REPORT

April 28, 2006
EWI Project No. 47961GTH
DoT Transaction Agreement No. DTRS56-05-T-0001

Innovative Welding Processes for Small to Medium Diameter Gas Transmission Pipelines

Task 2 Report
Property Testing of Preferred Root Pass Welding Process

Submitted to:

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

EWI®

MATERIALS JOINING TECHNOLOGY

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on

Innovative Welding Processes for Small to Medium Diameter Gas Transmission Pipelines
Task 2 – Property Testing of Preferred Root Pass Welding Process

to

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Research and Special Programs Administration
Washington, D.C.

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Executive Summary

Pipelines play a key role in energy distribution and major new investments in pipelines will continue for the next two decades. Productivity and quality of pipeline root runs is critical to pipeline installation and determines the rate at which a pipeline installation can progress. Current technologies for large-diameter pipe are mostly based on use of an internal welding machine, which has to be combined with the clamp that holds the pipes together in preparation for welding. For small- to intermediate-diameter pipe lines, manual welding is often used, and it is often necessary to use a copper backing bar combined with the welding clamp.

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.

The intent of this project is to evaluate the use of innovative welding techniques for pipeline root welding. There have been significant advances in welding processes over the last 10 years, with the introduction of several variants of the gas metal arc welding (GMAW) process, made possible by the adoption of microprocessor control of welding power supplies. In addition, there have been major advances in laser welding technology, with the introduction of high power, high efficiency fiber lasers, and with the development of combined laser/arc hybrid welding.

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 and results achieved in Task 2 – Property Testing of Preferred Root Pass Welding. The objective of Task 2 was to use one of the laser/laser hybrid root welding procedures developed in Task 1 of the project as a basis for making complete welds in high-strength pipeline steel.

The results indicated that welds made with laser root and tandem GMAW fill were of excellent quality and have very good strength and toughness properties.

The main conclusions were as follows:

1. Laser and laser hybrid root welds can be made with excellent weld quality and surface profile, together with very high productivity in X100 pipe material. Welds can be made with a 6-mm root throat thickness at 1.5 m/min and with a 4-mm throat thickness at 4 m/min.

2. Mechanical property measurements all gave acceptable results: the tensile and hardness results were acceptable, high Charpy toughness value were recorded at -18°C, and both nick-break and bend tests indicated acceptable ductility.

3. Four GMAW tandem fill passes were necessary to fill the 19.5-mm-thick joint. Each fill pass achieved a deposition rate of 10.8 kg/hr (23.7 lb/hr).

Based on the conclusions above, the following recommendations can be made:

1. The use of laser root passes was shown to produce acceptable mechanical properties in X100 pipe material and can be extrapolated to X80 pipe. A 4-mm root face and a 4-m/min travel speed is recommended since one laser would be used to make the root pass, equivalent to 2-m/min travel speed with a two torch “double-down” procedure currently employed.

2. The economic case for using an 8-kW fiber laser and associated equipment versus the case for two rotating electrode GMAW (GMAW-RE) torches for the root pass needs to be evaluated. This will be done within Task 7 of this project.

Acknowledgements

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Legal Notice

1.0 Introduction

Pipelines play a key role in energy distribution and major new investments in pipelines will continue for the next two decades. The state of the art for pipeline welding is based on mechanized gas metal arc welding (GMAW), but application of this process has seen little innovation since its introduction in the 1970s. In particular, a very limited range of welding technologies are currently available for welding the pipeline root run. This is in spite of the fact that the productivity and quality of pipeline root runs is critical to pipeline installation and determines the rate at which a pipeline installation can progress. Current technologies for large-diameter pipe are mostly based on use of an internal welding machine, which has to be combined with the clamp that holds the pipes together in preparation for welding. For small- to medium-diameter pipe lines, manual welding is often used, and it is often necessary to use a copper backing bar combined with the welding clamp.

