ACHIEVING TOUGHNESS IN P91 WELDS FROM ROOT TO CAP USING SEMIAUTOMATIC HIGH DEPOSITION METAL TRANSFER (HDMT) GTAW WELDING PROCESS

Charles W. "Pat" Patrick
Scott Witkowski
Brad Berglan
Ramon Solo
Jose Leza
Sammy Lloyd
ALS Maverick Testing Laboratories, Inc.
10001 Porter Road, Suite 100
La Porte, Texas 77571

William F. Newell, Jr., PE, PEng, IWE
Euroweld, Ltd.
255 Rolling Hills Road
Mooresville, NC 28117

Juvenal Calvo
TiP TiG USA, LLC
155 E 9th Avenue
Runnemede, New Jersey 08028

ABSTRACT

Welding of Grade 91 (9Cr-1Mo-V) chromium-molybdenum steel has presented numerous challenges since its introduction in the 1970s. The gas tungsten-arc (GTAW) process can produce welds of high quality; however, manual welding can be expensive and labor intensive, requiring skilled welders with extreme hand-eye coordination and dexterity. Grade 91 productivity can be increased in either shop or field fabrication by introducing a semiautomatic high deposition metal transfer (HDMT) GTAW welding process that combines controlled excitation of wire with a hot wire addition. This technique is cost effective and can be used for the entire weld from root to cap while producing high quality welds that industry expects from the GTAW process.

Power piping systems using Grade 91 materials that are designed, fabricated and installed in accordance with ASME Section I [1] and B31.1 [2] do not have minimum toughness rules. Some Owners and designers do, however, often impose minimum toughness requirements. Since Grade 91 was introduced over 50 years ago, no failure due to toughness of a properly post weld heat treated (PWHT'd) Grade 91 weldment has been reported.

The reasons for the low impact values of weld metal produced by some semiautomatic hot wire processes can be attributed to the inability to temper previously deposited weld beads due to the larger weld metal bead or layer thickness. The dynamics of the weld pool during deposition and the heat flow during solidification play an important role in the resulting mechanical properties of the weld metal. The principal difference is simply the manner in which the wire is aggressively manipulated while introduced into the weld puddle and the fact that the wire is preheated by a secondary current (producing the hot wire feed) while providing a dynamic weld pool.

Results of this study indicate that semiautomatic HDMT GTAW welding process is capable of producing toughness values comparable to or exceeding manual GTAW and that the process provides an attractive alternative for welding P91 root and hot passes or the entire weld from root to cap.

1.0 INTRODUCTION

Welding of Grade 91 (9Cr-1Mo-V) chromium-molybdenum steel has presented numerous challenges since its introduction in the 1970s. One of the principal challenges has been selection of the optimal welding process. For single-sided-groove welds, the root bead and hot pass(es), are typically deposited using the manual Gas Tungsten-Arc Welding (GTAW) process with an inert gas purge (most commonly argon), followed by another welding process(es) for completion of the weld. It goes without saying, that the GTAW process can produce welds of high quality; however, manual welding can be extremely expensive and labor intensive, requiring skilled welders with extreme hand eye coordination and dexterity yielding only 0.5 lbs/hr (0.23 kg/hr).

Power piping systems using Grade 91 materials that are designed, fabricated and installed in accordance with ASME Section I [1] and B31.1 [2] do not have minimum toughness rules; however, some owners and designers often impose minimum toughness requirements to accommodate start-up/shut-downs and handling. Other jurisdictions, such as the European Union, do require minimum toughness. Since Grade 91 was introduced over 50 years ago, no failure due to toughness of a properly PWHT'd Grade 91 weldment has been reported.

There have been reports (from multiple organizations) of very low toughness values of the deposited weld metal with average energy absorption ranging from single digits to low teens [ft-lbs (Joules)] at testing temperatures between 68°F (20°C) to 72°F (22°C) during welding procedure qualifications utilizing the semiautomatic HDMT GTAW welding process. These results are extremely low when compared to manual GTAW which typically produces weld metal with impact energy absorption above 70 ft-lbs (90 Joules) when tested at room temperature. The objective of this paper is not to highlight the many benefits and potential costing savings achieved when using the semiautomatic HDMT GTAW welding process, but to focus attention on the Charpy toughness values of the deposited weld metal and demonstrate that semiautomatic HDMT GTAW welding process is capable of producing weld metal with toughness comparable to that of weld metal produced by manual GTAW process.

The primary reason for low toughness values of weld metal produced by the semiautomatic hotwire process can be attributed to the inability to temper previously deposited weld beads due to the larger weld metal bead or layer thickness. It is suspected that the dynamics of the weld pool during deposition and the heat flow during solidification play an important role in the resulting mechanical properties of the weld metal. The principal difference between the two welding methods is simply the manner in which the wire is introduced into the weld puddle and the fact that the wire is preheated by a secondary current (producing the hot feed wire) while providing a dynamic weld pool by manipulating the wire introduced into the molten weld puddle.

