Special Basic Flux Cored Wire for All-Position Pulsed Welding

A specially formulated basic flux cored wire in combination with a pulsed welding machine has proven to be practical for all-position welding

BY I. E. FRENCH AND M. R. BOSWORTH

Introduction

The gas shielded, basic flux cored wires produce weld metal of inherently high quality because of the CaF_2-$CaCO_3$ flux system used. In particular, they routinely give weld metal with diffusible hydrogen levels of less than 6 ml per 100 g of deposit, good ductility and excellent low-temperature impact properties (Ref. 1).

A restriction to the wider application of such wires has, however, been their operating characteristics. Compared to other types of flux cored wires, notably those containing a rutile flux, basic flux cored wires have harsher arc action, less well regulated metal transfer, more convex beads and higher levels of spatter. In addition, basic flux cored wires have not been suited to out-of-position welding. This can be partially overcome by using small diameter wires with electrode negative polarity and short arc transfer conditions, but incomplete penetration remains a problem.

A possible means of improving the operating characteristics of basic flux wires is to combine them with pulsed welding, where the pulse parameters are designed to control metal transfer. This combination has been investigated for standard basic flux cored wires (Ref. 2). This earlier investigation used wire of AWS (Ref. 1) E70T-5 designation and found that the operating characteristics were considerably improved using pulsed welding, while weld metal mechanical properties were little affected. The practical usable range of welding current was greatly extended by pulsed welding, particularly at the lower end of the range. Even with this improved operation, however, the small diameter (1.2 mm) standard basic flux cored wires were only marginally usable for out-of-position welding.

An investigation was conducted to find a formula for basic flux cored wires that would provide true all-position capabilities with pulsed welding.

Methods and Materials

It was decided to concentrate on wire of 1.2 mm diameter, as larger diameters were considered to be less likely to be suitable for all-position welding. An argon, nominally 18% CO_2, shielding gas was used in all trials because this mixture is widely available and is known to promote controlled metal transfer from basic flux cored wires under pulsed welding conditions (Ref. 2). All trials were made using electrode positive polarity.

The pulse welding power supply used was a commercial one which incorporated microcomputer control of the output parameters. This allowed ready adjustment, via a serial link, of such parameters as peak current and voltage, background current and voltage, pulse duration and pulse frequency. These parameters were adjusted to optimize the welding operation with regard to metal transfer, bead shape, penetration and spatter level over the whole range of welding current. The optimum pulse parameters found for this wire were 480 A peak current and 2.4 ms peak current duration, for pulse frequencies from 50 to 250 Hz.

Considerable improvements in out-of-position welding were achieved through optimization of the parameters that control the adaptive characteristics of the power supply. Selective voltage sensing and processing enabled the output to adapt to changes in electrode extension and arc length while maintaining a transfer rate of one drop per pulse. This was accomplished by automatic adjustment of pulse frequency in response to changes in electrode extension and arc length. For positional welds in particular, the use of a weave technique generates comparatively large variations in arc voltage as electrode extension changes across the bead. This normally results in relatively large variations in pulse frequency as the adaptive control attempts to compensate. Such variations can be sufficient to destabilize the one drop per pulse synchronization. However, selection of adaptive control parameters which limited the rate of change of frequency in response to changes in electrode extension, resulted in a more stable arc and more uniform bead.

Using a standard, basic flux cored wire which employs a CaF_2-CaO-SiO_2 slag system as a starting point, an investigation was conducted into whether changes in core composition could be used to improve welding operation and bead shape under pulsed welding conditions. The amount of slag forming ingredients in the core was found to be an important factor, so this quantity was optimized for pulsed welding operation.