2.0 Technical Background

The intent of this project is to evaluate the use of innovative welding techniques for pipeline root welding. There have been significant advances in welding processes over the last 10 years, with the introduction of several variants of the GMAW process, made possible by the adoption of microprocessor control of welding power supplies. In addition, there have been major advances in laser welding technology, with the introduction of high-power, high-efficiency fiber lasers, and with the development of combined laser/arc hybrid welding.

The project is broken down into the following tasks:

- Task 1 – Development of Innovative Root Pass Welding Processes
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This report addresses the technical approach and results achieved in Task 2 – Property Testing of Preferred Root Pass Welding.

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.

2.1 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.

2.2 Results Achieved in Task 1

Task 1 achieved a major step forward in of laser/laser hybrid welding of pipe root runs. Pipe root welds were made over a wide range of weld preparation designs:

- Weld preparation angles: 12, 18, 45 degrees
- Root face thickness: 0, 1, 2, 6 mm
- Laser power: 4 to 8 kW

The main conclusions of Task 1 with respect to laser and laser/GMAW hybrid full-penetration root welds can be summarized as follows:

- 18-degree preparation angle, 0-mm root face – welding speed of 4 m/min at 4-kW laser power.
- 12-degree preparation angle, 1-mm root face – welding speed of 4 m/min at 5-kW laser 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.

In all cases, the welds were essentially defect free with no cracks and very few small inter-run defects.

These results are very significant in terms of their potential application to pipeline welding. Very high welding speeds of 1.5 m/min can be achieved with a large value of root face (up to 8 mm). This outcome is desirable, since a high thickness root run reduces the number of subsequent fill passes. Extremely high weld speeds of 4 m/min can be achieved for low values of root face (0 and 1 mm).

To put these results in perspective, note that the time taken for a complete root run with one laser in a 24-in.-diameter pipe would be 77 sec at 1.5 m/min and 29 sec at 4 m/min. These values easily exceed those required to achieve optimum performance. A fixed time is necessary to attach, align, and clamp a new section of pipe for welding, typically 2 to 3 min and hence any welding speed in excess of 1.5 m/min will provide high productivity.

3.0 Objectives

The overall project objective is development of 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 GMAW fill pass techniques. Advanced automation techniques will be used to improve weld quality, process control, seam tracking, and robustness.

The objective of Task 2 (Property Testing of Preferred Root Pass Welding Process) is to use one of the laser/laser hybrid root welding procedures developed in Task 1 of the project as a basis for making complete welds in high-strength pipeline steel.

4.0 Equipment and Experimental Procedures

The laser equipment used was as follows:

- IPG Ytterbium Fiber laser: YLR 8000
- Wavelength: 1070 nm
- Work fiber: 20-m long, 300-μm diameter
- Precitec welding head: 250-mm focal length
- Beam quality: 15.8-mm radius.

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

Welds were made in the flat position, on X100 plate material, 19.5-mm thick, in plates 240-mm long × 140-mm wide, to produce a welded plate sample 240 × 280 mm. X100 pipe material was used as an alternative to the X80 material originally proposed because of material supply problems. However, the use of X100 provides a more stringent test of the application of laser and laser hybrid welding and the results are directly applicable to X80 pipe material. The weld preparation used had a 6-mm root face and 45-degree initial preparation angle, as shown in Table 8.

Laser root welds were made at 8-kW laser power and a 1.5-m/min welding speed at 100°C preheat. Four plate samples were welded with the tandem GMAW process, using four passes to complete the weld in each case. Full details of the welding parameters used are given in Table 8. A constant preheat of 100°C was used and the start temperature was controlled to be 100°C before each pass.

Four commercial solid wires, 1.0-mm diameter, were used to complete the welds:

- Lincoln SuperArc LA 100
- Bohler Tyyssen Union MoNi
- Oerlikon Carbofil NiMo1
- Bohler X70-1G.

Completed welds were sectioned for metallography and mechanical property tests.

