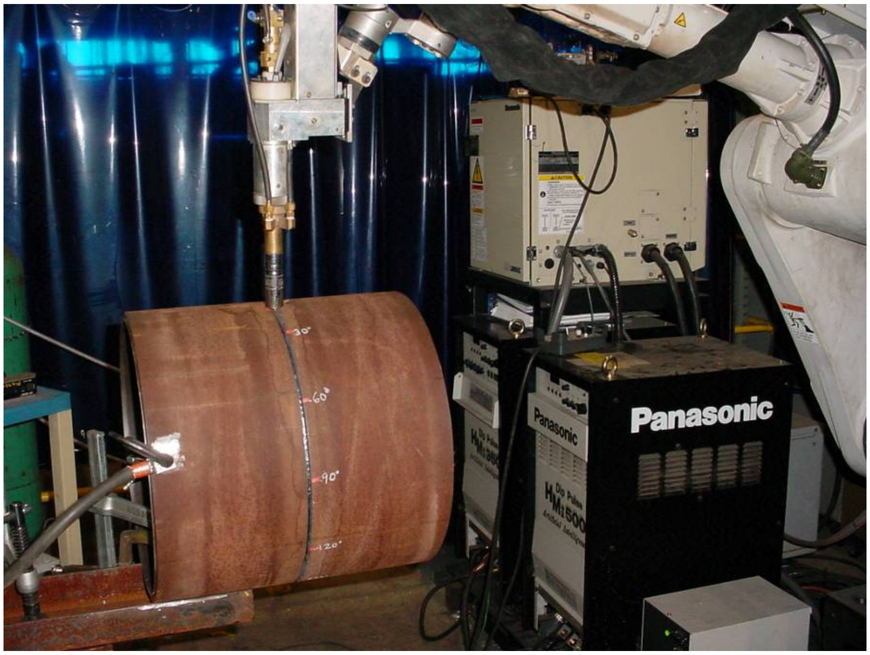


Figure 10. Spin Arc System Including Robot Controller and Power Sources

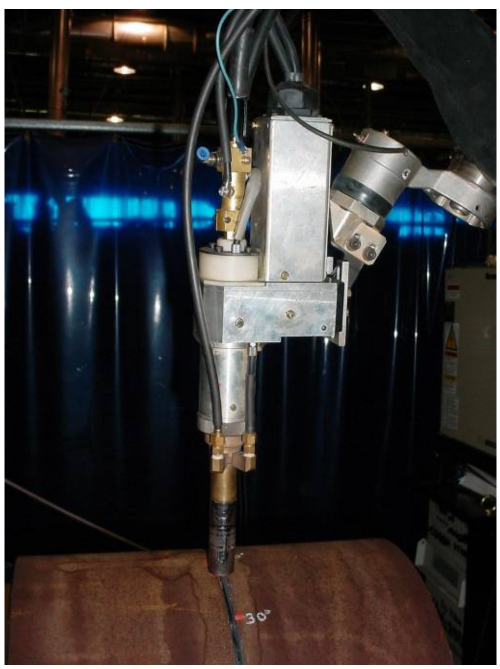


Figure 11. Spin Arc Torch Mounted on Robot Arm

Figure 12. Tapered Contact Tip Machined for Narrow Gap Pipe Joint Access

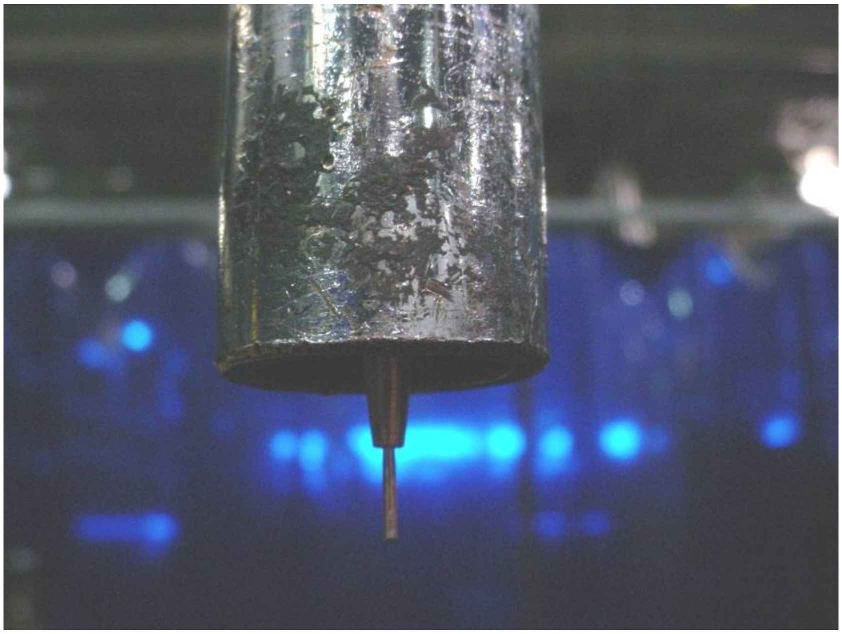


Figure 13. Setup of Contact Tip and Gas Nozzle Showing Wire Extension

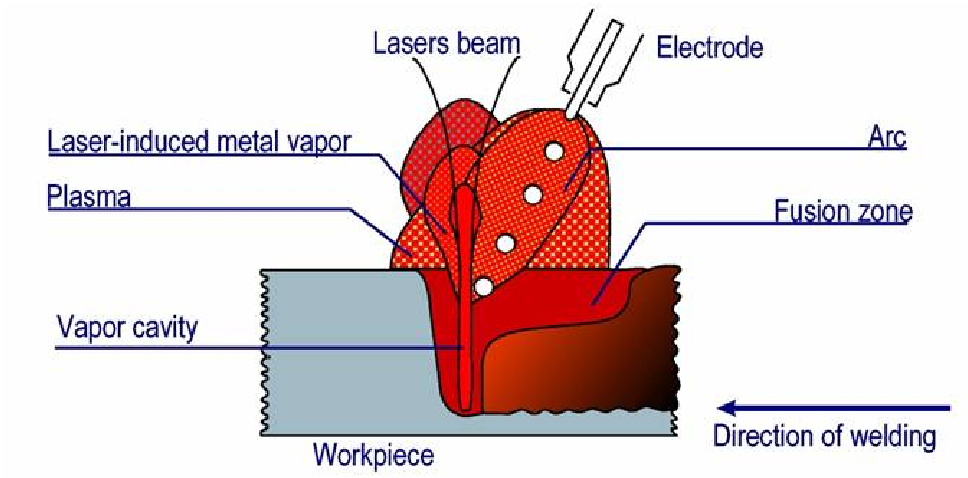


Figure 14. Schematic Diagram of Hybrid Laser/Arc Welding Process

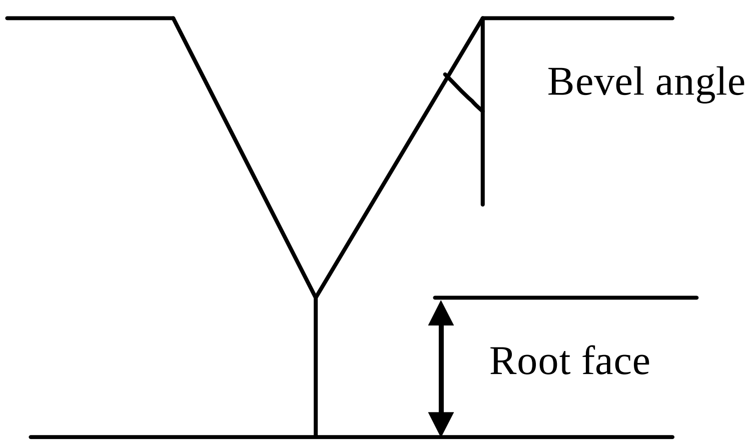


Figure 15. Weld Preparation Geometry

Figure 16. GMAW-VP Weld V5 – Penetration Bead on Inside of Pipe

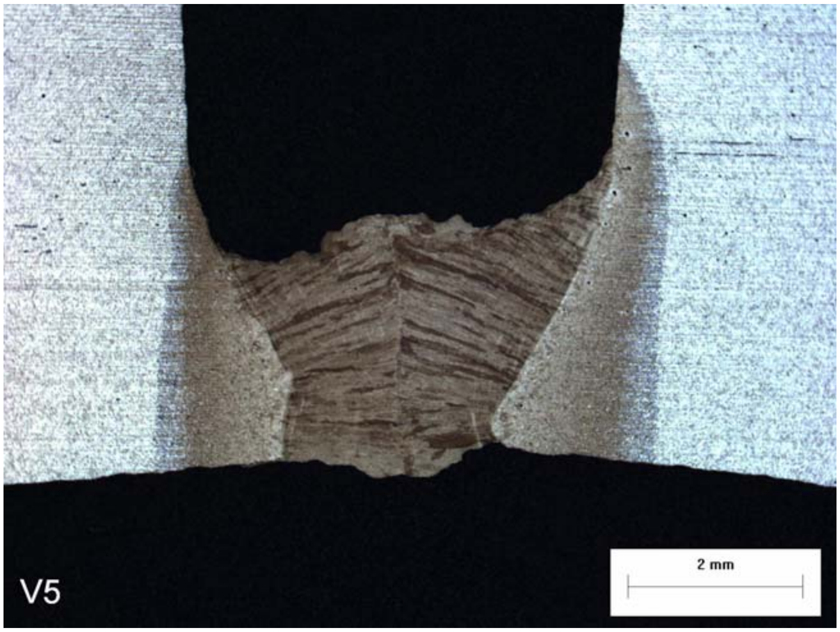


Figure 17. Macrosection of GMAW-VP Weld V5

Figure 18. Macrosection of GMAW-VP Weld V6

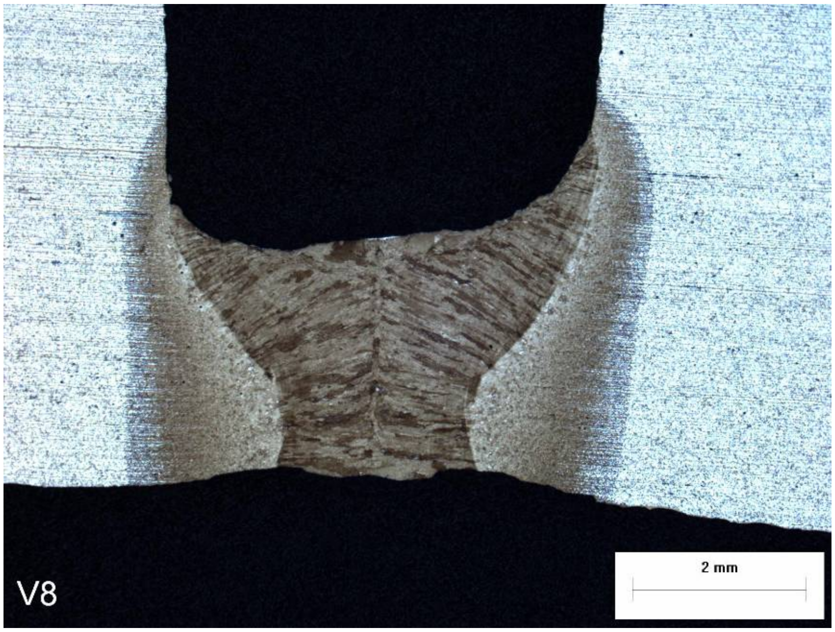


Figure 19. Macrosection of GMAW-VP Weld V8

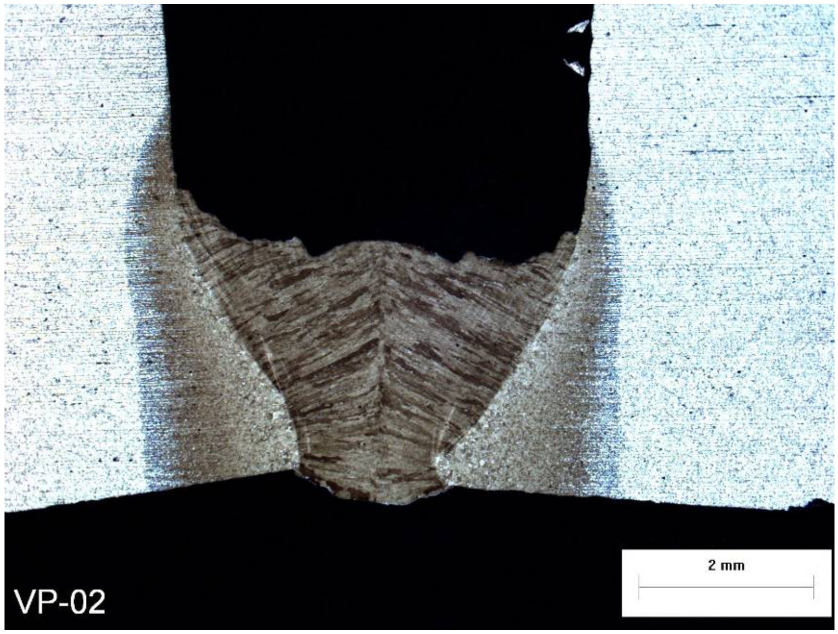


Figure 20. **Macrosection of Weld VP-02 Made in the Flat Position using GMAW-VP**