Wire Feed and Metal Transfer

In an effort to better understand the HDMT GTAW welding process, the dynamics of the wire feed and the droplet transfer were captured with a high speed video and special lens to enable visual observation of not only the wire entry but the associated dynamics of the weld puddle. A still photo from the high speed video is presented in Figure 1. However, what is not seen in Figure 1, but clearly notable from the video, is that both the wire and the molten droplets are being vibrated as the droplets are being transferred to the work and into the molten weld puddle resulting in an increased deposition rate. This raises the question how the increased deposition rate would affect the deposited weld bead profile, solidification pattern of the weld metal, the heat flow from the weld metal to its surroundings, and the overall tempering effects on the prior deposited weld beads. Based on the observations from the high speed video, the weld bead profile warranted further consideration.

2.0 WELD BEAD PROFILE

Shielding gas has a pronounced influence on the energy transfer into the work and the overall weld penetration and the weld bead profile, plus can be a very important component in welding procedure qualifications. A test matrix was developed to evaluate the influence of various shielding gases on the weld bead profile, especially with respect to the potential influence on inter-bead tempering based on the thickness, width, and depth of penetration of the weld bead and the extent of the associated HAZ. For clarity and simplicity, a single weld bead was welded in the flat position on 1/2 inch (13 mm) thick SA-387, Grade 91, Class 2 [3] plate preheated to 400°F (200°C) using ER90S-B9 [4], 0.035 inch (0.9 mm) diameter filler metal. Welding parameters utilized are listed in Table 1.

Four gases were selected based on commercial availability: Argon, 75% Argon/25% Helium, 75% Helium/25% Argon and 95% Argon/5% Helium [5]. The various effects of shielding gas on weld bead profile is summarized in Table 2. The weld bead deposited with 100% Argon exhibited both the greatest thickness and depth of penetration while the weld bead deposited with 25% Argon/75% Helium exhibited the widest width (toe-to-toe) and HAZ among the various gases tested.

3.0 PROCEDURE QUALIFICATION DATA

Based on the testing evaluations, 100% Argon was chosen as the shielding gas of choice for welding procedure qualification testing. The second gas of choice was 75% Helium/25% Argon; however, after welding several beads in the vertical position with uphill progression, it was dismissed due to excessive fluidity of the weld puddle. Elimination of the 75% Helium/25% Argon resulted in 75% Argon/25% Helium being chosen over the 95% Argon/5% Helium simply because of the greater width of the HAZ. Two test plates of SA-387: Grade P91, Class 2, 2 inches (50 mm) thick X 16 inches (400 mm) long X 6 inches (150 mm) wide were joined with a double-V-groove, Figure 2.

Weld joint fit-up (i.e., root opening and alignment) was maintained by clamping the test coupon to a welding fixture in the 3G position, followed by wrapping with induction heating coils (Figure 3) and preheating to 400°F (200°C) prior to welding. Welding parameters throughout welding of Sides 1 & 2 were monitored using a calibrated T.V.C. Mini Arc Logger (MAL II) [6], Figure 4. The root pass data recorded for Side 1 is shown in (Figure 5) and is typical of data recorded for all additional passes. All recorded welding parameters, for Side 1 are listed in Tables 3.

The root beads and hot passes for Sides 1 & 2 were deposited using stringer beads (Figures 6 & 7), respectively. All fill passes were deposited with a weave technique, oscillating approximately 3/8 in. (9.5 mm) wide (Figures 8 & 9) allowing maximum welding parameters to be used in order to maximize the deposited weld metal without compromising the depth-to-weld bead width ratio thus ensuring tempering of the underlying weld bead. Once the groove was filled to a sufficient depth to allow a minimum of three weld beads per layer, welding was accomplished by welding from each bevel side to the center with the last weld bead being deposited as close as possible to the center of the weld. This technique was utilized for all subsequent layers in order to ensure bead placement and maximize tempering of the HAZ from the previously deposited weld bead thereby producing a degree of grain refinement and increasing toughness properties.

After Side 1 was completed and allowed to cool to ambient temperature the test coupon was removed from the welding fixture and the root pass was ground to clean bright metal and a liquid penetrant examination (PT) was performed to ensure the back side was free of discontinuities. The test coupon was once again clamped to the welding fixture in the 3G position with Side 2 accessible for welding. The test coupon was again wrapped with induction heating coils and preheated to 400°F (200°C) prior to welding. Welding data for Side 2 is listed in Table 4.

All welding for both Sides 1 & 2 was performed in the vertical uphill progression with the test plate in the 3G position, Figure 10.

4.0 MECHANICAL & METALLURGICAL TESTING FOR PROCEDURE QUALIFICATION

The completed test coupon was subjected to ASME Section IX, mechanical testing per QW-141.1 and QW-141.2 i.e., tension and guided-bend tests, respectively [7]. Both tension and guided-bend tests were performed on the combined weld thickness; results are listed in Table 5 and tested specimens are shown in Figures 11 & 12.

Three full size (10 x 10 x 2v mm), Charpy V-notch specimens were removed from Sides 1 & 2 weld centerline (WCL) and heat-affected zone (HAZ) as illustrated in Figure 13 and tested in accordance with ASTM A370 and E23 [10, 11], respectively at +72°F (22°C). The individual test results are listed in Table 7

Further testing was performed at +68°F (20°C), +64°F (18°C) and +60°F (16°C) on a single test specimen remove from both the WCL and HAZ of Sides 1 & 2. The individual test results for each test temperature is listed in Table 8. One additional test was also conducted on single specimen removed from the WCL and HAZ from Side 1 at +50°F (10°C) on a single specimen take at WCL and HAZ; individual test results are also listed in Table 8.