5.0 Results

Macrographs of the completed welds are shown in Figures 1 through 4. High-quality welds were produced in every case, with no cracks, and only one instance of an inter-run discontinuity. This discontinuity (in Figure 2) was less than 100 μm in width and was not detectable by nondestructive evaluation (NDE). The decision was taken not to perform inter-run cleaning for these welds, and hence silica islands formed on the surface of the weld metal, and were likely to lead to some inter-run defects. From the macros that very flat root weld beads were achieved. The laser root weld was in excess of 6-mm thick on completion, but about half of the laser weld has been consumed by the first (tandem) pass, leaving between 3 and 4 mm of the original laser weld.

The Charpy V-notch was located in this area so that the laser root weld could have some influence on the measurement of toughness. A high welding speed of 1.5 mm/min was chosen for the tandem fill pass welds. The GMAW fill passes were made under very similar conditions with no change in wire feed speed from pass to pass. However, the oscillation width was increased from 2.4 mm for the first pass, to 3.2 mm for the final pass, to achieve adequate wetting and sidewall penetration. Lack of sidewall fusion is the most common defect in GMAW narrow-groove welding, but no instance of this occurred in the four test welds.

The results of hardness scans taken 10 mm below the top surface are shown in Tables 1 through 4. The results were in general fairly similar and exhibited desirable hardness values. There was no softening in the heat-affected zone (HAZ) and the weld metal hardness was greater than the pipe or HAZ hardness. For three of the welds, the peak weld metal hardness was in the range of 330 to 350 HVN, which provided an acceptable increment of hardness for the weld compared to the pipe. This is a requirement for strain-based design. In one case, L1, the weld metal peak hardness was about 300 HVN, which still provided an increment of hardness of 20% over the parent metal hardness of 240/260 HVN.

Laser root weld hardness was measured for two welds, L3 and L4, as shown in Tables 5 and 6. In both cases the laser root weld metal hardness was in the range 260 to 280 HVN, slightly harder than the parent metal. This is also acceptable, since the remaining laser root after the fill passes does not make a major contribution to the weld strength, and a slightly weaker root is much preferred to a very hard root.

As would be expected from these results, the cross-weld tensile tests all failed in the parent material, with a ultimate tensile strength (UTS) of 785 N/mm^2, as shown in Table 7. This value of course represents the parent material strength.

Excellent Charpy results were obtained in the range of 180 to 250 J at -18°C. There were some variations in energy absorbed, but these were to be expected, since the values obtained can be strongly influenced by the precise position of the Charpy notch. However, all the values obtained indicated high toughness from these welds. By placing the notch in the laser root weld metal, some influence of the laser weld metal properties was expected. These results indicated the toughness of the weld was not diminished by the laser root weld metal.

Side bend tests and nick-break tests were conducted in accordance with the requirements of API 1104. In all case the results were satisfactory, indicating an acceptable level of ductility in these welds.

6.0 Discussion

Previous work on fill pass welding using a small root face resulted in satisfactory welding, with a root run throat thickness of about 4 mm. However, the first GMAW fill pass (the “hot pass”) penetrated through most of the laser weld. As a result, very little of the laser weld remained in the final completed weld. Hence for Task 2, a high root face thickness of 6 mm was chosen, so that at least some of the laser weld would remain, and would be capable of influencing the mechanical property tests of the completed weld. This also allowed the weld to be completed in 19.5-mm pipe material in only four passes using the tandem GMAW process. The overall deposition rate of the process is high at 10.8 kg/hr (23.7 lb/hr).

Laser and laser hybrid root welds can be made with excellent weld quality and surface profile, together with very high productivity in X100 pipe material. Welds can be made with a 6-mm root throat thickness at 1.5 m/min and with a 4-mm throat thickness at 4 m/min. These welding speeds easily exceed the requirement for high productivity root welding, corresponding to a total root welding time of 77 and 29 sec, respectively, for a single laser head welding the root of a 24-in. pipe. This would equate to 116 and 44 sec, respectively, for a 36-in.-diameter X80 pipe.