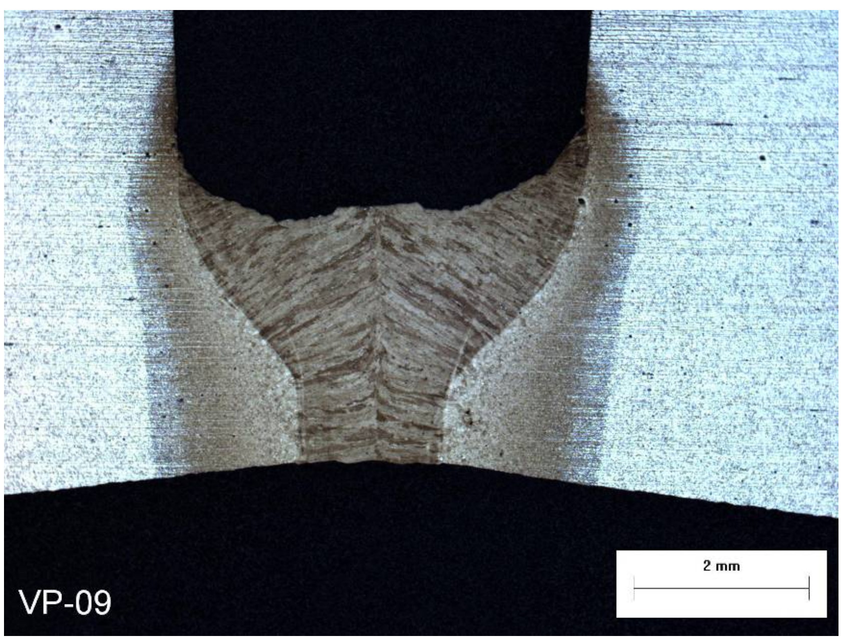


Figure 21. **Macrosection of Weld VP-09 Made in the Vertical-Down Position using GMAW-VP**

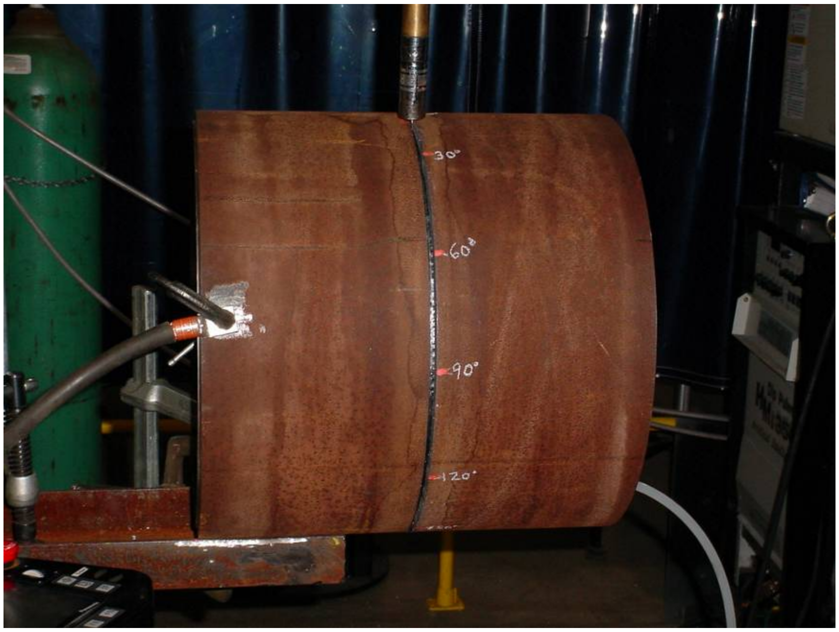


Figure 22. Pipe Joint with Completed Root Pass Made using Spin Arc

Figure 23. External View of Spin Arc GMAW Root Pass Weld W13 about 60 Degrees from TDC

Figure 24. Spin Arc GMAW Weld W13 Showing Root Pass Penetration – 90-160 Degree Downhill

Figure 25. Spin Arc GMAW Weld W13 Showing Root Pass Penetration – 130-180 Degree Downhill

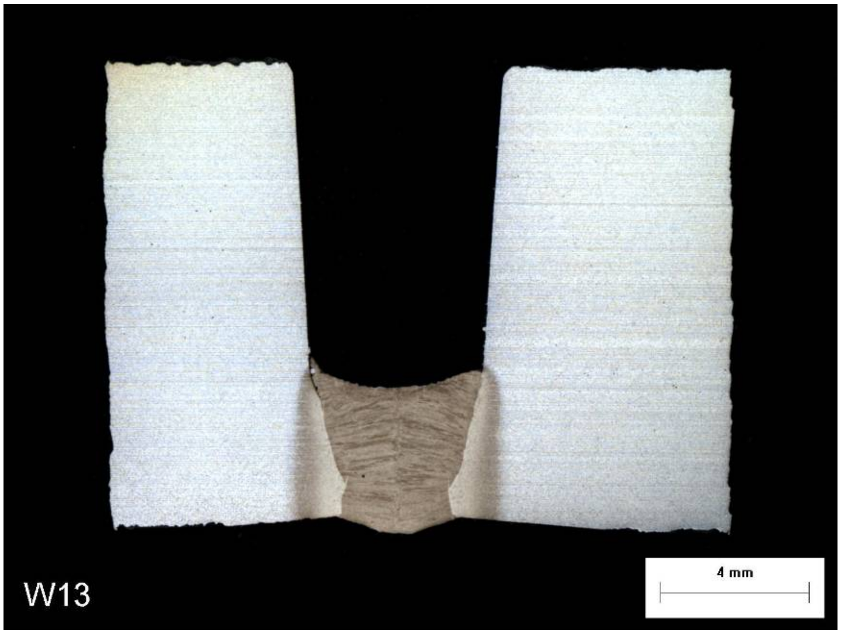


Figure 26. **Macrosection of Spin Arc GMAW Root Pass – about 3.8-mm Throat Thickness – Showing the Full Weld Preparation**

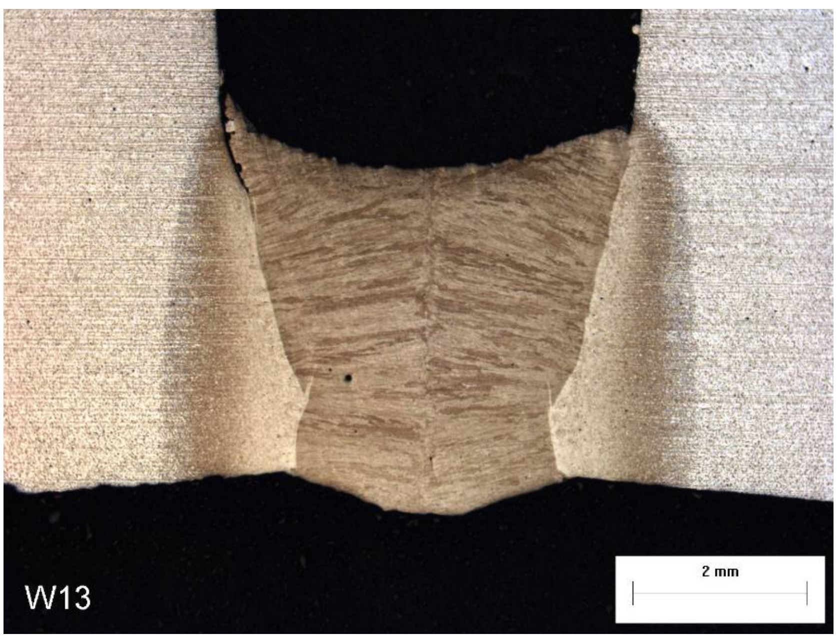


Figure 27. **Macrosection of Spin Arc GMAW Root Pass showing about 3.8-mm Throat Thickness and some Lack of Fusion at Left Sidewall**