All values recorded in both Tables 7 and 8 are comparable with those typically observed with manual GTAW.

A hardness survey was performed in accordance with ASTM E384 [9] on a macro cross section using the Vickers hardness test method with a 10 kgf load. The results of the hardness survey are listed in Table 6 for both Sides 1 & 2. The hardness survey was performed as illustrated in Figure 14, which show the hardness test locations and values.

Table 9 list the chemical analysis of the ER90S-B9 filler metal used during procedure qualification. It is interesting to note the silicon content is on the high end of the allowable range. Typically, silicon is an element that is detrimental in terms of toughness; however, as shown in Tables 7 and 8 the impact values even at +50°F (10°C) were still acceptable.

5.0 CONCLUSION

Results of this study indicate that semiautomatic HDMT GTAW welding process is capable of producing impact values comparable to or exceeding manual GTAWT. The process also provides an attractive alternative for welding P91 root and hot passes or the entire weld from root to cap. The semiautomatic HDMT GTAW welding process permits an increase in energy (heat input), larger weld puddle and increased deposition rate while still providing tempering of the previously deposited weld beads or layers.

6.0 REFERENCES

[1] ASME Section I, *Rules for Construction of Power Boilers*, American Society of Mechanical Engineers, 2017 Edition.
[2] ASME B31.1, *Power Piping*, American Society of Mechanical Engineers, 2016 Edition.
[3] ASME Section II, Part A, *Ferrous Material Specifications*, SA-387/387M, *Specification for Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum*, American Society of Mechanical Engineers, 2017 Edition.
[4] ASME Section II, Part C, *Specification for Welding Rods, Electrodes, and Filler Metals*, SFA-5.28/SFA-5.28M, *Specification for Low-Alloy Steel Electrodes and Rods for Gas Shielded Arc Welding*, American Society of Mechanical Engineers, 2017 Edition.
[5] ASME Section II, Part C, *Specification for Welding Rods, Electrodes, and Filler Metals*, SFA-5.32/SFA-5.32M, *Specification for Welding Shielding Gases*, American Society of Mechanical Engineers, 2017 Edition.
[6] The Validation Centre (TVC), Ltd., Unit 15, Brinell Way, Harfreys Industrial Estate, Great Yarmouth, Norfolk NR31 0LU, UK, *Mini Arc Logger (MAL II)*.
[7] ASME Section IX, *Qualification Standard for Welding, Brazing, and Fusing Procedures; Welders; Brazers; and Welding, Brazing, and Fusing Operators*, American Society of Mechanical Engineers, 2017 Edition.
[8] ASME Project STIN-0154, *Effect of Hot Wire Filler Metal Addition on GTAW Heat Input for Corrosion-Resistant Overlays (CROs) and its Resulting Effect on Heat-Affected Zone (HAZ) Hardness and Toughness and CRO Chemical Composition*, May 31, 2017.
[9] ASTM E384 (2016), *Standard Test Method for Microindentation Hardness of Materials*, ASTM Annual Book of Standards, Vol 03.01, 2016.
[10] ASTM A370 (2016), *Standard Test Method and Definitions for Mechanical Testing of Steel Products*, ASTM Annual Book of Standards, Vol 01.03, 2016.
[11] ASTM E23 (2016b), *Standard Test for Notched Bar Impact Testing of Metallic Materials*, ASTM Annual Book of Standards, Vol 03.01, 2016.

Acknowledgments

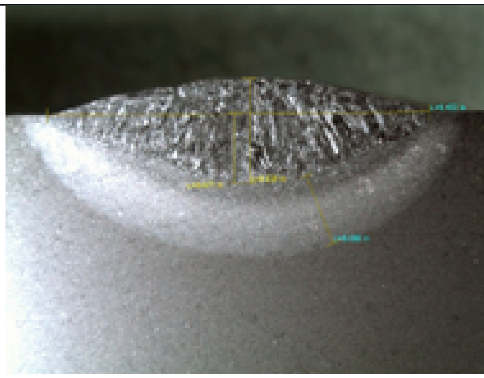
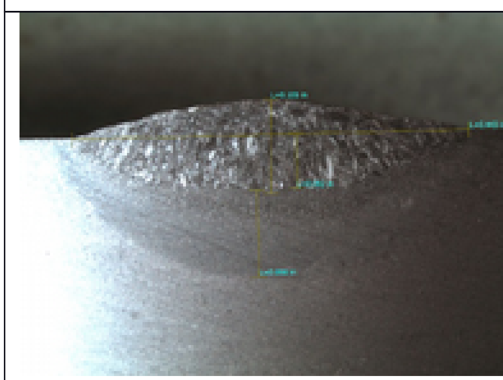
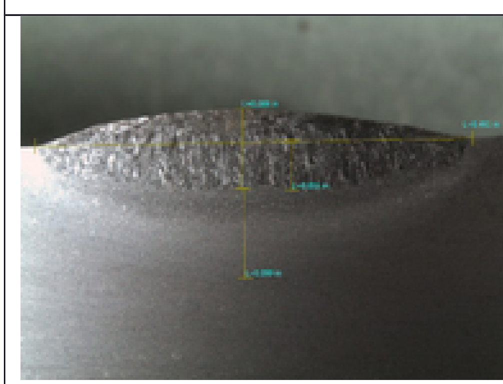
The authors gratefully acknowledge the financial and technical support provided by ALS Maverick Testing Laboratories, Inc. Thanks are also due to TiP TiG USA, LLC for providing the welding system and voestalpine Bohler Welding USA, Inc. for weld filler metal donation.

