#510307 ②

DONELAD LIMITED
ENGINEERING SERVICES

Pulsed Welding of HY80/HY100 Using the T.I.M.E.™ Process

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ABSTRACT

Over the past number of years, the Defence Research Establishment Atlantic has sponsored a number of projects aimed at evaluating welding processes suitable for the fabrication of submarines. The objective of these evaluations has been to maximize weldment toughness as determined by dynamic tear specimen testing. The Transferred Ionized Molten Energy **(T.I.M.E.™) Process** has emerged superior to other potential welding processes. The purpose of the present investigation was to optimize weldment properties employing the T.I.M.E.™ Process with state-of-the-art pulsing controllers and power sources.

The project involved preparing welding procedures for the pulse T.I.M.E.™ Process employing a T.I.M.E. 540 power source coupled with a TR-19 synergic pulsing unit, pre-programmed for use with the patented T.I.M.E.™ Process. These procedures were first proven on mild steel before they were applied each to HY100 and HY80 steels in both the 3G (vertical down) and 1G/4G (flat/overhead) positions.

A number of dynamic tear and explosion panels were prepared to evaluate the properties of the weldments.

Mechanical and non-destructive test results for both HY80 and HY100 are given.

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1.0 INTRODUCTION

Over the past number of years, the Defence Research Establishment Atlantic has sponsored several projects aimed at evaluating welding processes and procedures suitable for the fabrication of submarines. The objective of these evaluations has been to maximize weldment toughness as determined by dynamic tear specimen testing. The T.I.M.E.™ Process emerged with superior advantages over other potential welding processes. The purpose of the this investigation was to optimize weldment properties employing the T.I.M.E.™ Process with state-of-the-art pulsing controllers and power sources.

This investigation involved preparing welding procedures for pulse welding with the T.I.M.E.™ Process employing a T.I.M.E. 540 power source coupled with a TR-19 synergic pulsing unit, pre-programmed for use with T.I.M.E.™ gas. These procedures were first proven on mild steel, before they were applied each to HY100 and HY80 steels in both the 3G (vertical down) and 1G/4G (flat/overhead) positions.

A number of dynamic tear and explosion panels were prepared to evaluate the properties of the weldments. Hardness, chemical and macro examinations were also performed.

Results from explosion bulge testing were not available at the time this paper was written.

2.0 BACKGROUND

A great deal of work has been done over the last 25 years to establish the credibility of the gas shielded, solid wire GMAW Process. There are two challenges that face Industry with this process.

The first challenge is the ability to fuse weld metal from a small diameter solid wire into a prepared joint producing quality welds with sufficient penetration and dependable fusion. Lack of fusion, or cold lap, is a discontinuity in the weld deposit between fused faces that consist of weld to substrate or weld to weld. This condition in a welded joint is one of the major causes of failure in weldments which are subjected to load transfer and must be either prevented or removed and repaired by rewelding.

The second challenge is to deposit weld metal at a rate that is economically feasible. The process must compete with the shielded metal arc and submerged arc welding processes common to shipyard fabrication.

The penetration, fusion and deposit rates of the wire welding processes are controlled by the wire feed speed, voltage and arc speed. Therefore these variables can be classified as the quality controllers of all the welding procedures. The productivity and quality of the weld deposit is a direct result of the electrode's current density and its transferred condition across the arc.

The shielding gas's ability to transfer metal from the electrode across the arc into a satisfactorily fused geometric shape is the critical catalyst in the synergy of all the welding variables.

Each shielding gas mixture produces a primary event at the arc and triggers the consequences of the wire feed speed and current density at the arc. When wire feed speeds or current densities exceed the allowable limits of good fusion within the transfer capabilities of its shielding gas mixture, weld quality deterioration, poor appearance and repair costs increase dramatically.

Shielding gas chemistries control the weld metal transfer characteristics and is the single most important control factor for solid wire welding processes in achieving uniform quality and productivity reliability. Each shielding gas mixture ionizes into its own plasma size, shape, motion and structure. The shielding gas mixture determines the size of the metal droplets, their shapes, frequency, regularity and direction as they transfer across the arc. The droplets can be concentric or eccentric - they can drop in-line or off-line with the electrode. They can be micro droplets or macro globules. The droplets can transfer inside and/or outside the plasma and shielding gas. They can move in the direction of the rotational forces and the magnetic forces between the electrode and the plate. The droplets can absorb atmosphere or remain atmospherically inert in their journey from the electrode tip across the arc into the weld geometry design.