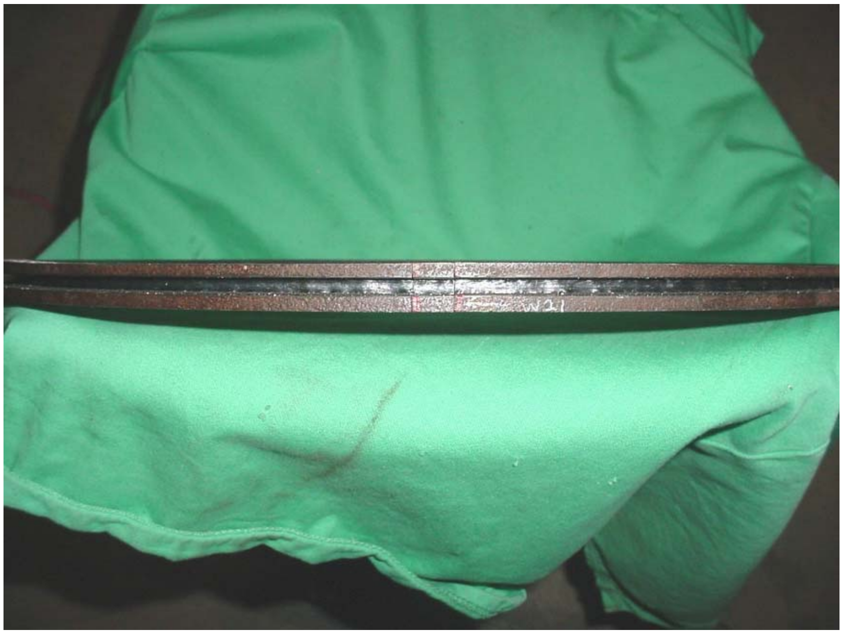


Figure 28. **Spin Arc Weld W21 – Outside View of Root Pass Profile**

Figure 29. **Spin Arc Weld W21 – Inside View of Penetration Bead**

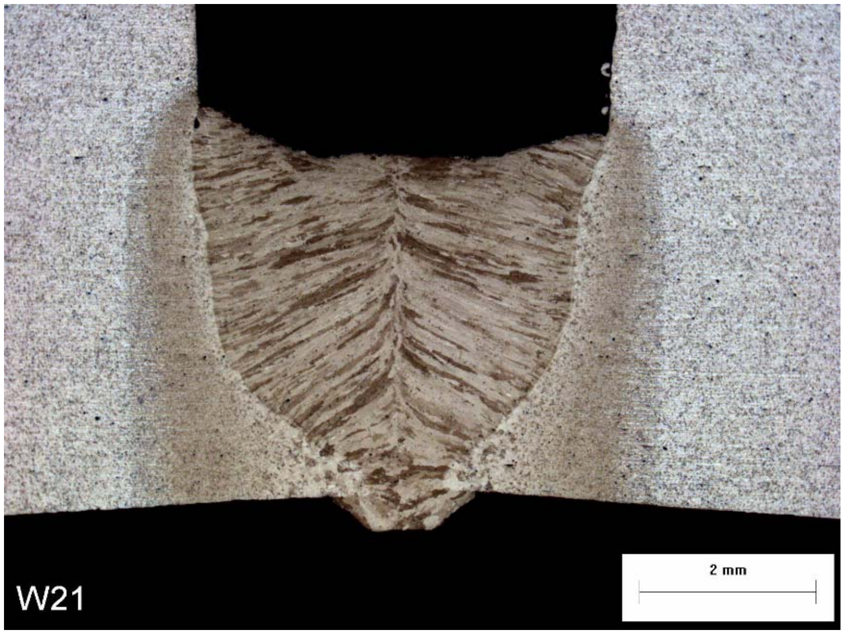


Figure 30. **Macrosection of Spin Arc Weld W21 Weld 4.2-mm Throat Thickness**

Figure 31. **View of Typical Penetration Bead Profiles in Welds SA-7 and SA-8**

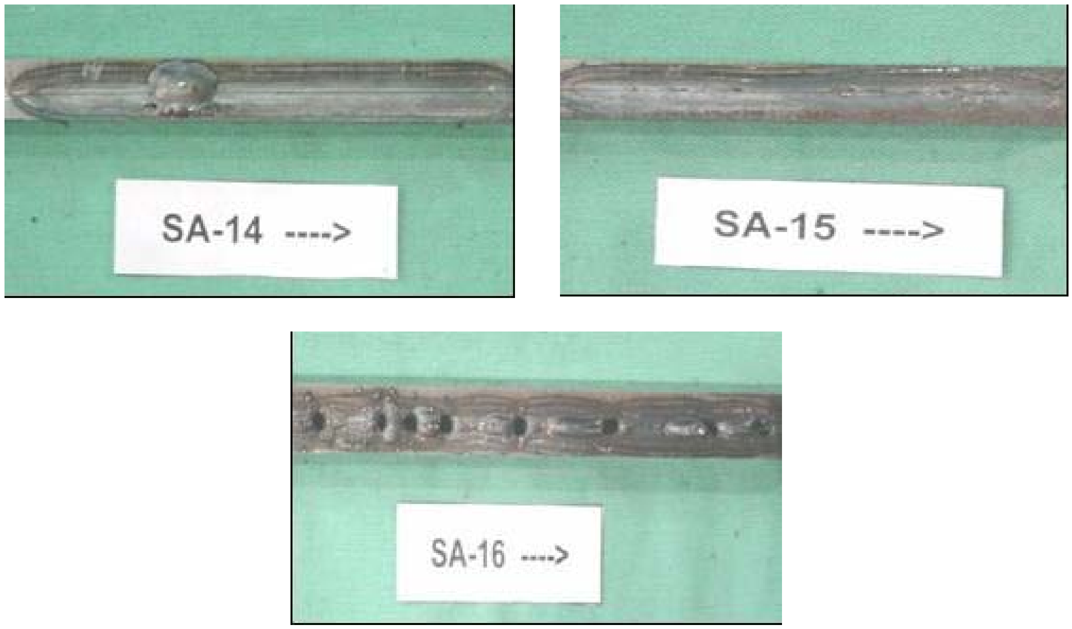


Figure 32. View of Typical Penetration Bead Profiles in Welds SA-14 through SA-16

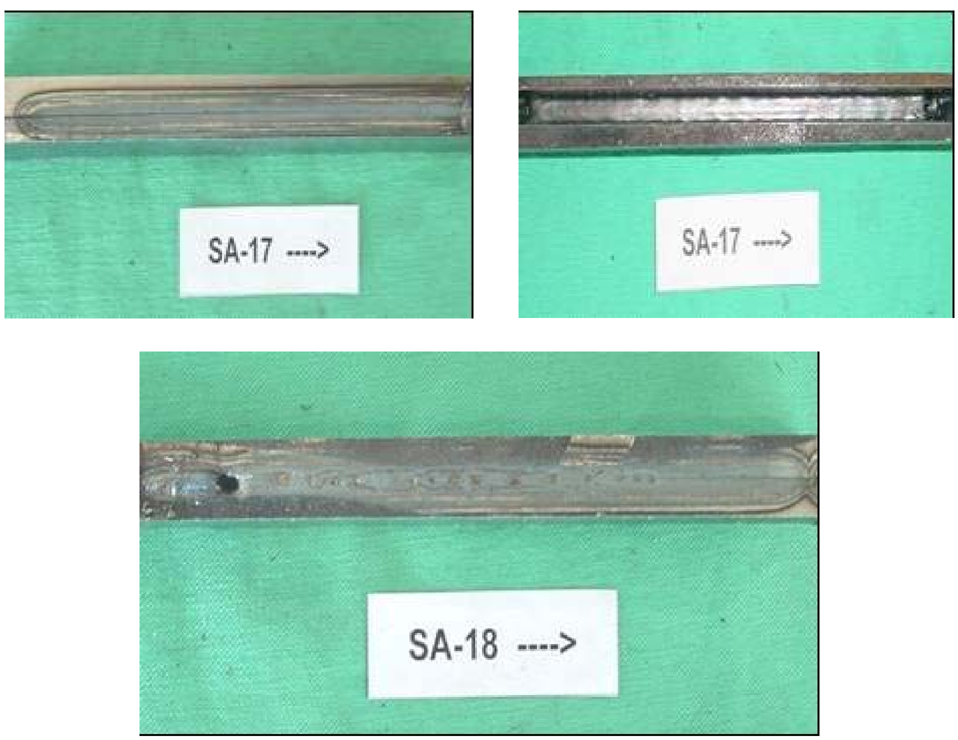


Figure 33. View of Typical Penetration Bead Profiles in Welds SA-17 and SA-18

Figure 34. View of Typical Penetration Bead Profiles in Welds SA-29, SA-32, SA-33, and SA-34

Figure 35. Macrosection of Weld SA-22 (Wire feed speed/travel speed ratio: 11.1, throat thickness: 3.5 mm, travel speed: 0.8 m/min.)

Figure 36. Macrosection of Weld SA-33 Showing Subsurface Centerline Hot Crack (Wire feed speed/travel speed ratio: 15.1, throat thickness: 4.7 mm, travel speed: 0.7 m/min, magnification: 14×.)

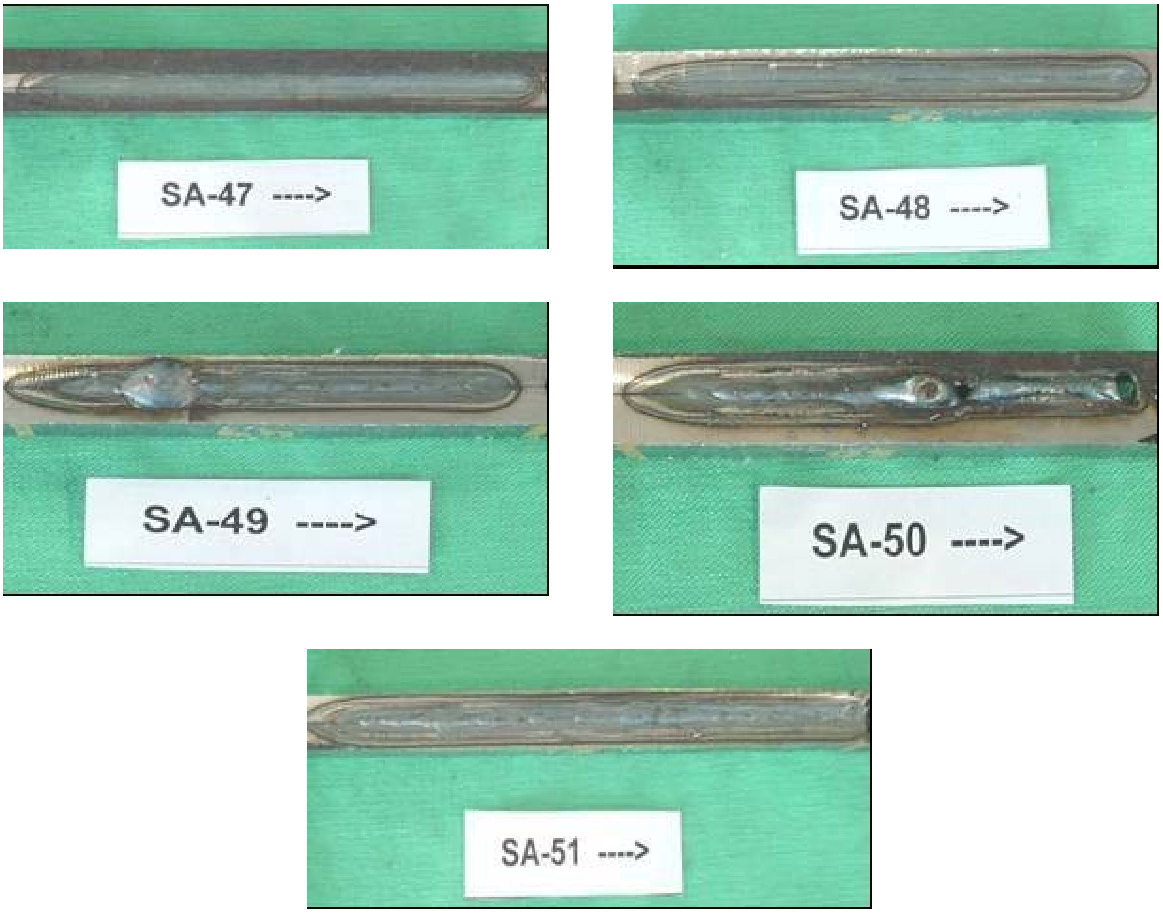


Figure 37. View of Typical Penetration Bead Profiles in Welds SA-47 through SA-51

Figure 38. Macrosection of Weld SA-51 Showing a Good Fusion Profile (Wire feed speed/travel speed ratio: 9.1, travel speed: 1.5 m/min, throat thickness: 4 mm, magnification: 14×.)