Table 1 SINGLE WELD BEAD WELDING PARAMETERS

Amperage	Voltage	Travel Speed in. (mm)	Wire Feed Speed ipm (m)	Heat Input kJ/in. (kJ/mm)
211 – 223	11.6 – 15.0	3.8 – 6 (96.5 – 152)	135 (3.4)	27.1 (1.07)

Note: *Adjustments were made in welding parameters to accommodate the specific gases; however, they were minor and every effort was made to keep the parameters as similar as possible. Direct current, electrode negative, was used.*

Table 2 EFFECT OF SHIELDING GAS ON WELD BEAD PROFILE

Single Weld Bead	Shielding Gas	Total Thickness of Weld Bead in. (mm)	Width of Weld Bead (toe-to-toe) in. (mm)	Depth of Weld Bead Penetration in. (mm)	Total Width of HAZ in. (mm)
	100% Argon	0.116 in. (2.9 mm)	0.432 in. (11.0 mm)	0.077 in. (2 mm)	0.080 in. (2.0 mm)
	75% Argon 25% Helium	0.105 in. (2.7 mm)	0.443 in. (11.3 mm)	0.062 in. (1.6 mm)	.098 in. (2.5 mm)
	75% Helium 25% Argon	0.098 in. (2.5 mm)	0.491 in. (12.5 mm)	0.055 in. (1.4 mm)	0.099 in. (2.5 mm)

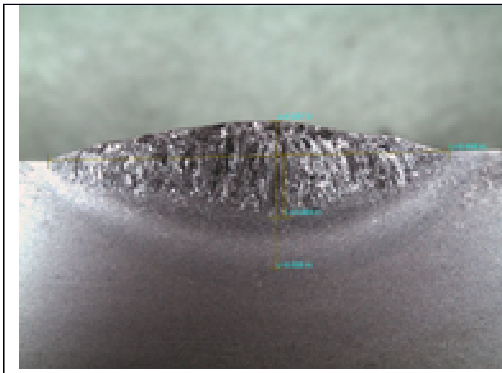
	95% Argon 5% Helium	0.107 in. (2.7 mm)	0.448 in. (12.4 mm)	0.069 in. (1.8 mm)	0.058 in. (1.5 mm)

Table 3 WELDING DATA FOR SIDE 1

WELDING PROCESS:	GTAW	TYPE:	Semiautomatic

BASE METAL	
Material Spec.	SA-387
Grade	91, Class 2
P-No.	15E
Group No.	1
Thickness of Test Coupon	2 inches (50 mm)
Backing	None
FILLER METAL	
SFA Specification	5.28
AWS Classification	ER90S-B9
Filler Metal F-No.	6
Weld Metal A-No.	5
Filler Metal Manufacturer	voestalpine Bohler
Filler Metal Trade Name	Thermanit MTS 3-LNi
Filler Metal Size	0.035 in (0.9 mm)
Deposit Thickness	1 in (25 mm)
Maximum Pass Thickness	0.125 in (3.2 mm)

POSITION			
Position of Groove	3G	Weld Progression	Uphill

ELECTRICAL	
Tungsten Size	0.125 in (3.2 mm)
Tungsten Type	EWTh-2
Current/Polarity	DCEN
DC Pulsing Current	None

PREHEAT	
Preheat Temperature	400°F (200°C) min.
Interpass Temperature	600°F (315°C) max.
Preheat Maintenance	Yes
Notes:	Minimum preheat was maintained until completion of welding at which time the weld was wrapped and cooled at a control rate of 200°F/hr (93°C/h) to below 200°F (93°C) and allowed to slow cool to ambient temperature in still air.

POSTWELD HEAT TREATMENT	
Temperature	1425°F (774°C)
Holding Time	2 hours
Heating & Cooling Rate	Above 600°F (315°C) the heating and cooling rate did not exceed 600°F/hr (315°C/hr).

GASES			
Shielding	100% Argon	Flow Rate	30 cfh (14 L/min)
Backing	100% Argon	Flow Rate	20 cfh (9 L/min)

TECHNIQUE	
String or Weave Bead	Stringer & Weave
Gas Cup Size	#10
Initial & Interpass Cleaning	Brushing & Grinding
Multiple or Single Pass per Side	Multiple

Wire	Hot-Wire - DCEP – 80 amps	Multiple or Single Electrode	Single

ELECTRICAL CHARACTERISTICS

PASS (# of passes)	AMPS	VOLTS	TRAVEL SPEED ipm (mm/min)	WIRE FEED SPEED ipm (m/min)	MAXIMUM HEAT INPUT[4] kJ/in (kJ/mm)
Root (1)	117 - 120	9.5 – 10.3	3.4 (86.4)	75 (1.9)	20.7 (0.82)
Hot (1)	198 - 200	12.0 – 12.3	7.3 (185)	120 (3)	19.9 (0.78)
Fills (30)	211 - 223	11.6 – 15.0	3.8 – 9 (97 – 229)	135 (3.4)	27.1 (1.07)
Cap (4)	183 - 201	11.8 – 13.7	3.8 – 5 (97 – 127)	135 (3.4)	33.4 (1.32)