The T.I.M.E.™ gas mixture of argon, helium, carbon dioxide and oxygen has been designed to overcome many of the challenges associated with gas shielded, solid wire

GMAW and displays a stable, high frequency axial spray transfer resulting in a continuous, uniform droplet size transfer of weld metal in line with the direction of the electrode and totally within the arc cone. The result is a dramatic increase in both weld quality and productivity.

The T.I.M.E.™ Process

The Transferred Ionized Molten Energy (T.I.M.E.) Process is a modification of the gas metal arc welding (GMAW) technique consisting of a four component shielding gas and new types of welding equipment. The Patented T.I.M.E. gas is a mixture of argon, helium, carbon dioxide and oxygen. The gas creates a unique arc plasma that provides stability at wire feed speeds up to 2000 IPM with 0.045" diameter wire. This compares to less than 800 IPM for conventional GMAW welding processes. A specially designed wire feeder (T.I.M.E. 51) and inverter power source (T.I.M.E. 540) coupled with the new TR-19 pulse controller allows "one knob" synergic pulsing control of welding parameters.

The result is a process capable of depositing weld metal with high quality (i.e. higher toughness, no spatter, no undercut) at a very high deposition rate and welding speed (up to 8 times faster than SMAW).

Pulse Welding with T.I.M.E.™ Process

The pulsed gas metal arc welding process is a technique developed over 10 years ago to bridge the gap between short circuit and spray mass transfer of weld metal. In this process, a pulsating current is superimposed over the steady DC current causing brief inputs of energy. These current pulses produce a controlled droplet transfer which corresponds to the rhythm of the pulse frequency. The background current ensures that the tip of the electrode and the welding pool are kept molten. With each rise in current, a droplet is transferred to the workpiece due to the "pinch effect". In sophisticated pulsing systems, the size of the droplet can be controlled and adjusted to provide one droplet per pulse.

The background current is adjustable to suit the weld wire material and shielding gas composition. Since the critical level of current necessary to shed the droplets is a function of pulse current, the amount of heat produced is relatively low compared with conventional methods.

There are two features of P-GMAW that are of interest in welding HY80/HY100 steels. First, the critical level of current needed to achieve spray transfer is low enough to allow deposition rates in excess of that which can be easily controlled in normal GMAW for making out-of-position welds hence providing operational economy. Second, it has also been found that pulsing can actually enhance the quality and toughness of the deposited weld metal while maintaining acceptable levels of other mechanical properties. The reason for the increase in toughness is not clear. However, it is hypothesized that at similar heat inputs, the pulses cause changes in the solidification pattern resulting in a more desirable microstructure.

Pulsed welding introduces a number of new variables in addition to those normally controlled in the T.I.M.E.™ Process (i.e. WFS, tip recess, voltage, travel speed). These are:

I_p - pulse current
T_p - pulse duration
I_b - background current
T_b - background current duration
F_p - pulse frequency

Earlier work with the T.I.M.E.™ Process with and without pulsing (Ref. 6.1) reported unsurpassed toughness values approaching those of the base metal HY80/HY100. In the past two years, significant equipment improvements have evolved and now state-of-the-art synergic pulsing coupled with an ultra-responsive inverter power source is now commercially available and was used for this project.

3.0 EXPERIMENTAL PROCEDURE

Consumable Wires for the Program

Lincoln LA100 (ER 100S-G) wire was specified for welding of HY80 and L-Tec ER120 (ER 120S-1) was specified for welding HY100 panels. Both wires were 1.2 mm in diameter. The chemical analyses (typical) are given in Table 1.

Welding Equipment

The following equipments were used for this project:

(i) T.I.M.E. 540 Power Source
(ii) T.I.M.E. 51 Wire Feeder
(iii) T.I.M.E. Torch (750 amp water cooled)
(iv) T.I.M.E. Gas Diffuser/Tips
(v) Fronius TR-19 Synergic Pulsing Controller

Preparation of Steel Panels for Welding

Each of the HY80/HY100 steel panels was flame cut to rough dimensions (mechanical properties and chemical analyses are given in Tables 1 and 2). The final preparation was a balanced double vee groove with 60° included angles, (root face = 0 mm) prepared by machining. A total of 1.8 meters of weldment were required for each position/base material combination. This was achieved by welding the following panels for each combination:

(i) 1200 mm x 300 mm
(ii) 600 mm x 300 mm

Preheat Equipment

Preheat was provided by electric resistance heating. A Honeywell electronic chart recorder coupled with a 6 zone mini-controller and a 75 kw transformer were connected to the four heaters. Up to ten K-type thermocouples were spot welded to the 1200 mm panels and five to the 600 mm panels. The 100^{0}C minimum preheat was controlled by the set-point on the mini-controller. Interpass and peak temperatures were closely monitored and welding was delayed until interpass temperatures reduced to acceptable values.