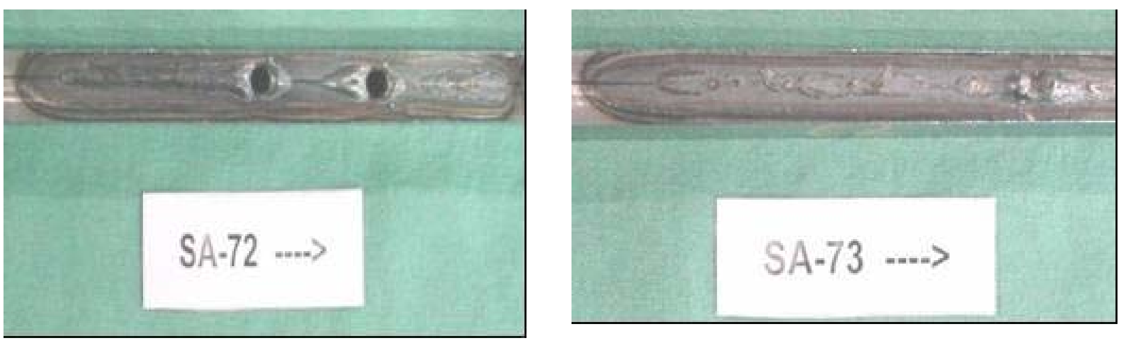


Figure 39. View of Typical Penetration Bead Profiles in Welds SA-72 and SA-73

Figure 40. **View of Typical Penetration Bead Profiles in Welds SA-79 and SA-84, and Macrosection of Weld SA-79 Showing Buried Solidification Crack**

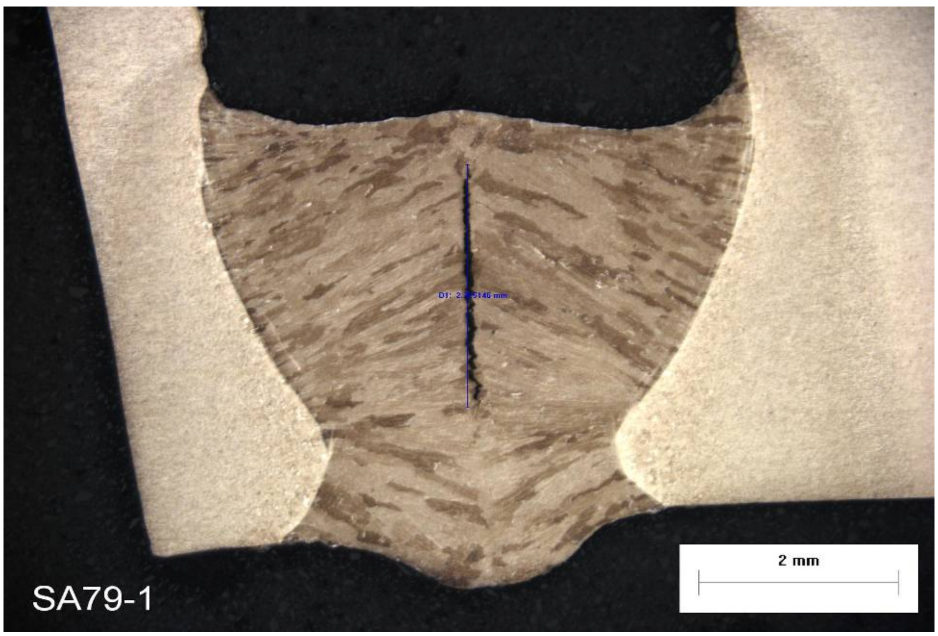


Figure 41. **Macrosection of Weld SA-79 Showing Subsurface Centerline Hot Crack**

Figure 42. View of Penetration Bead Profiles for Weld SA-93

Figure 43. Macrosection of Weld SA-93 Showing Good Fusion Profile (Wire feed speed/travel speed ratio: 12., throat thickness: 4 mm, travel speed: 0.7 m/min, magnification: 14×.)

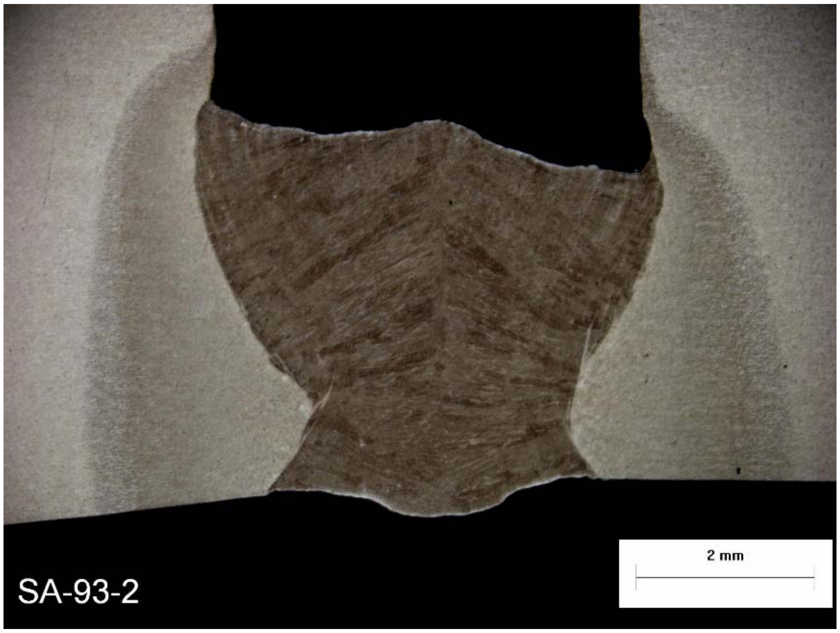


Figure 44. Macrosection of Weld SA-93 Showing a Good Fusion Profile (Wire feed speed/travel speed ratio 12.3, throat thickness: 4 mm, travel speed: 0.7 m/min.)

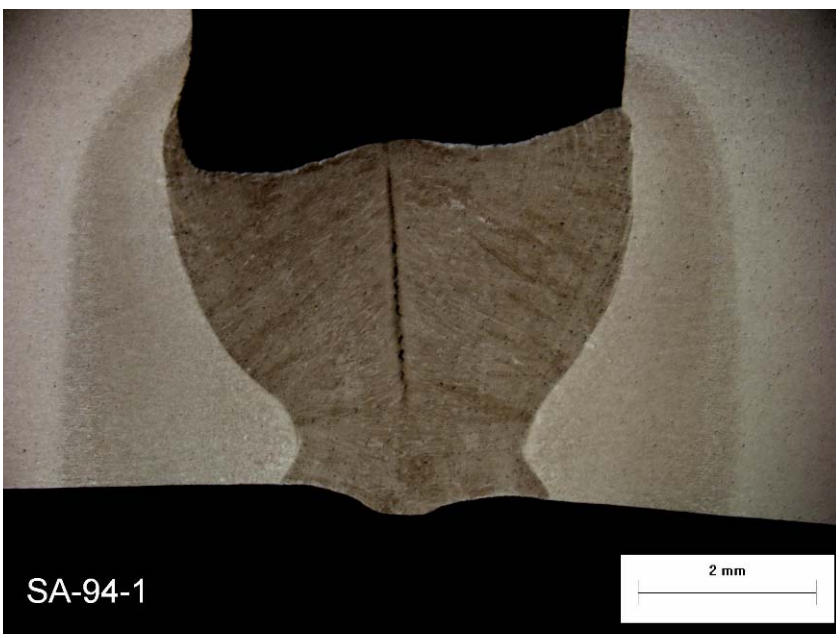


Figure 45. Macrosection of Weld SA-94 Showing Subsurface Centerline Hot Crack (Wire feed speed/travel speed ratio: 1.5, travel speed: 0.7 m/min.)

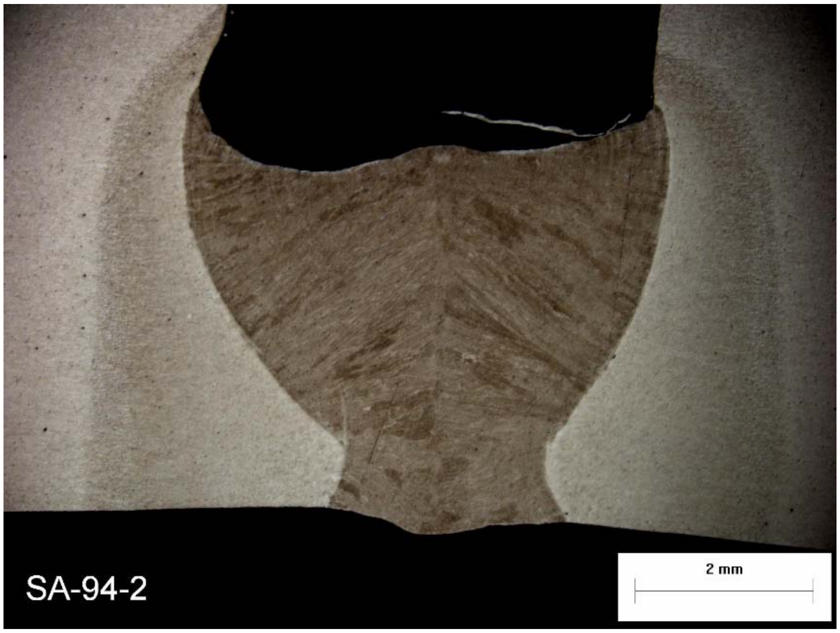


Figure 46. **Macrosection of Weld SA-94 Showing a Good Fusion Profile** (Wire feed speed/travel speed ratio 11.5, travel speed: 0.7 m/min.)

Figure 47. **36-in.-Diameter X80 Pipe Joint Setup for Robotic Spin Arc GMAW-RE**

Figure 48. 36-in.-Diameter X80 Pipe Joint

Figure 49. 36-in.-Diameter X80 Pipe Joint Showing Crossing Seam for Spiral Wound Pipe Welded with SAW

Figure 50. Root Bead Penetration in X80 Pipe Section for Weld SA-95

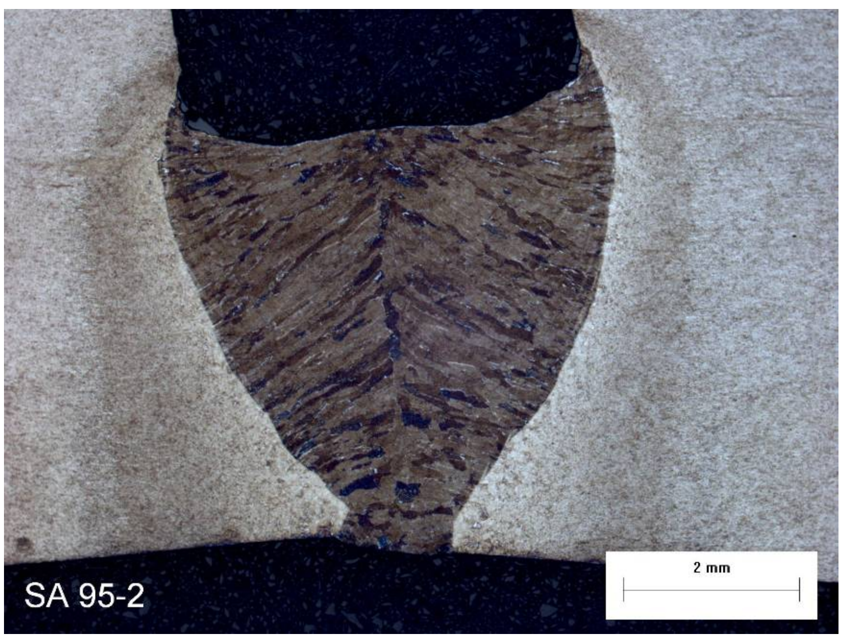


Figure 51. Macrosection of Weld SA-95 Made in X80 Pipe in the Flat Position (Wire feed speed/travel speed ratio: 12.8, travel speed: 0.7 m/min, through thickness: 5 mm, magnification: 14×.)

Figure 52. **Macrosection of Weld SA-95 Made in X80 Pipe in the Flat Position** (Wire feed speed/travel speed ratio: 12.8,, travel speed: 0.7 m/min, throat thickness: 4 mm, magnification: 14×.)