Notes:
1) Total recorded arc time from root to cap 1.7 hours
2) Total 3.6 lbs. (1.6 kg) deposited weld metal/measured weight
3) 2.1 lbs. (1 kg) deposited weld metal/hour
4) Heat input for GTAW torch only, hot wire not included per ASME Research Project No. STIN-0154 [8]

Table 4 WELDING DATA FOR SIDE 2

WELDING PROCESS:	GTAW	TYPE:	Semiautomatic

BASE METAL	
Material Spec.	SA-387
Grade	91, Class 2
P-No.	15E
Group No.	1
Thickness of Test Coupon	2 inches (50 mm)
Backing	Weld Metal
FILLER METAL	
SFA Specification	5.28
AWS Classification	ER90S-B9
Filler Metal F-No.	6
Weld Metal A-No.	5
Filler Metal Manufacturer	voestalpine Bohler
Filler Metal Trade Name	Thermanit MTS 3-LNi
Filler Metal Size	0.035 in (0.9 mm)
Deposit Thickness	1 in (25 mm)
Maximum Pass Thickness	0.125 in (3.2 mm)

POSITION			
Position of Groove	3G	Weld Progression	Uphill

ELECTRICAL	
Tungsten Size	0.125 in (3.2 mm)
Tungsten Type	EWTh-2

PREHEAT	
Preheat Temperature	400°F (200°C) min.
Interpass Temperature	600°F (315°C) max.
Preheat Maintenance	Yes
Notes:	Minimum preheat was maintained until completion of welding at which time the weld was wrapped and cooled at a control rate of 200°F/hr (93°C/h) to below 200°F (93°C) and allowed to slow cool to ambient temperature in still air.

POSTWELD HEAT TREATMENT	
Temperature	1425°F (774°C)
Holding Time	2 hours
Heating & Cooling Rate	Above 600°F (315°C) the heating and cooling rate did not exceed 600°F/hr (315°C/hr).

GASES			
Shielding	100% Argon	Flow Rate	30 cfh (14 L/min)
Backing	None	Flow Rate	---

TECHNIQUE	
String or Weave Bead	Stringer & Weave
Gas Cup Size	#10

Current/Polarity	DCEN	Initial & Interpass Cleaning	Brushing & Grinding
DC Pulsing Current	None	Multiple or Single Pass per Side	Multiple
Wire	Hot-Wire - DCEP – 80 amps	Multiple or Single Electrode	Single

ELECTRICAL CHARACTERISTICS

PASS (# of passes)	AMPS	VOLTS	TRAVEL SPEED ipm (mm/min)	WIRE FEED SPEED ipm (m/min)	MAXIMUM HEAT INPUT[4] kJ/in (kJ/mm)
Root (1)	117 - 120	9.5 – 10.3	3.4 (86.4)	75 (1.9)	20.7 (0.82)
Hot (1)	198 - 200	12.0 – 12.3	7.3 (185)	120 (3)	19.9 (0.78)
Fills (30)	211 - 223	11.6 – 15.0	3.8 – 9 (97 – 229)	135 (3.4)	27.1 (1.07)
Cap (4)	183 - 201	11.8 – 13.7	3.8 – 5 (97 – 127)	135 (3.4)	33.4 (1.32)

Notes:
1) Total recorded arc time from root to cap 1.5 hours
2) Total 3.4 lbs. (1.5 kg) deposited weld metal/measured weight
3) 2.3 lbs. (1 kg) deposited weld metal/hour
4) Heat input for GTAW torch only, hot wire not included per ASME Research Project No. STIN-0154 [8]

TABLE 5 CROSSWELD TENSION & TRANSVERSE GUIDED-BEND TESTS

Specimen	Width Thickness, in. (mm)	Area, in² (mm²)	.2% Offset Yield, lbs. (kg)	.2% Offset Yield Strength, ksi (MPa)	UTL, lbs. (kg)	UTS, ksi (MPa)	(%) EL.	(%) RoA	Fracture Location / Type
T1	.749 x 1.940 (19.0 x 49.3)	1.453 (937.42)	103,400 (46,902)	71.1 (490.3)	140,500 (63,730)	96.7 (666.9)	36.0	48.4	Base/Ductile
T2	.751 x 1.954 (19.1 x 49.6)	1.467 (946.45)	103,200 (46,811)	70.3 (484.8)	141,800 (64,320)	96.7 (666.9)	38.5	38.5	Base/Ductile

Side Bend 1	Side Bend 2	Side Bend 3	Side Bend 4
Acceptable	Acceptable	Acceptable	Acceptable

TABLE 6 CHARPY IMPACT TESTS: 0.394 in. (10 mm) x 0.394 in. (10 mm) x 0.079 in. (2 mm) V