Mechanical property measurements all gave acceptable results: the tensile and hardness results were in the desired range, high Charpy toughness value were recorded at -18°C, and nick-break and bend tests indicated acceptable ductility. Hardness within the laser root was also acceptable and location of the Charpy notch in the laser root weld metal provided high values of toughness.

Only four GMAW tandem fill passes were necessary to fill the 19.5-mm-thick joint, reflecting both the high productivity of the tandem narrow groove process, and the benefit of using the high throat thickness laser weld to minimize the number of subsequent passes. Each fill pass achieved a deposition rate of 10.8 kg/hr (23.7 lb/hr).

7.0 Conclusions

This work indicates that welds made with laser root and tandem GMAW fill were of excellent quality and have very good strength and toughness properties.

The main conclusions are as follows:

1. Laser and laser hybrid root welds can be made with excellent weld quality and surface profile, together with very high productivity in X100 pipe material. Welds can be made with a 6-mm root face thickness at 1.5 m/min and with a 4-mm root face thickness at 4 m/min.

2. Mechanical property measurements all gave acceptable results: the tensile and hardness results were acceptable, high Charpy toughness value were recorded at -18°C, and both nick-break and bend tests indicated acceptable ductility.

3. Four GMAW tandem fill passes were necessary to fill the 19.5-mm-thick joint. Each fill pass achieved a deposition rate of 10.8 kg/hr (23.7 lb/hr).

8.0 Recommendations

Based on the conclusions above, the following recommendations can be made:

1. The use of laser root passes was shown to produce acceptable mechanical properties in X100 pipe material and can be extrapolated to X80 pipe. A 4-mm root face and a 4-m/min travel speed is recommended since one laser would be used to make the root pass, equivalent to 2-m/min travel speed with a two torch "double-down" procedure currently employed.

2. The economic case for using an 8-kW fiber laser and associated equipment versus the case for two GMAW-RE torches for the root pass needs to be evaluated. This will be done within Task 7 of this project.

9.0 Future Work

The laser and laser/GMAW hybrid processes were used only in the 1G position so the following needs to be accomplished in future work:

- Develop parameters for 5G welding by first welding in the vertical-down, vertical-up, and overhead positions.

- Demonstrate the ability to refine welding parameters for 5G welding of pipe.

Table 1. **L1 Vickers Hardness** (10 mm from top surface)

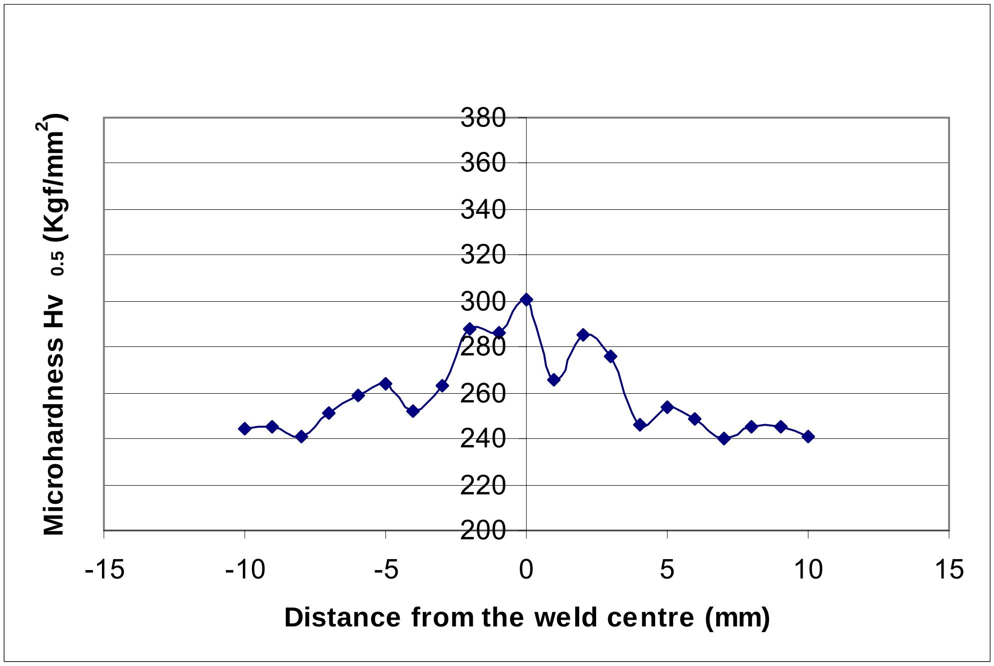


Table 2. **L2 Vickers Hardness** (10 mm from top surface)