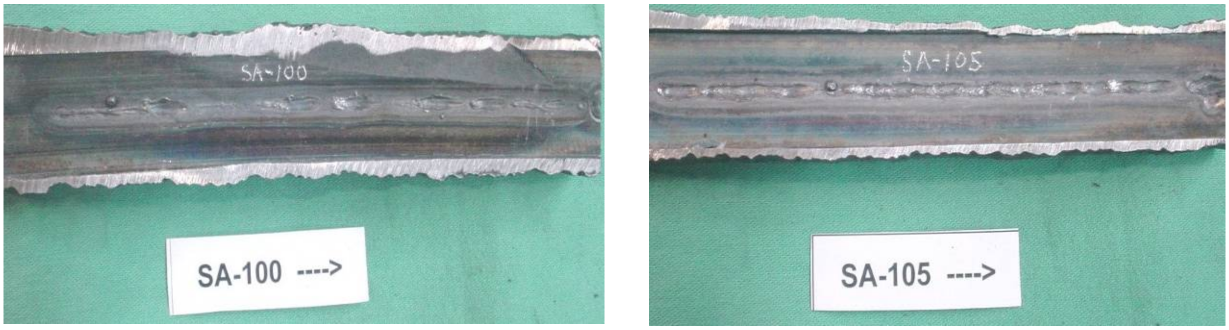


Figure 53. **View of Penetration Bead Profiles in Welds SA-100 and SA-105**

Figure 54. View of Penetration Bead Profiles in Welds SA-108 and SA-110

Figure 55. Root Bead Penetration in X80 Pipe Section for Weld SA-115

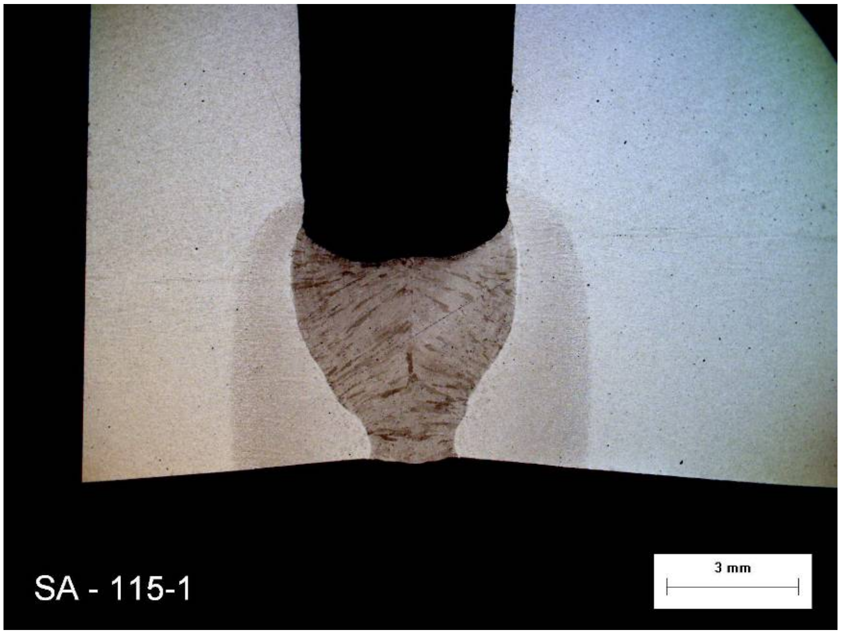


Figure 56. **Macrosection of Weld SA-115 Made with ER70S-6 Wire in X80 Pipe in the Flat Position** (Wire feed speed/travel speed ratio: 12.7,, travel speed: 0.7 m/min, throat thickness: 4.5 mm, magnification: 17×.)

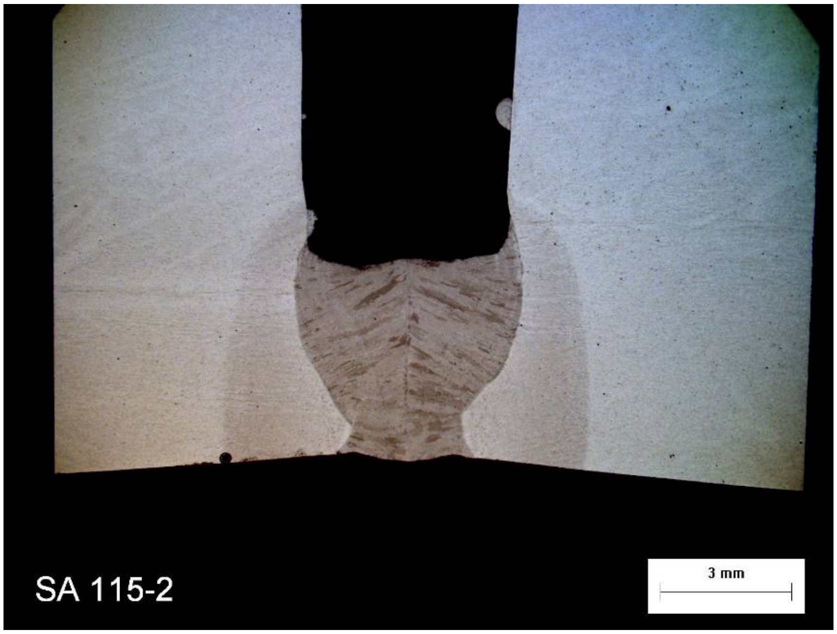


Figure 57. **Macrosection of Weld SA-115 Made with ER70S-6 Wire in X80 Pipe in the Flat Position** (Wire feed speed/travel speed ratio: 12.7, travel speed: 0.7 m/min, throat thickness: 4.5 mm, magnification: 7×.)

Figure 58. Root Bead Penetration in X80 Pipe Section for Weld SA-125

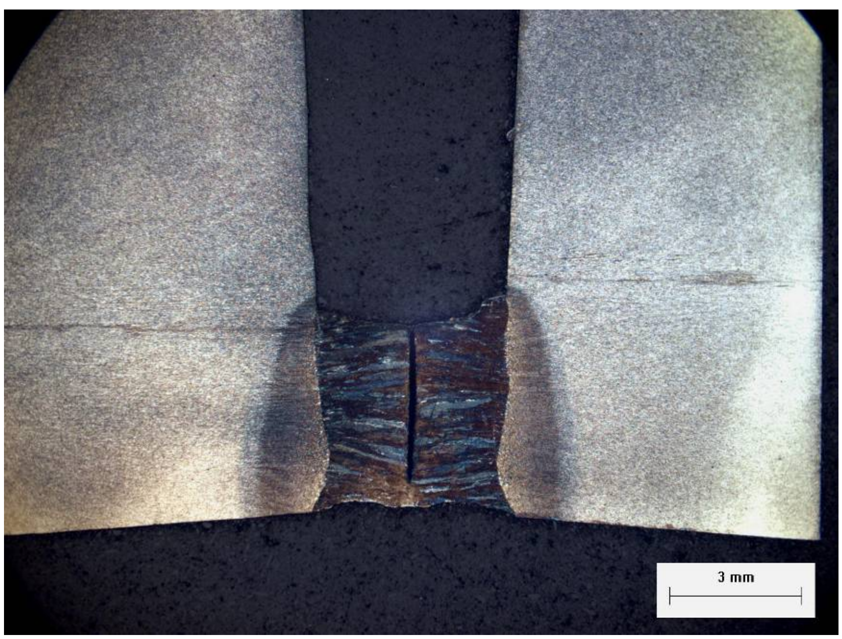


Figure 59. Macrosection of Weld SA-125 Made with ER80S-D2 Wire in X80 Pipe in the Vertical-Down Position Showing a Buried Solidification Crack (Wire feed speed/travel speed ratio: 11.6, travel speed: 1.2 m/min, throat thickness: 4 mm, magnification: 7×.)

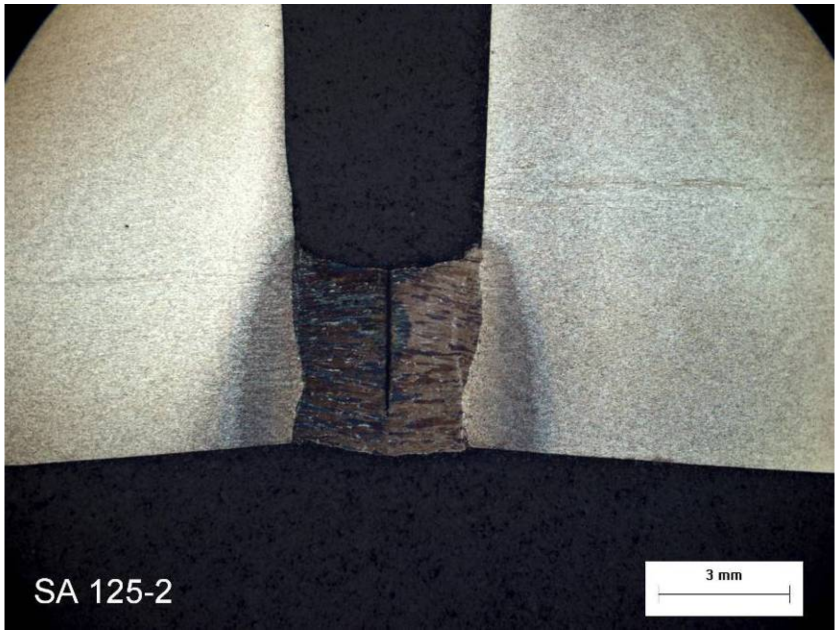


Figure 60. Macrosection of Weld SA-125 Made with ER80S-D2 Wire in X80 Pipe in the Vertical-Down Position Showing a Buried Solidification Crack (Wire feed speed ratio: 11.6, travel speed: 1.2 m/min, throat thickness: 4 mm, magnification: 7×.)

Figure 61. Root Bead Penetration in X80 Pipe Section for Weld SA-126

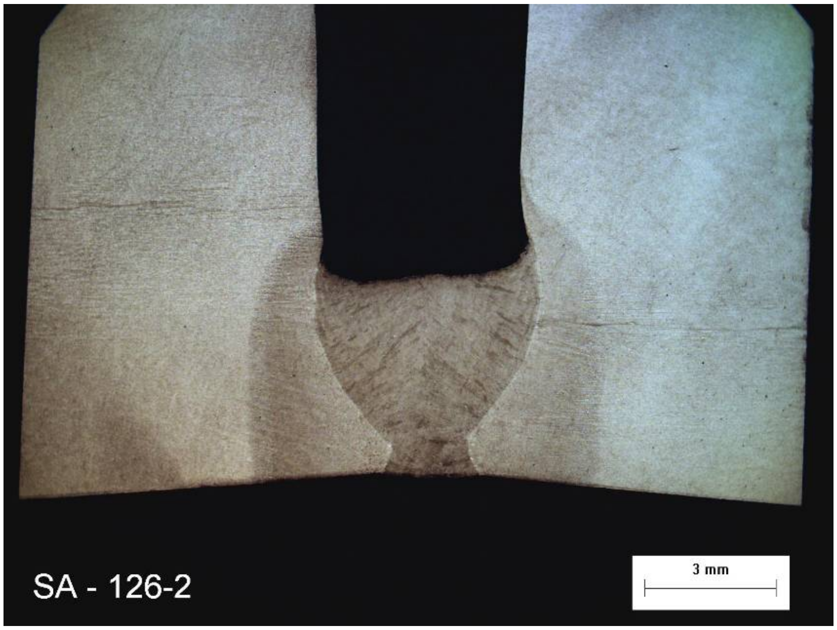


Figure 62. **Macrosection of Weld SA-126 Made with ER80S-D2 Wire in X80 Pipe in the Vertical-Down Position** (Wire feed speed/travel speed ratio: 12.9, travel speed: 0.7 m/min, throat thickness: 4.4 mm, magnification: 7×.)

Figure 63. **Macrosection of Weld SA-126 Made with ER80S-D2 Wire in X80 Pipe in the Vertical-Down Position** (Wire feed speed/travel speed ratio: 12.9, travel speed: 0.7 m/min, throat thickness: 4.2 mm, magnification: 7×.)

Figure 64. **Root Bead Penetration in X80 Pipe Section for Weld SA-129**

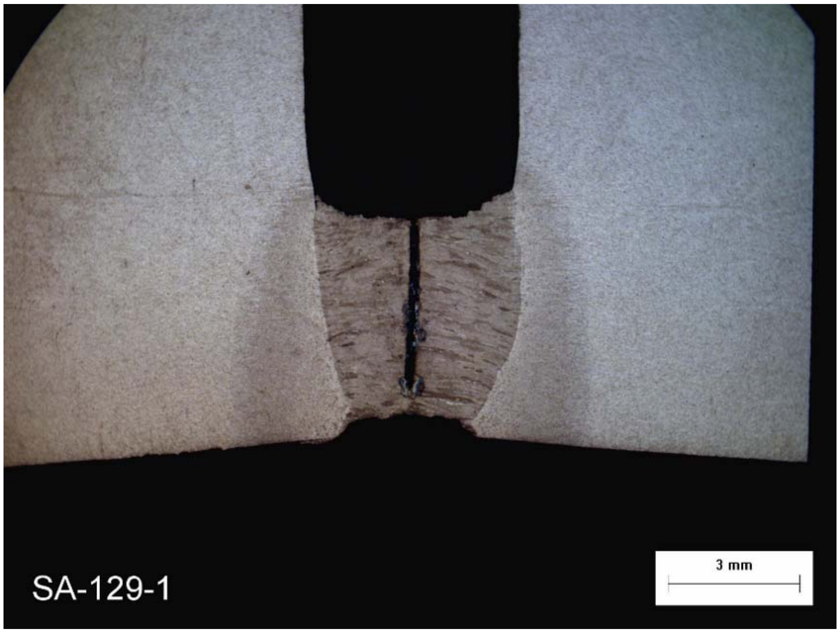


Figure 65. **Macrosection of Weld SA-129 Made with ER80S-D2 Wire in X80 Pipe in the Vertical-Down Position Showing an Open Solidification Crack** (Wire feed speed/travel speed ratio: 14.2 , travel speed: 0.8 m/min, throat thickness: 4.6 mm, magnification: 7×.)