Location	Temperature °F (°C)	Ft/lbs. (J)			Avg.	MILS Lateral Expansion	% Shear
WCL – 1st Side	+72 (22)	111 (150.9)	115 (155.9)	114 (154.6)	113.3 (153.6)	75, 73, 75	90, 90, 90
HAZ 1st Side	+72 (22)	162 (219.6)	160 (217.0)	166 (225.1)	162.7 (220.6)	88, 85, 103	100, 100, 100
WCL – 2nd Side	+72 (22)	82 (111.2)	96 (130.2	83 (112.5)	87.0 (118.0)	54, 67, 60	85, 90, 85
HAZ 2nd Side	+72 (22)	162 (219.6)	158 (214.2)	156 (211.5)	158.7 (215.2)	99, 94, 91	100, 100, 100

TABLE 7 CHARPY IMPACT TESTS: 0.394 in. (10 mm) x 0.394 in. (10 mm) x 0.079 in. (2 mm) V

Location	Temperature °F (°C)	Ft/lbs. (J)	MILS Lateral Expansion	% Shear
WCL – 1st Side	+68 (20)	83 (112.5)	65	80
HAZ 1st Side	+68 (20)	170 (230.5)	103	100

WCL – 2nd Side	+68 (20)	93 (126.1)	69	90
HAZ 2nd Side	+68 (20)	186 (252.2)	97	100
WCL – 1st Side	+64 (18)	112 (151.8)	71	90
HAZ 1st Side	+64 (18)	184 (249.5)	96	100
WCL – 2nd Side	+64 (18)	93 (126.1)	63	90
HAZ 2nd Side	+64 (18)	190 (257.6)	96	100
WCL – 1st Side	+60 (16)	82 (111.2)	58	80
HAZ 1st Side	+60 (16)	185 (250.8)	96	100
WCL – 2nd Side	+60 (16)	97 (131.5)	67	90
HAZ 2nd Side	+60 (16)	190 (257.6)	97	100
WCL – 1st Side	+50 (10)	74 (100.3)	57	75
HAZ 1st Side	+50 (10)	182 (246.8)	80	100

TABLE 8 VICKERS 10 kgf HARDNESS SURVEY

SIDE 1	Base Metal	HAZ	Weld	HAZ	Base Metal
Cap	196	206, 214, 220	233, 233	214, 210, 197	195
Root	209	198, 224, 247	254, 254	252, 222, 200	209

SIDE 2	Base Metal	HAZ	Weld	HAZ	Base Metal
Cap	201	200, 211, 220	239, 247	224, 220, 205	195
Root	189	214, 217, 226	244, 241	219, 207, 200	194

TABLE 9 CHEMICAL ANALYSIS (%wt.) of THERMANIT MTS-3-LNi (ER90S-B9)

C	Si	Mn	P	S	Cr	Mo	Ni	V	Cu	Al	Nb	N
0.11	0.43	0.68	0.005	0.001	8.87	1.00	0.08	0.20	0.03	< 0.01	0.06	0.05