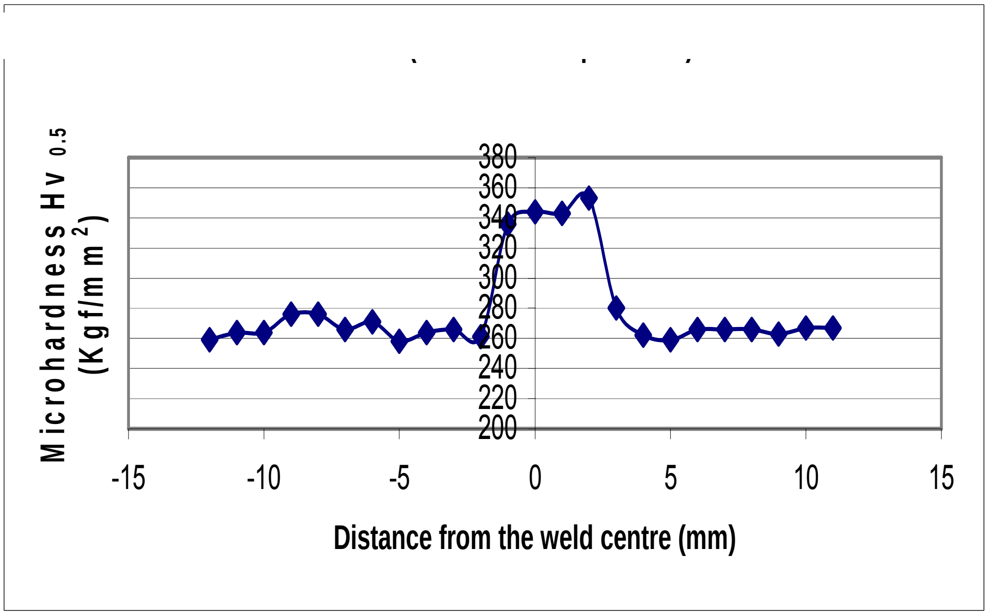


Table 3. **L3 Vickers Hardness** (10 mm from top surface)