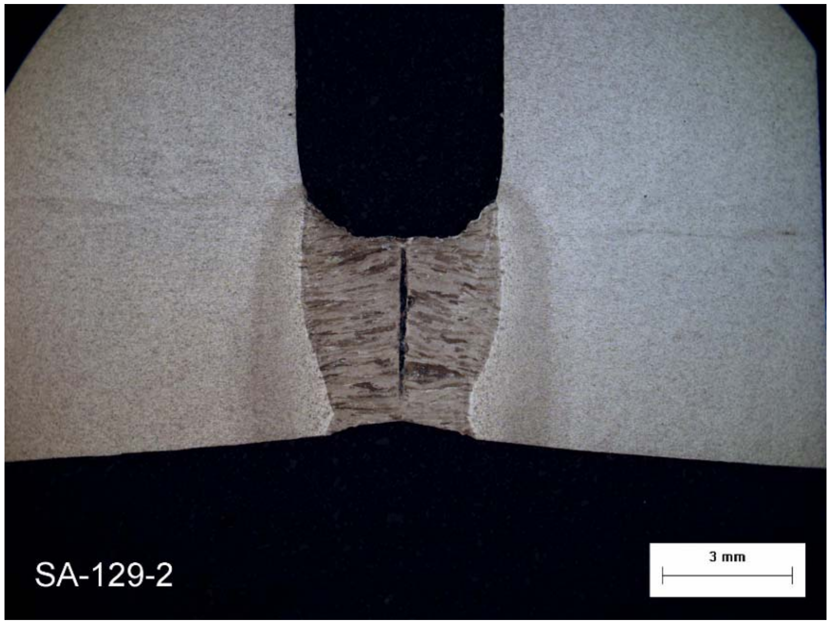


Figure 66. Macrosection of Weld SA-129 Made with ER80S-D2 Wire in X80 Pipe in the Vertical-Down Position Showing a Buried Solidification Crack (Wire feed speed/travel speed ratio: 14.2, travel speed: 0.8 m/min, throat thickness: 4.6 mm, magnification: 7×.)

Figure 67. Macrosection of Weld SA-137 Made with ER90S-G Wire in X80 Pipe in the Vertical-Down Position Showing Absence of Cracking (Wire feed speed/travel speed ratio: 11.9, travel speed: 1.2 m/min, throat thickness: 4.1 mm, magnification: 4×.)

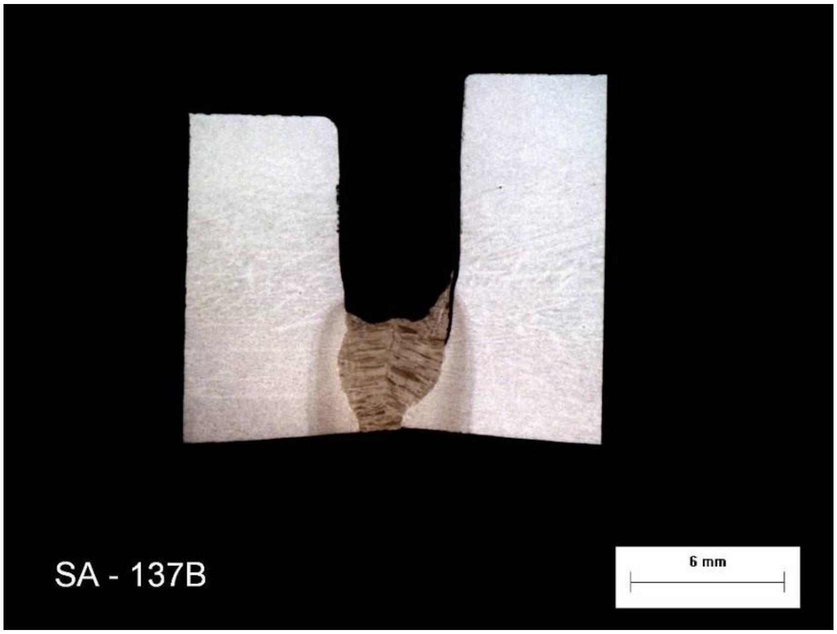


Figure 68. Second Macrosection of Weld SA-137 Made with ER90S-G Wire in X80 Pipe in the Vertical-Down Position Showing Absence of Cracking (Wire feed speed/travel speed ratio: 11.9 , travel speed: 1.2 m/min, throat thickness: 4.6 mm, magnification: 4×.)

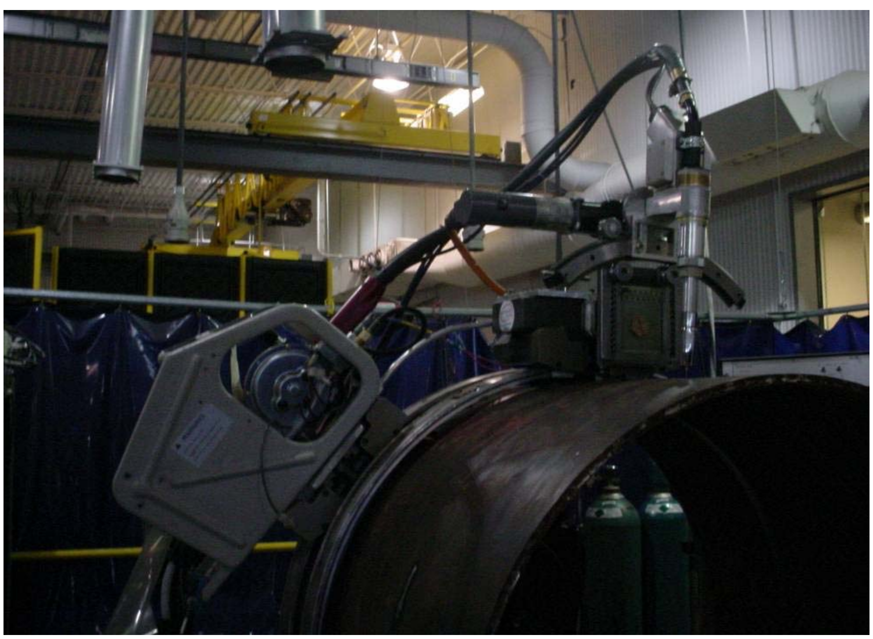


Figure 69. STX Tractor with Spin Arc Torch and Integrated Torch Travel Angle Control with Wire Feeder Carried on a Second Tractor and Band (the wire spool was at ground level)

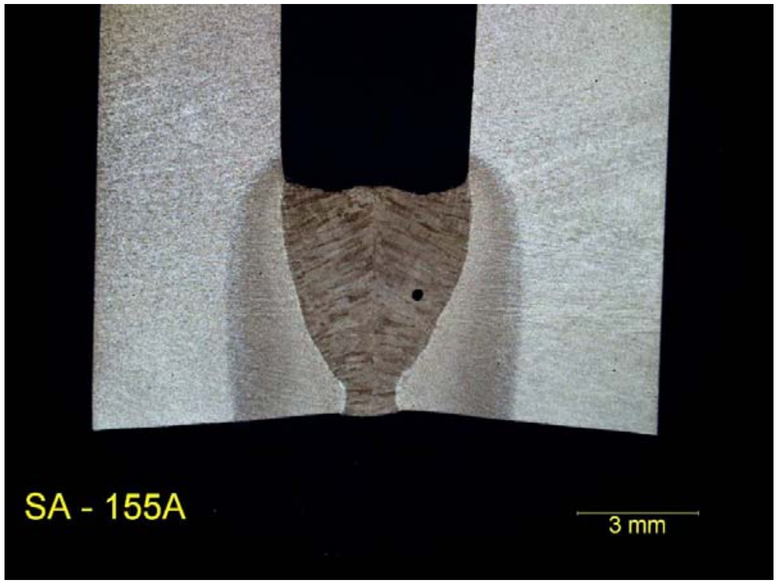


Figure 70. **Macrosection of Weld SA-155 Made with ER90S-G Wire in X80 Pipe in the Flat Position Showing Absence of Cracking** (Wire feed speed/travel speed ratio: 18.0 , travel speed: 0.7 m/min, throat thickness: 5.6 mm, magnification: 7×)

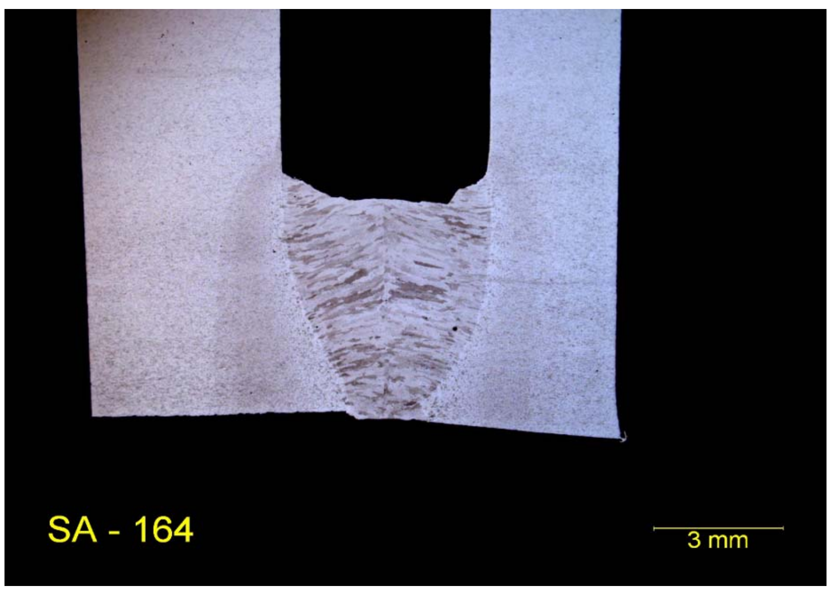


Figure 71. **Macrosection of Weld SA-164 Made with ER90S-G Wire in X80 Pipe in the Vertical-Down Position Showing Absence of Cracking** (Wire feed speed/travel speed ratio: 16.7, travel speed: 0.7 m/min, throat thickness: 5.0 mm, magnification: 7×.)