Note: Mn + Ni = 0.76

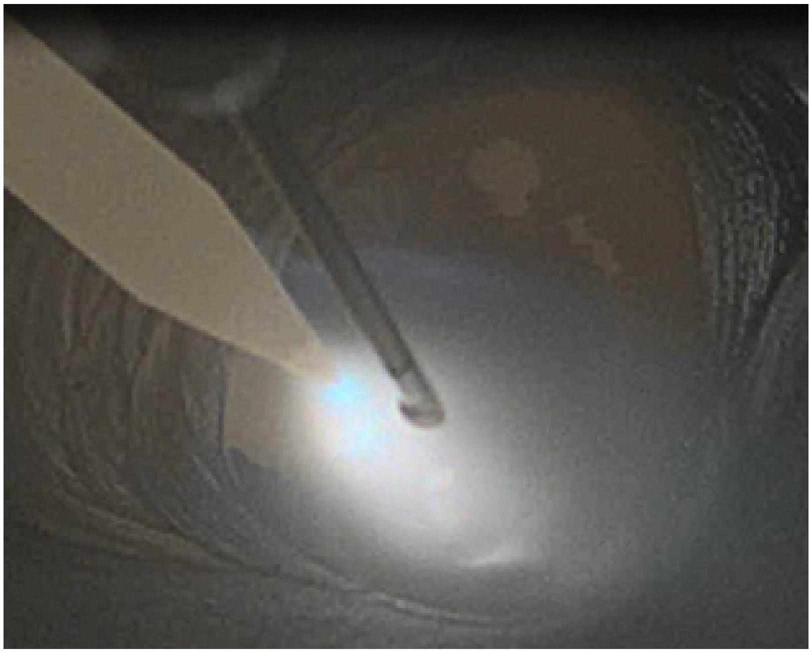


Figure 1 Still shot of high speed video

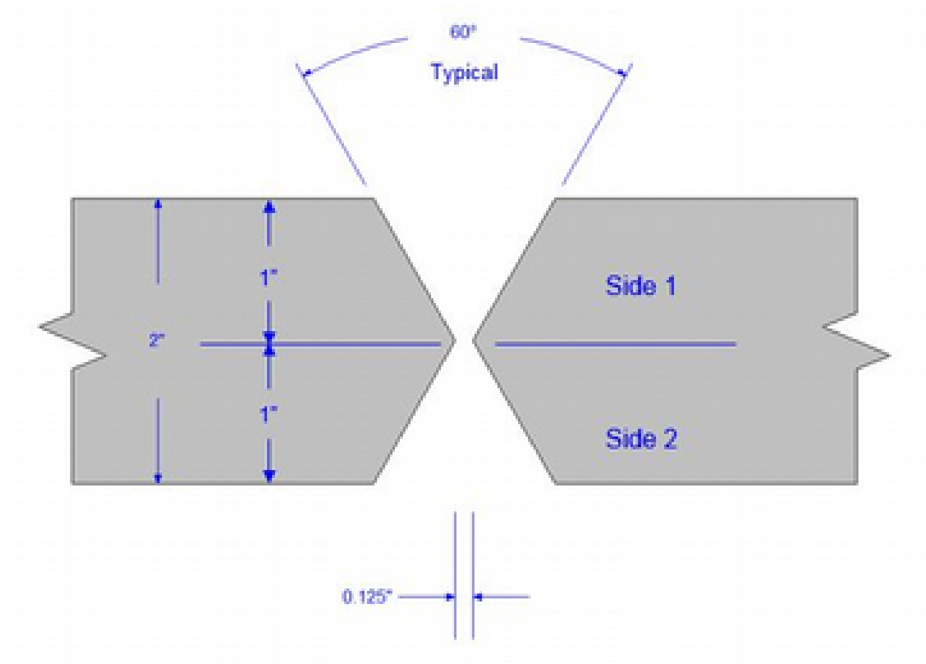


Figure 2 Test Coupon

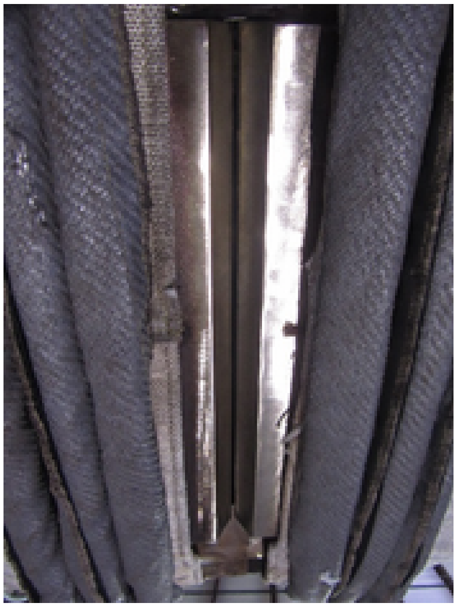


Figure 3 Fit-up of Test Coupon in 3G Position with Induction Heating Coils

Figure 4 Digital Real Time Readout T.V.C. Mini Arc Logger (MAL II)

Figure 5 Typical Data Recorded by T.V.C. Mini Arc Logger

Figure 6 Close-Up of Root Pass Side 1 (prior to wire brushing)

Figure 7 Close-Up of Hot Pass (Typical)

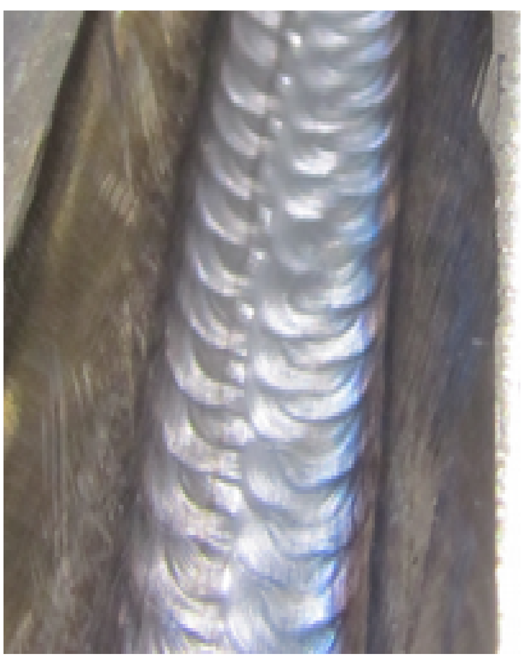


Figure 8 Close-Up of Fill Passes (Typical)

Figure 9 Close-Up of Cap Passes (Typical), prior to wire brushing

Figure 10 Vertical Uphill Progression (Typical)