After all welding was completed on a panel, the temperature was allowed to stabilize for approximately 45 minutes before disconnecting the heaters. The panels were removed from the jig, wrapped with insulation and allowed to slow cool to room temperature. They were allowed to remain in this condition for 72 hours before non-destructive examination (NDE) was conducted.

Welding Method

Welding procedures in the development stage of the project were optimized on mild steel with each of the electrodes. The tolerance of each parameter was investigated in this manner and documented.

Joint design was specified to be a balanced double vee groove with 60^0 included angles and feather edge preparation (i.e. root face of 0 mm).

A similar technique was used for both materials in each position. A "push" angle of approximately 10^0-20^0 was used in all but the root pass of side 2, vertical down (3G) plates where a "drag" angle of 10^0-20^0 was used (layer R1). All passes were applied as stringer beads with little or no oscillation of the torch.

Backgrinding to sound metal of the root prior to welding side 2 was conducted on all panels. Magnetic particle inspection was used to verify that all suspect root material was removed before continuing the welding. Interpass grinding was only applied if visually the weld cap required dressing to allow proper blending with subsequent layers.

The number of passes varied with the fit-up of the panels and the Welding Procedure Data for each steel are given in Table 4 and 5. Average heat inputs varied from 0.67 - 0.76 kJ/mm for 1G/4G welds and from 0.47 - 0.55 kJ/mm for 3G.

Grounding at the workpiece was accomplished by clamping the ground cable in line of the weld groove on the weldment run-off tab. Welding progression was towards the ground.

The T.I.M.E.™ Process allows for variations in the tip recess causing marked changes in the welding characteristics through variations in electrode preheat from the tip to the arc. In the root passes, the tip was extended to 0 - 3 mm (+ve) to allow deeper penetration. Subsequent passes called for the tip to be recessed into the nozzle 0 - 6 mm (-ve).

The wire feed speeds, welding current and voltage settings used for the project were operated generally on the low end of the range for spray transfer and bordered on the transitional arc zone.

Torch travel speeds for the various positions ranged as follows:

Vertical (Down)	-	670 - 770 mm/min.
Flat/Overhead	-	420 - 430 mm/min.

These settings represented "manageable" ranges that an operator can achieve with a minimal amount of training.

Non-Destructive Examination

The ultrasonic examination was performed on the finished plates using a Krautkramer USK 7 and the following probes with Ultragel II used as the gel couplant:

(a) Longitudinal 2.25 MHz x 1.0"
(b) Shear Angle: 2.25 MHz x 0.625" x 0.625" x 70° AWS
(c) Shear Angle: 2.25 MHz x 0.75" x 0.75" x 60° AWS
(d) Shear Angle: 2.25 MHz x 0.75" x 0.625" x 45° AWS

Ultrasonics was employed to examine the completed weld in accordance with ASME Section V, Article 5. Twenty-five percent of reference was used as the record level.

Scanning from Face 1 (first side welded) detected the highest level of reflections in the first half skip. These reflectors are located on Face 2 in the root area. Some welds were scanned from Face 2 in addition to Face 1. In all cases, each weld was scanned from both sides of the weld on the same face.

Macroexamination, Hardness Testing and Chemical Analysis

Four welds were prepared for macroexamination, hardness testing and chemical analysis.

A metallographic cross-section was prepared from each weld, and ground to 600 Grit finish. The sections were then etched with 10% nital and photographed.

Hardness readings were obtained from each section using a Vickers machine and 10 kg load. Generally, eight or more identations were placed uniformly along the thickness of the specimen, at the weld centreline. The range and average of these readings is shown in Table 3. As well, three additional identations were placed in the weld metal at the half thickness location, and four in the heat affected zone of the capping passes, next to the fusion boundary on the second side. These data are also shown in Table 3.