Figure 72. Root Bead Profile for 0.5 mm High/Low Root Mismatch

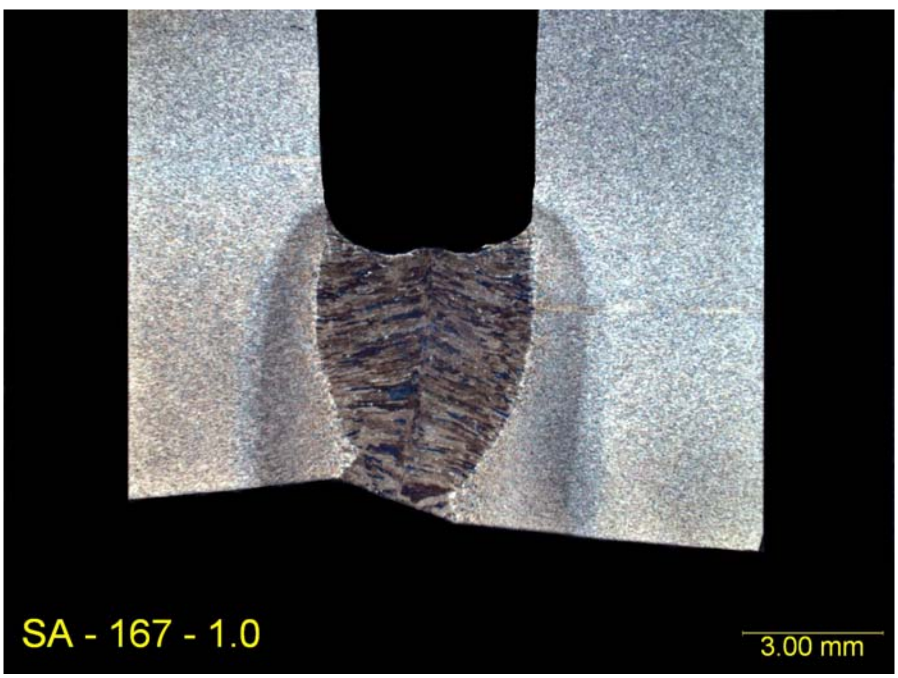


Figure 73. Macrosection Showing Fusion Profile and Root Bead Profile with 1.0 mm High/Low Root Mismatch

Figure 74. **Root Bead Profile for 1.5 mm High/Low Root Mismatch**

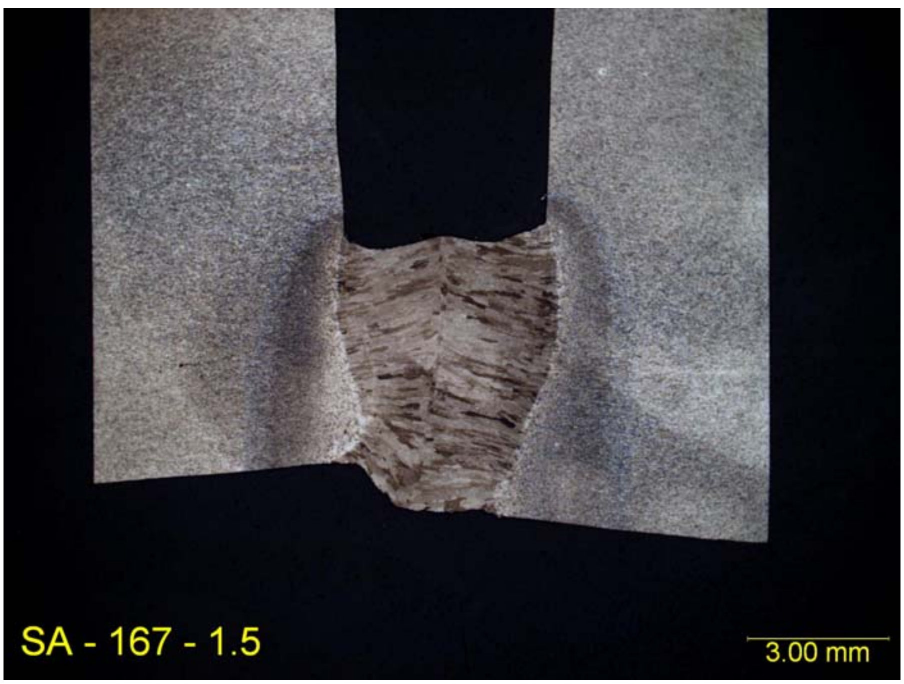


Figure 75. **Macrosection Showing Fusion Profile and Root Bead Profile with 1.5 mm High/Low Root Mismatch**

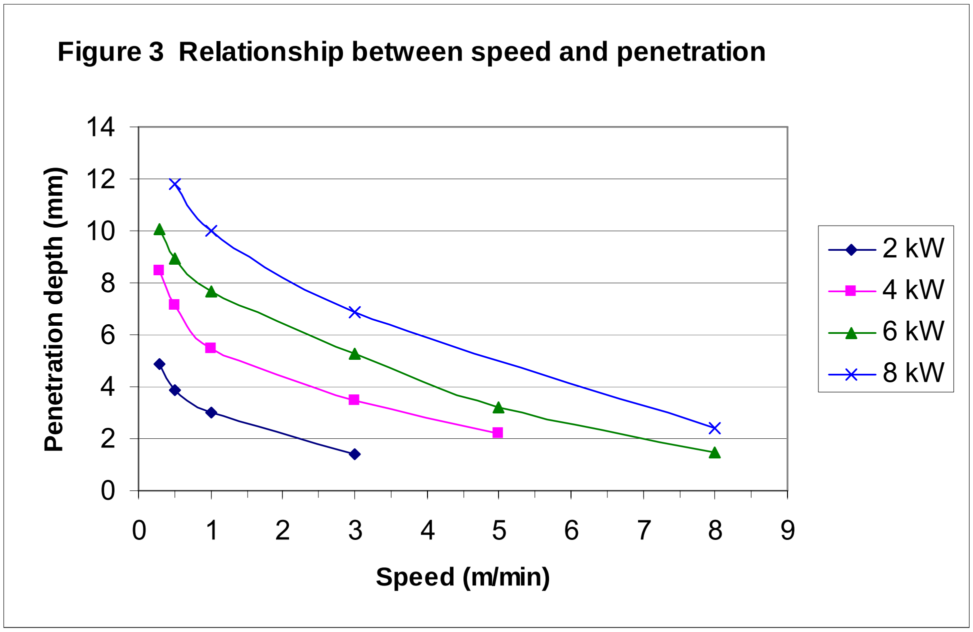


Figure 76. **Relationship Between Travel Speed and Laser Power for Various Fiber Laser Power Levels**

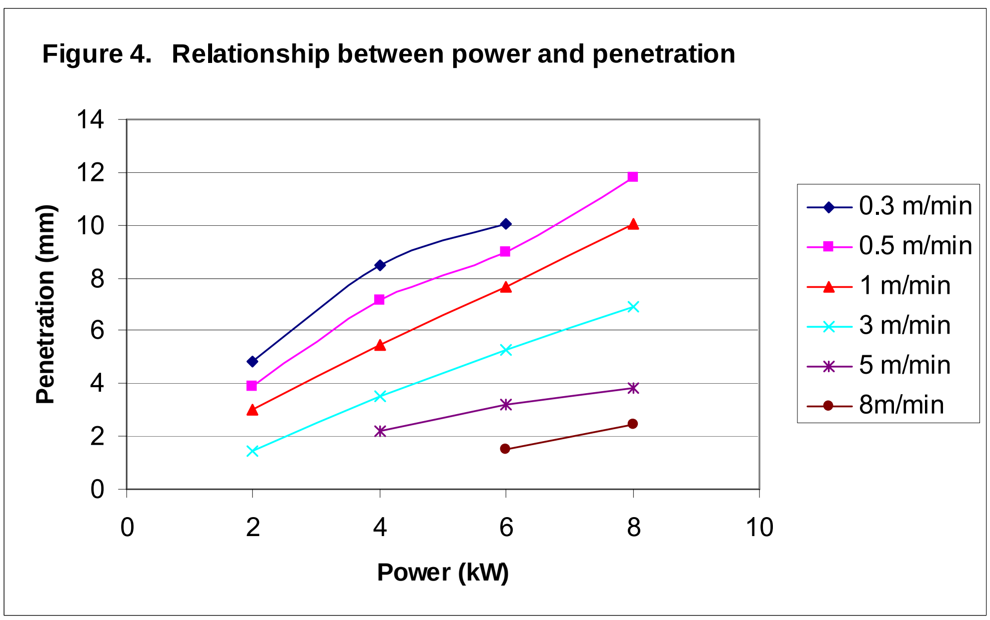
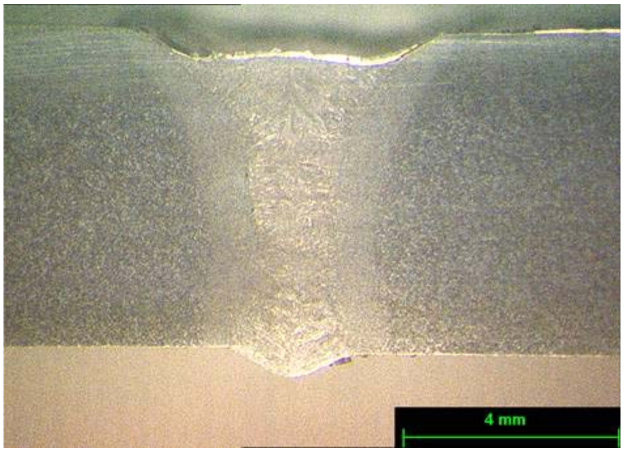
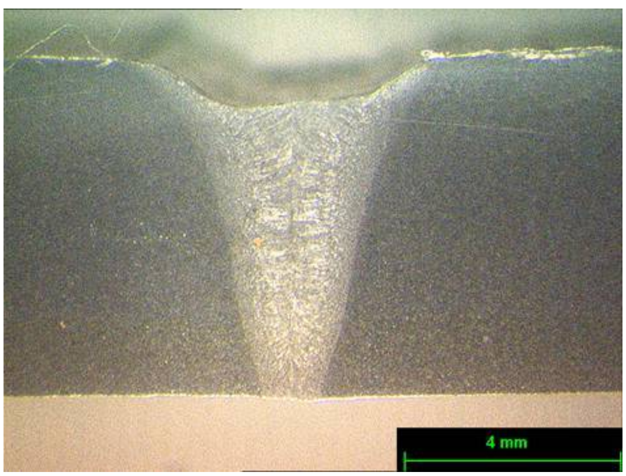


Figure 77. **Relationship Between Laser Power and Penetration Depth for Various Fiber Laser Power Levels**



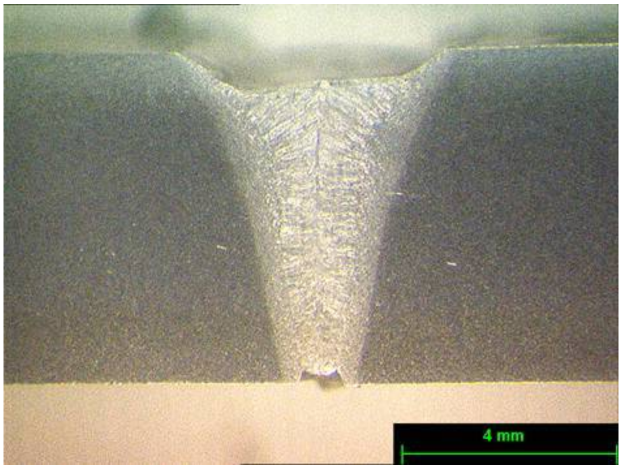
Laser power: 6.25 kW
Wire feed speed: 10 m/min
Arc current: 192 A
Arc voltage: 27.0 V
Bevel angle: 12 degrees
Root face: 1 mm
CTWD: 14 mm
Laser/arc distance: 2 mm

Figure 78. Travel Speed 2.5 m/min



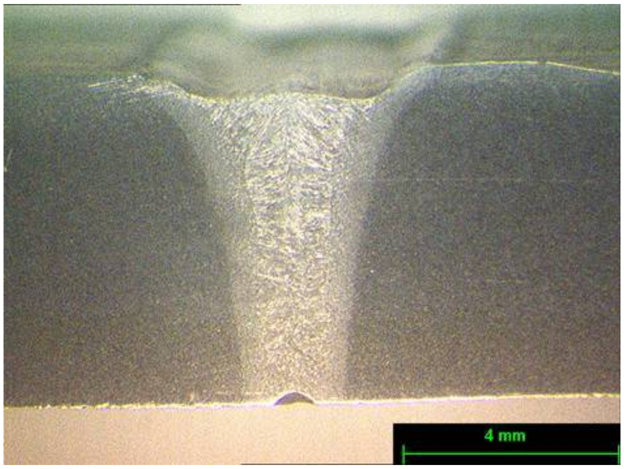
Laser power: 6.25 kW
Wire feed speed: 10 m/min
Arc current: 191 A
Arc voltage: 27.0 V
Bevel angle: 12 degrees
Root face: 1 mm
CTWD: 14 mm
Laser/arc distance: 2 mm