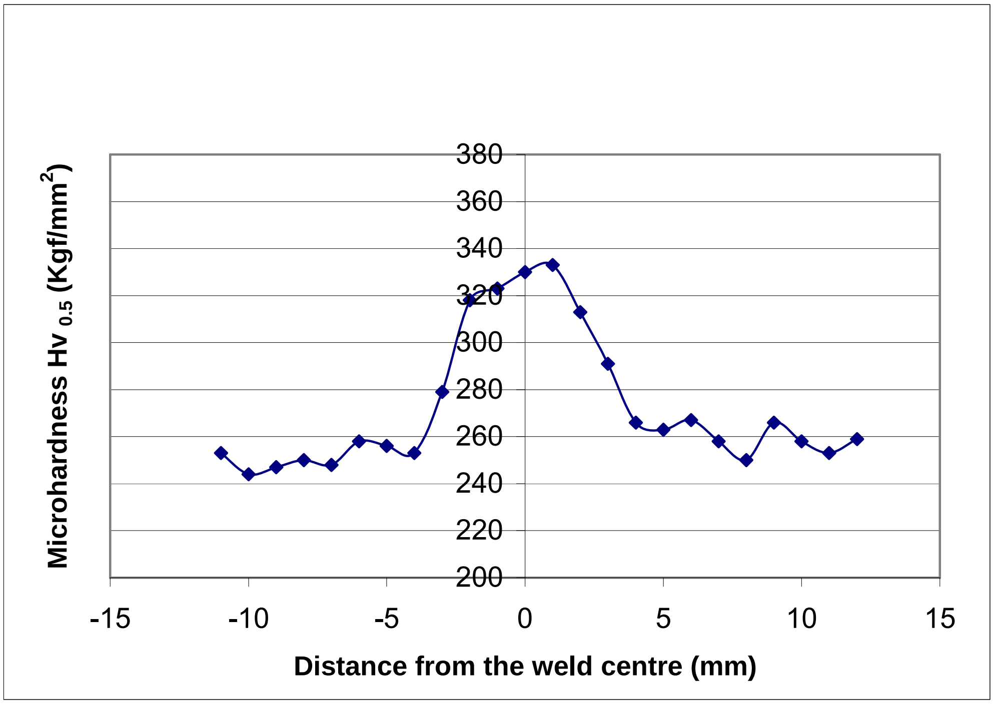


Table 4. **L4 Vickers Hardness (10 mm from top surface)**

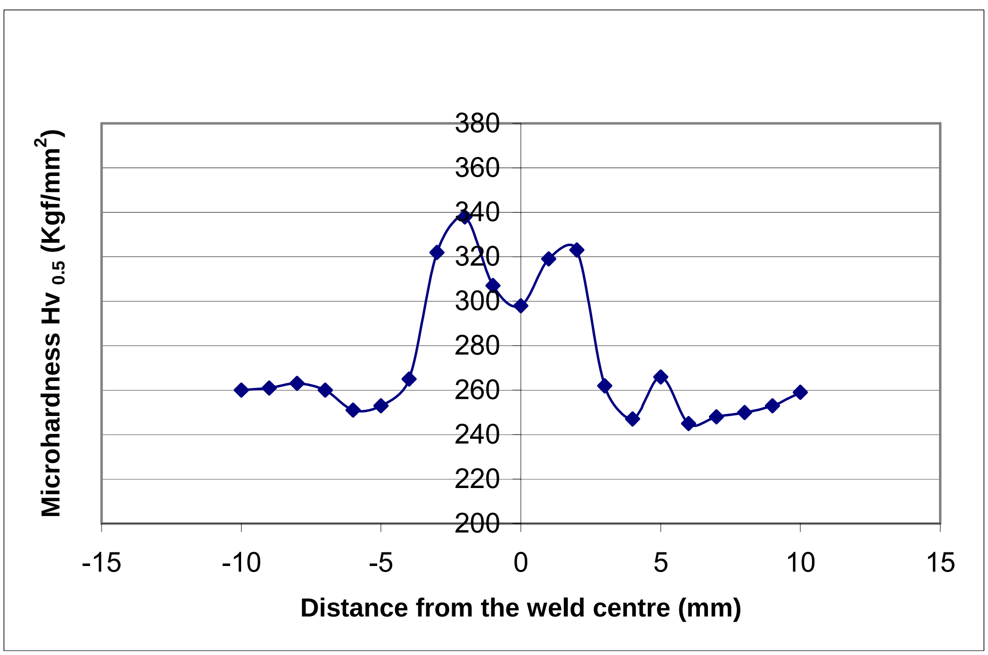


Table 5. **L2 Vickers Hardness** (2 mm from bottom in laser root)