Figure 11 Crossweld Tensile Specimens

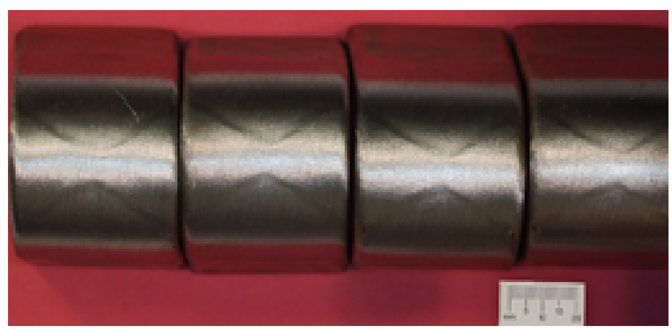


Figure 12 Side Bend Specimens

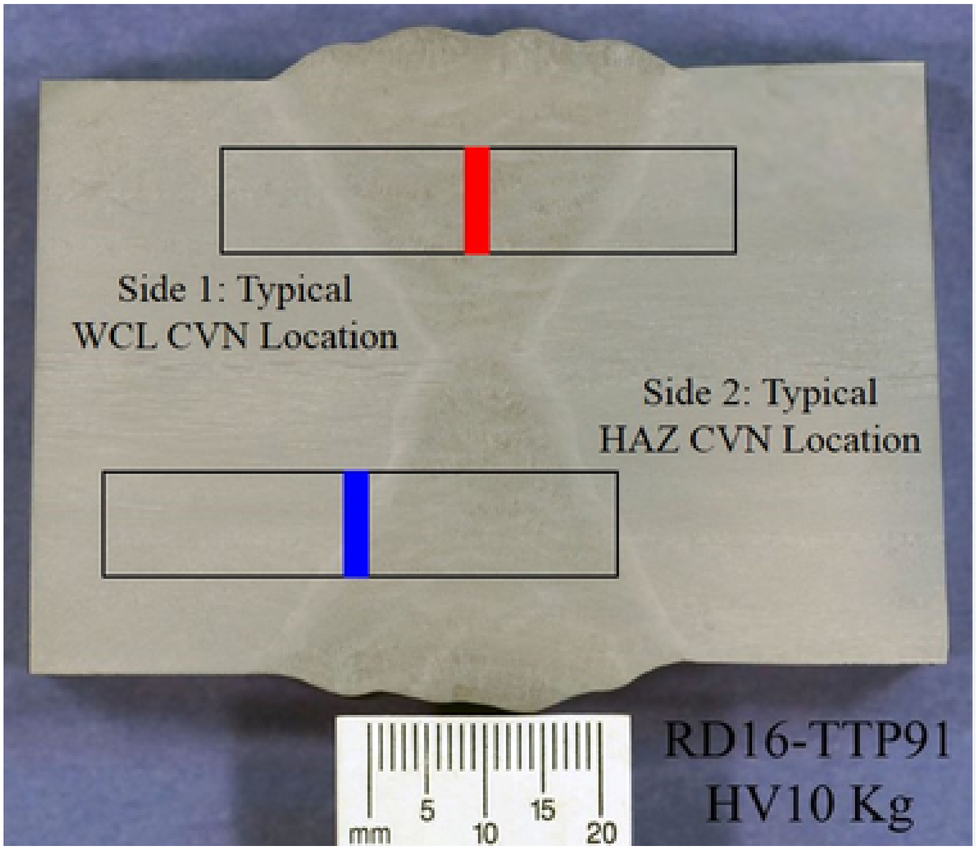


Figure 13 Charpy V-Notch Locations (Typical)

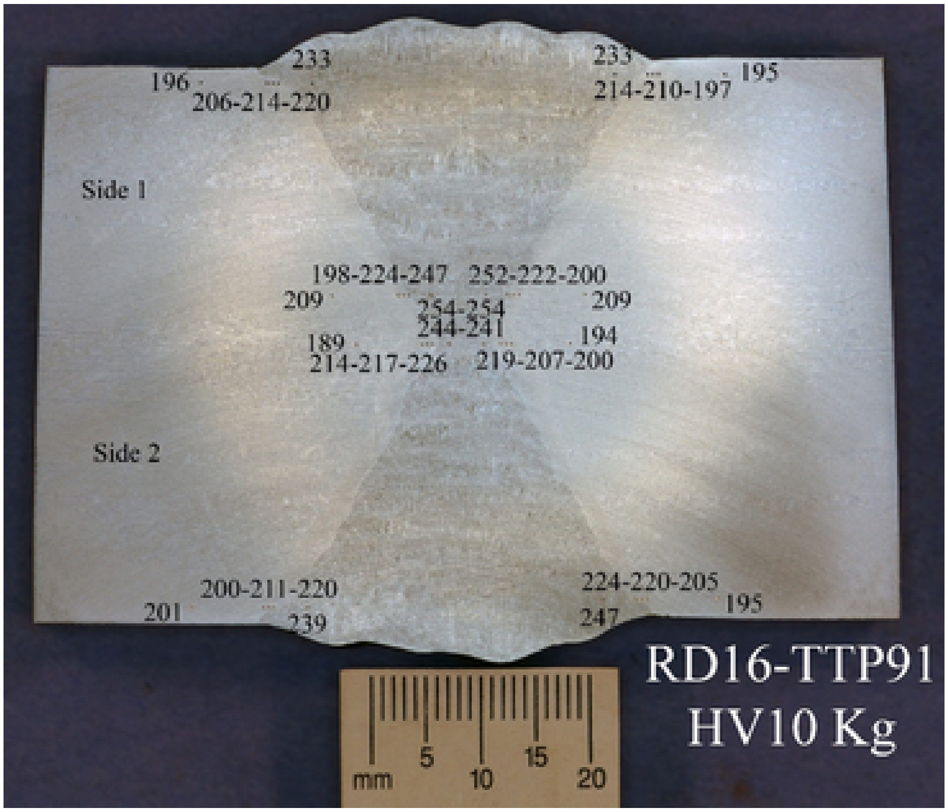


Figure 14 Vickers 10 kg Hardness Survey