After hardness testing, weld metal chemical analysis was obtained using optical emission spectroscopy. For oxygen and nitrogen analysis, ≈ 1 mm thick slice of weld metal at the weld centre line (≈15 mm along weld length) was removed, and divided into three 5 mm long pieces for triplicate analysis. The middle 10 mm was then removed from each piece for oxygen and nitrogen analysis.

The chemical analysis results are reported in Table 1, noting that Oxygen and Nitrogen values are in ppm and represent the average of three specimens for each weld.

4.0 DISCUSSION

The purpose of this project, as previously mentioned, was to optimize weldment properties (i.e notch toughness) using the T.I.M.E. Process and synergic pulsing equipment pre-programmed for T.I.M.E. Gas.

The experience gained during the development of procedures on mild steel was invaluable and a number of factors contributing to welding performance were improved upon before striking an arc on HY steel. However, with the objective to maximize high notch toughness, the low heat inputs increased the risk of fusion defects in the root pass of Face 2 (layer R1). The sophisticated TR-19 pulsing controller allowed heat inputs to be lowered to 0.32 kJ/mm while still achieving stable arc characteristics.

One observation of interest was made during the welding of the 1.2 m long plates. It was discovered that the power cables were neatly coiled resulting in the formation of inductance which limited the pulse current peak. Further testing revealed that the peak current was reduced as much as 30% and caused arc characteristics in a transition zone between non-free flight and free flight mass transfer. This condition was corrected for the 0.6 m plates and the arc displayed stable, spatterless, free flight mass transfer.

Although defect free weldments were not the primary objective of this Project, the smaller plates revealed only minor amounts of discontinuities and were acceptable to current DND inspection standards as well as to ASME IX.

Throughout the course of this work, the difference in the operating characteristics of the weld wires was very pronounced. The Lincoln LA100, used for joining HY80 has excellent characteristics and has a much lower tendancy to cause discontinuities when compared to L-Tec ER120-S1 (used for joining HY100). The operator appeal of LA100, coupled with overlapping chemistries and mechanical properties with ER120 S-1, makes LA100 wire a potential and the preferred consumable for joining HY100.

The equipment used performed flawlessly and the TR-19 synergic controller is very easy to program and operate. There were no operational problems with the power source or the wire feeder.

With the pursuit of notch toughness, it was unfortunate that the weld groove was positioned in line with the rolling direction of the plate instead of transverse as was the case in previous projects. For example, HY80 exhibits a dynamic tear energy of 1960 J@-29° (L-T orientation, i.e. notch transverse to rolling direction) and only 1140 J@ -29° C. (T-L orientation, i.e. notch parallel to rolling direction). The effect this has on the resultant weld metal and HAZ properties is not clear.

The Dynamic Tear Results for both steels and positions are given in Table 6. The standard 16 mm size samples were tested at -29°C and all specimens were notched in the T-L orientation. Heat affected zone results were excellent with dynamic tear energy as high as 1757 J@ -29°C. Weld metal results although not as good as the HAZ more than met military requirements for this application.

The quality of the final weld deposits are visually far superior to that of comparable Shielded Metal Arc Welding with no undercut or spatter. Ultrasonic examination revealed some fusion defects in the larger plates due to inductance in the welding circuit but with the welding parameter adjustments made on the smaller plates, defect free welds were deposited.

5.0 CONCLUSIONS

5.1 All position welding of HY80 and HY100 was successful using pulsed welding and the T.I.M.E. Process. The welding procedures developed will pass DND non-destructive examination acceptance criteria and dynamic tear toughness requirements.

5.2 Lincoln LA 100 has superior operating characteristics to the L-Tec ER 120S-1 and may be suitable as a filler metal for both HY80 and HY100.

5.3 The T.I.M.E. equipment performed flawlessly throughout this project and was able to maintain free flight transfer with heat inputs as low as 0.32 kJ/mm.

5.4 Travel speeds employed with the T.I.M.E. Process ranged from 670 mm/min. to 770 mm/min. (26-30 IPM) in the 3G position and 420 mm/min. to 430 mm/min. (16 - 17 IPM) in the 1G/4G positions. These speeds are very manageable, although 3-5 times faster than SMAW and are representative of the torch speeds associated with aluminum welding.

5.5 Vertical down (3G) weldments require less manual skill than welding vertically up and with the T.I.M.E. Process, fusion and penetration were found to be excellent.