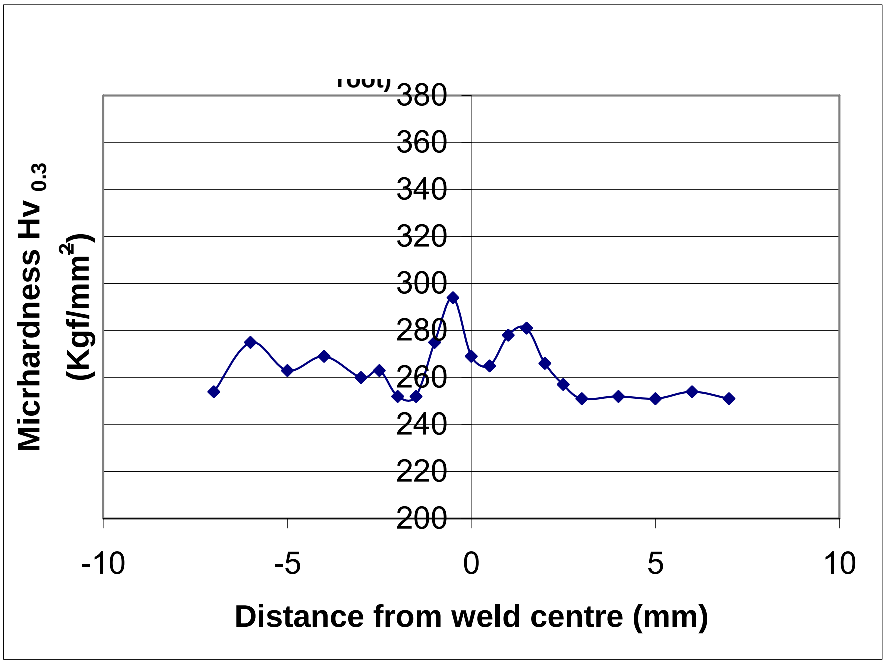


Table 6. **L3 Vickers Hardness** (2 mm from bottom in laser root)

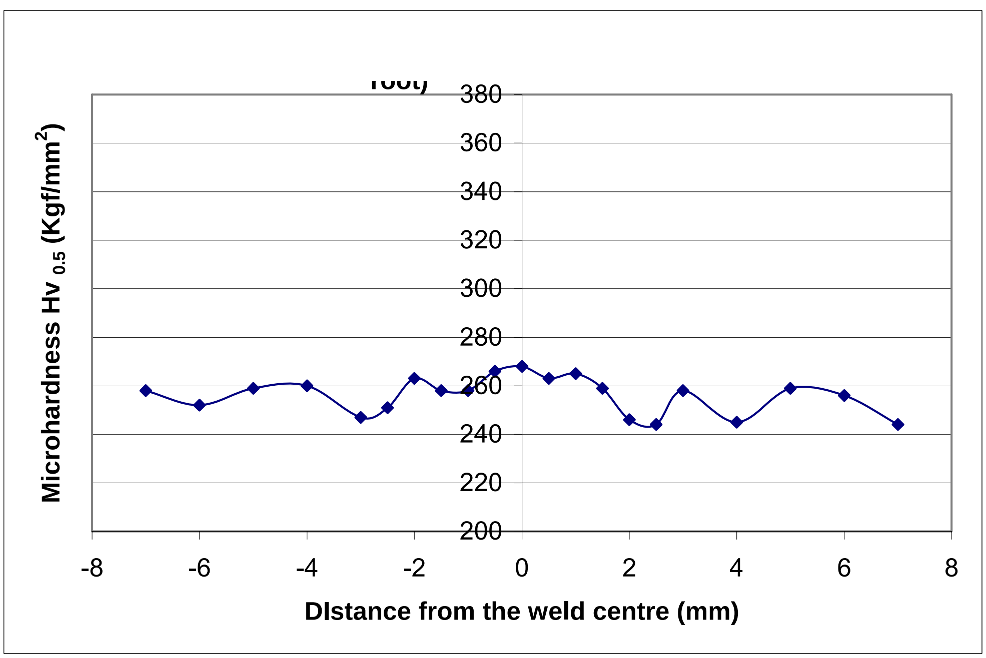


Table 7. Mechanical Properties

Test Sample	UTS N/mm^2	Charpy Test, EN875, Average of 3 Tests, Energy Absorbed, Joules at -18°C		Side bend Test API 1104	Fracture Test (Nick-Break) API 1104
		Weld Root	Weld Fusion Line		
L1	785	207	257	Acceptable	Acceptable
L2	779	219	231	Acceptable	Acceptable
L3	785	238	245	Acceptable	Acceptable
L4	783	181	240	Acceptable	Acceptable