Figure 79. Travel Speed 4 m/min



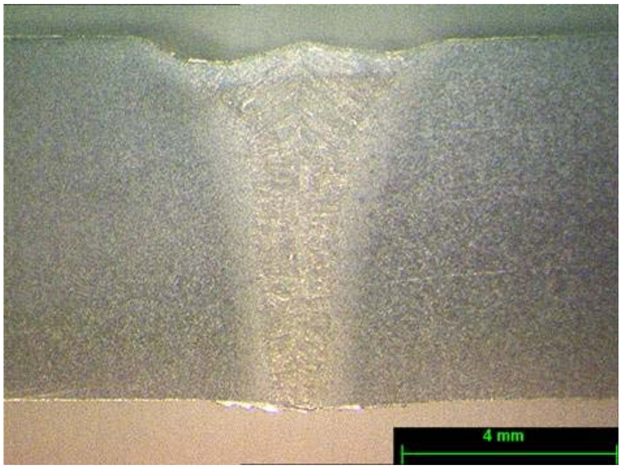
Travel speed: 4 m/min
Wire feed speed: 12.7 m/min
Arc current: 230 A
Arc voltage: 26.7 V
Bevel angle: 12 degrees
Root face: 1 mm
CTWD: 14 mm
Laser/arc distance: 2 mm

Figure 80. 6.25-kW Laser Power



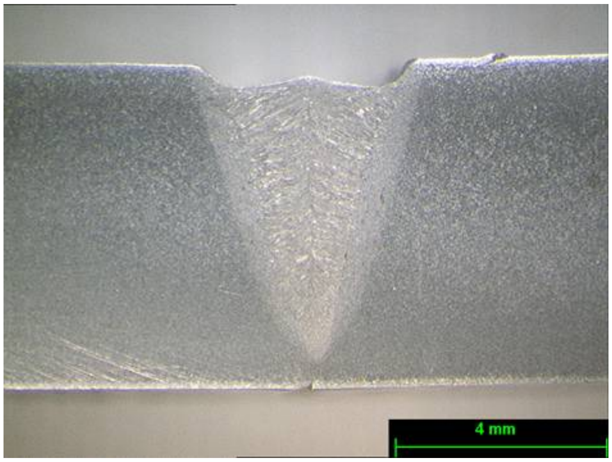
Travel speed: 4 m/min
Wire feed speed: 12.7 m/min
Arc current: 231 A
Arc voltage: 26.8 V
Bevel angle: 12 degrees
Root face: 1 mm
CTWD: 14 mm
Laser/arc distance: 2 mm

Figure 81. 6.50-kW Laser Power



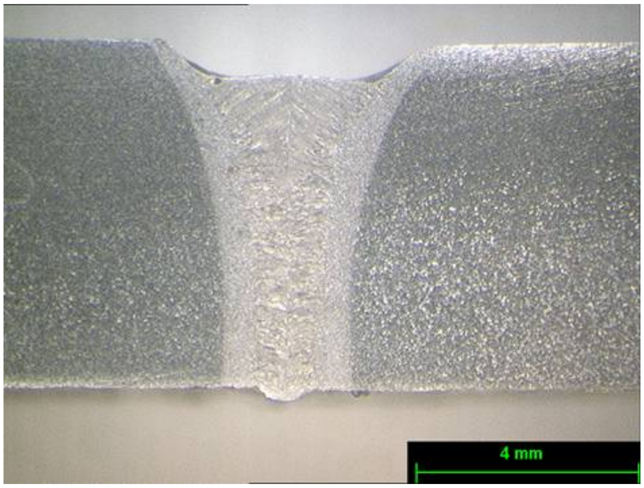
Travel speed: 4 m/min
Wire feed speed: 12.7 m/min
Arc current: 234 A
Arc voltage: 27.2 V
Bevel angle: 12 degrees
Root face: 1 mm
CTWD: 14 mm
Laser/arc distance: 2 mm

Figure 82. 6.75-kW Laser Power



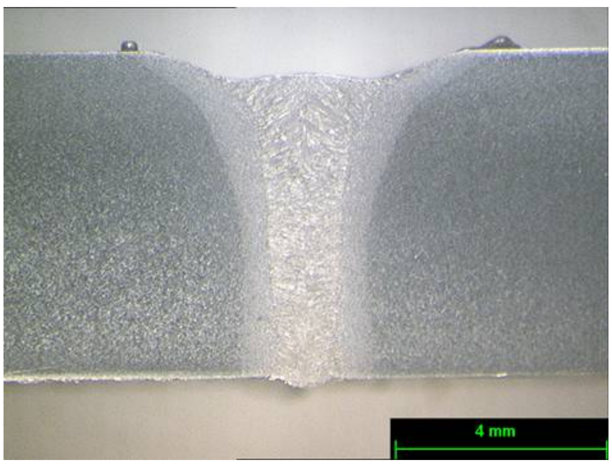
Laser power: 6.5 kW
Wire feed speed: 12.7 m/min
Arc current: 234 A
Arc voltage: 22.9 V
Bevel angle: 12 degrees
Root face: 1 mm
CTWD: 14 mm

Figure 83. 5-mm Laser – Arc Distance



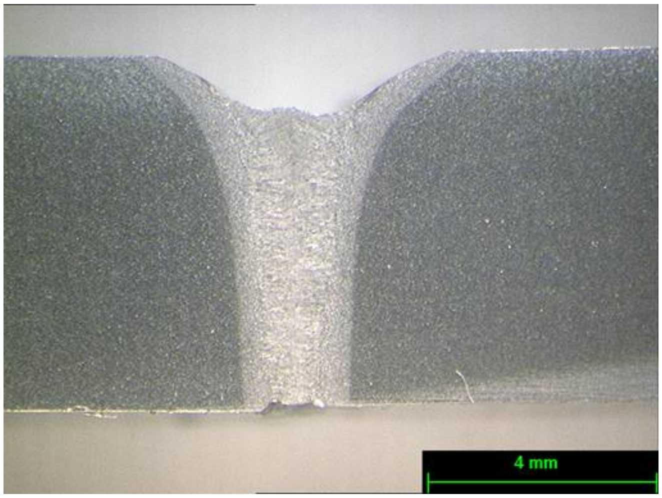
Laser power: 6.50 kW
Wire feed speed: 12.7 m/min
Arc current: 231 A
Arc voltage: 26.4 V
Bevel angle: 12 degrees
Root face: 1 mm
Laser/arc distance: 2 mm

Figure 84. 15-mm CTWD



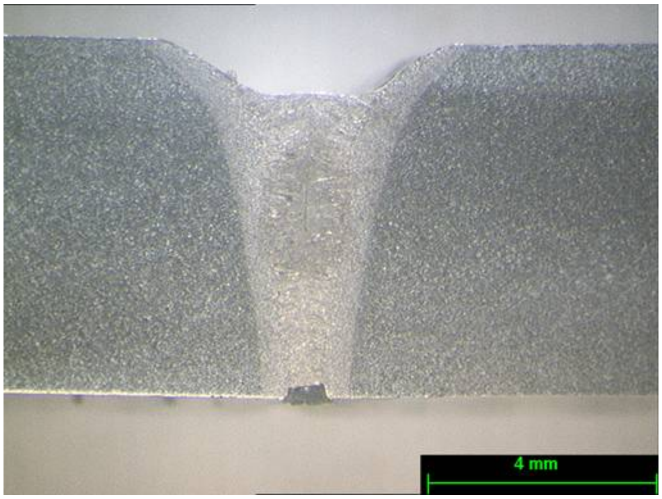
Laser power: 6.50 kW
Wire feed speed: 14 m/min
Arc current: 256 A
Arc voltage: 28.8 V
Bevel angle: 12 degrees
Root face: 1 mm
Laser/arc distance: 2 mm

Figure 85. 17-mm CTWD



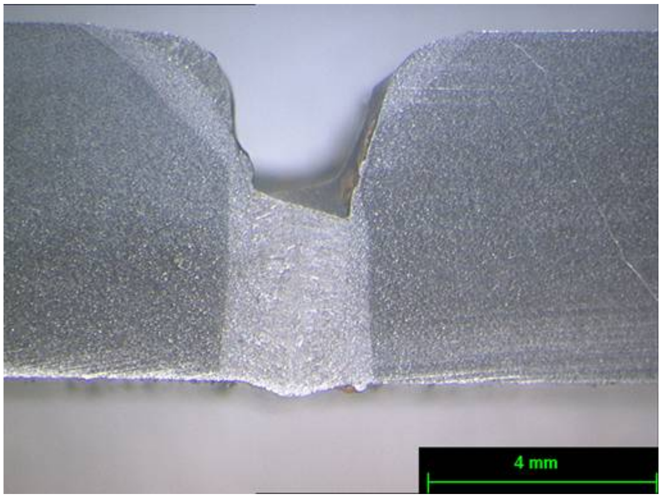
Wire feed speed: 10 m/min
Arc current: 193 A
Arc voltage: 26.2 V
CTWD: 14 mm
Laser/arc distance: 2 mm

**Figure 86.	12-Degree Bevel Angle, 0 Root Face, 5.5 kW**



Wire feed speed: 10 m/min
Arc current: 192 A
Arc voltage: 26.0 V
CTWD: 14 mm
Laser/arc distance: 2 mm

**Figure 87.	12-Degree Bevel Angle, 0 Root Face, 5 kW**



Wire feed speed: 14 m/min
Arc current: 245 A
Arc voltage: 30.4 V
CTWD: 14 mm
Laser/arc distance: 2 mm

Figure 88. 18-Degree Bevel Angle, 0 Root Face, 4.5 kW

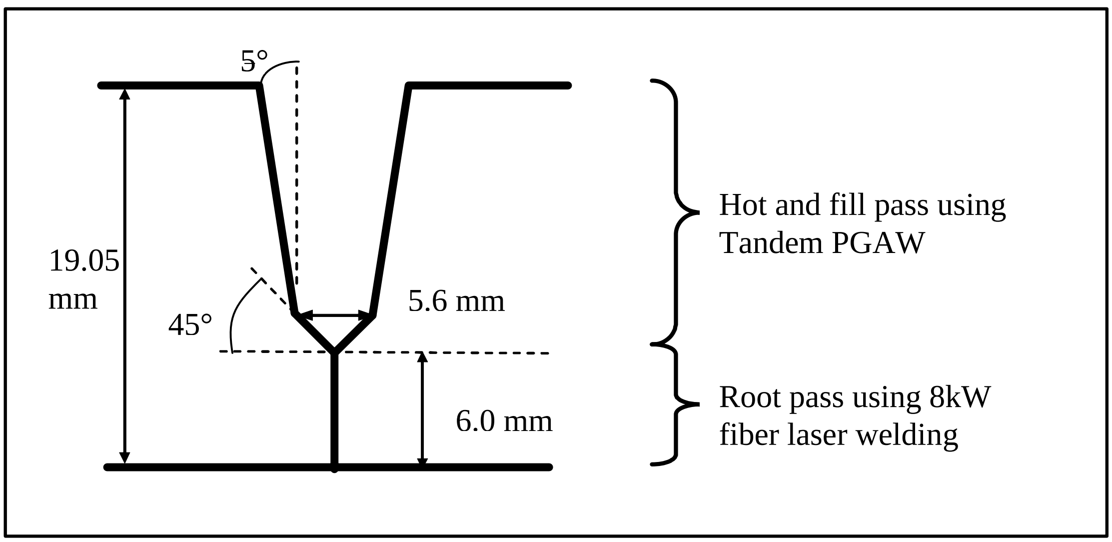


Figure 89. Weld Preparation for Laser Root Welds

Figure 90. Laser Root Weld Plus Tandem GMAW-P Fill