5.6 The T.I.M.E. welding equipment is easy to operate, durable and dependable making it an ideal candidate for shipyard use.

6.0 REFERENCES

6.1 Malik, L.; Morrison, K.; Pussegoda, L.; "All Position Gas Metal Arc Welding of HY80 and HY100 Steels", DREA CR/91/434. Defence Research Establishment Atlantic.

TABLE 1

COMPARISON OF CHEMICAL ANALYSIS

MATERIAL	C	Si	Mn	S	P	Al	Cr	Ni	Mo	Cu	O	N
HY80	.145	.19	.26	.007	.008	-	1.4	2.23	.34	.11	-	-
LINCOLN LA100	.07	.34	1.47	.007	.007	-	.05	1.81	.34	.11	-	-
WELD 3G	.71	.36	1.4	<0.008	.012	<.005	.14	1.8	.44	.10	308	128
1G/4G	.80	.33	1.2	<.008	.012	.01	.35	1.8	.43	.10	298	110
HY100	.140	.20	.25	.004	.007	.30	1.41	2.67	.34	.12	-	-
L-TEC 120S-1	.06	.38	1.63	.005	.006	.012	.31	2.37	.50	.01	-	-
WELD 3G	.059	.27	1.3	.0089	.008	<.005	.39	<2.1	.50	.02	553	117
1G/4G	.066	.24	1.2	.0082	.008	<0.005	.46	>2.1	.46	.03	422	129

NOTE: OXYGEN AND NITROGEN IN PPM

TABLE 2

MECHANICAL PROPERTIES OF

THE STEELS USED IN THE PROGRAM

Property	HY80	HY100
Yield Strength (MPa)	638	724
UTS (MPa)	741	805
Hardness (BHN)	229	245
CVN @ - 18^0C (J)	200	191
CVN @ - 84^0C (J)	184	125

TABLE 3

HARDNESS RESULTS

HARDNESS HV_0			
STEEL		WELD CENTRE	HAZ
HY80	3G	293-332	370
HY80	1G/4G	288-293	384
HY100	3G	308-349	392
HY100	1G/4G	289-291	370

TABLE 4

EXPERIMENTAL PROCEDURE

WELDING PROCEDURES:

- HY80 3G POSITION

AMPS	197-290	AVG. 220
TRAVEL SPEED	460-1110 mm/min (18-44 IPM)	AVG. 770 mm/min (30.5 IPM)
HEAT INPUT	0.32-1.04 kJ/min	AVG. 0.47 kJ/min
NUMBER OF PASSES	22	

- HY80 1G/4G POSITION

AMPS	175-230	AVG. 192
TRAVEL SPEED	310-560 mm/min (12-22 IPM)	AVG. 430 mm/min (17 IPM)
HEAT INPUT	0.5-0.95 kJ/mm	AVG. 0.67 kJ/mm
NUMBER OF PASSES	15	

TABLE 5

EXPERIMENTAL PROCEDURE

WELDING PROCEDURES:

- HY100 3G POSITION

AMPS	195-270	AVG. 217
TRAVEL SPEED	320-1010 mm/min (13-40 IPM)	AVG. 670 mm/min (26.5 IPM)
HEAT INPUT	0.35-1.00 kJ/min	AVG. 0.55 kJ/min
NUMBER OF PASSES	21	

- HY100 1G/4G POSITION

AMPS	160-230	AVG. 190
TRAVEL SPEED	275-600 mm/min (11-24 IPM)	AVG. 420 mm/min (16.5 IPM)
HEAT INPUT	0.46-1.40 kJ/mm	AVG. 0.76 kJ/mm
NUMBER OF PASSES	14	

TABLE 6

DYNAMIC TEAR RESULTS

			DYNAMIC TEAR ENERGY J@ - 29°C	
MATERIALS	POSITION	HEAT INPUT (kJ/mm)	WELD METAL (# OF DATA POINTS)	HAZ (# OF DATA POINTS)
HY80	3G	0.32-1.04 X = 0.47	916 (4)	1436 (2)
HY80	1G/4G	0.55-0.95 X = 0.67	1101 (2)	1395 (2)
HY100	3G	0.35-1.00 X = 0.56	670 (1)	1757 (1)
HY100	1G/4G	0.46-1.40 X = 0.76	689 (2)	1368 (2)

* ALL SPECIMENS TAKEN IN T-L ORIENTATION