Table 8. Laser/GMA Welding Parameter Record

Cranfield UNIVERSITY — **As-run Parameter Record**

Weld No.: L1,L2,L3,L4

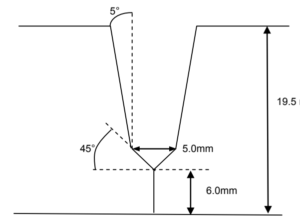
Date: 25/11/2001

Description:
Laser weld Root
X100 Tandem Wire Weld

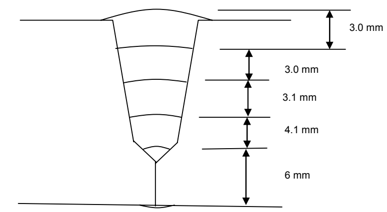
Welders Name
John Savill

Material Grade: X100
Type: Plate
Thickness: 19.5 mm
Welding Position: Flat
Preparation Method: Machined
Preheat Method: Propane
Preheat temperature: 100°C
Backing System: N/A
Inter run Cleaning Method: None

Joint Preparation:



Run Sequence:



Pass	Process	Shielding Gas Type	Flow L/min	Temp @ Start °C	Lead WFS m/min	Amps I	Volts V	Trail WFS m/min	Amps I	Volts V	Osc Width mm	Osc Frequency Hz	CTWD mm	Travel Speed m/min	Laser Power kW	Laser Energy kJ/mm	Arc Power kW	Arc Energy kJ/min
Ext root	Laser	82.5%Ar/ 12.5%CO2/ 5%He	20	100							-			1.5	8.0	0.32	-	-
1	PGMAW	82.5%Ar/ 12.5%CO2/ 5%He	20	100	14.50	233	21.4	14.50	233	21.5	2.40	10	13.5	1.5	-	-	10.00	0.40
2	PGMAW	82.5%Ar/ 12.5%CO2/ 5%He	20	100	14.50	233	21.4	14.50	233	22.5	2.70	10	13.5	1.5	-	-	10.23	0.41
3	PGMAW	82.5%Ar/ 12.5%CO2/ 5%He	20	100	14.50	233	21.4	14.50	233	22.5	2.90	10	13.5	1.5	-	-	10.23	0.41
4	PGMAW	82.5%Ar/ 12.5%CO2/ 5%He	20	100	14.50	233	21.7	14.50	233	23	3.20	10	13.5	1.5	-	-	10.42	0.42

Additional Data:
Dual Lincoln 455R Synchonised Power supplies, 180° antiphase

Weld Number	Consumable	Dia, mm
L1	Lincoln SuperArc LA 100	1.0
L2	Bohler Tyyssen Union MoNi	1.0
L3	Oerlikon Carbofil NiMo1	1.0
L3	Bohler X70-1G	1.0

Figure 1. **L1 Macro** (No visible defects, flat root bead, 3.4 mm of laser weld remains after hot pass.)

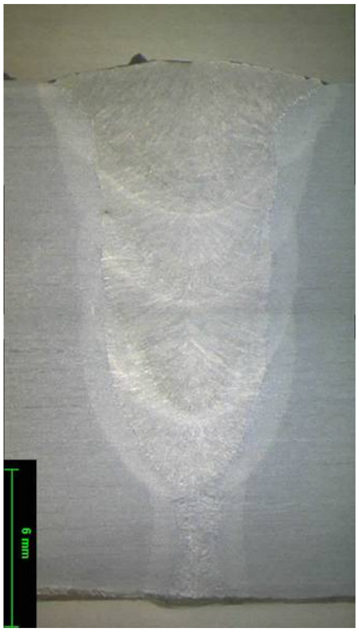


Figure 2. **L2 Macro** [One small defect visible between Runs 3 and 4 (not detecbale by NDE) proably due to silica formation. (Inter run cleaning not used.) Flat root bead.]

Figure 3. **L3 Macro** (No visible defects, flat root bead.)

Figure 4. **L4 Macro** (No visible defects, flat root bead.)