Having settled on what was considered to be an optimum basic flux wire design for pulsed welding and an

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I. E. FRENCH and M. R. BOSWORTH are with CSIRO, Division of Manufacturing Technology, Woodville, South Australia.

optimum pulse program for the wire, a series of trials was conducted, aimed at assessing the usability and resulting weld properties. The trials assessed the operating range and bead features for fillet welds in both the horizontal-vertical (2F) and vertical (3F) positions (Ref. 3). Multipass all-weld test plates to AWS joint geometry (Ref. 1) were made in the downhand (1G) position for a range of heat inputs to assess weld metal tensile and Charpy V-notch (CVN) impact properties. Mechanical test specimens were also extracted to AWS (Ref. 1) specification, that is with the center of the specimen corresponding to the mid-thickness of the plate. In addition, V-groove welds to Shipping Classification Society (Ref. 4) specifications were made in the horizontal (2G), vertical (3G) and overhead (4G) positions to assess the CVN impact, transverse tensile and bend test properties of the resulting welds. Composition and me/metallographic features of the welds were also measured.

In this work only wires giving weld metal of AWS (Ref. 1) E70 strength level were considered, although it is recognized that basic flux cored wires readily provide a basis for development of higher strength weld metal.

Results

Quantity of Slag Formers

The standard for 1.2 mm diameter basic flux cored wire used as the starting point for this work has a slag former content of approximately 5% of wire weight. It was noted previously that for pulsed welding and particularly for positional welding, the resulting volume of slag was difficult to remove and tended to interfere with bead shape. Consequently, a series of wires was obtained with the amount of slag forming components reduced to 75, 50 and 25% by weight of those in the standard wire.

The wire with 75% of the of original slag former level gave very similar behavior to the standard one with regard to slag characteristics. The wire with 50% of the of original level showed considerable improvement in that the slag formed discrete islands on the beads with minimal interference to bead shape and was relatively easy to remove. The wire with 25% of the original slag former level gave a thin layer of slag which was difficult to remove. In light of these results, it was decided to concentrate on the wire with 50% of the original slag former level and all of the following results were obtained with this wire.

Fillet Welds

The operating range for this wire/pulsed welding combination was established by preparation of series of 2F and 3F position fillet welds between 10-mm thick plates. In the 2F position, beads of excellent appearance with mitre-shaped profile and minimal spatter were achieved at average welding currents over the range 120 to 290 A. Table 1 lists the deposition rates and efficiencies measured at what were considered minimum, optimum and maximum currents. These values indicate the range of deposition rates achieved and the generally high deposition efficiencies. Table 2 lists root penetration and convexity ratio for a typical 2F position fillet of 7 mm leg length to illustrate the minimal convexity and adequate penetration achieved. An example of a section through one of these welds is shown in Fig. 1.

The range of average welding currents over which satisfactory 3F position welds could be achieved was more restricted. This range was 100 to 130 A, depending on plate thickness and welding technique (*i.e.*, stringer or weave beads). For 3F stringer and weave beads in the 10 mm plate, the optimum welding conditions were 115 A average current and 22 V. This corresponds to a deposition rate of 1.5 kg/h. Table 2 lists the root penetration and bead convexity measured for stringer and weave beads of 5 and 10 mm respective leg lengths, made under these optimum conditions. The values obtained indicate that adequate penetration and quite acceptable convexity were achieved.

Butt welds in preparations requiring a root opening of 2–3 mm (Ref. 4), were readily accomplished in the 2G, 3G and 4G positions with beads of relatively flat profiles being achieved. The soundness of these deposits was checked using x-ray radiography which showed that no significant defects were present.

Weld Mechanical Properties

The series of 1G position all-weld-metal test plates were produced using the joint geometry specified in Ref. 1 and gross heat inputs of 1.1, 1.8 and 2.6 kJ/mm (see Table 3 for weld parameters). These heat inputs were calculated according to the method described in (Ref. 4) for pulsed welding. The test plates made at 1.1 and 1.8 kJ/mm were welded using stringer bead techniques while that made at 2.6 kJ/mm was welded using a weave technique.

Standard size (Ref. 1) all-weld-metal tensile specimens of nominally 12.7 mm gauge diameter were extracted from each test plate. The tensile properties are given in Table 4. Note that the low heat input weld was made at a reduced average current and voltage compared to the other test plates. The trend apparent from these tensile results is that yield and tensile strength decreased significantly with increasing heat input, while elongation increased. If the changes are assumed to be linear, yield strength decreased by 84 MPa per unit of heat input (*i.e.*, per kJ/mm) while tensile strength decreased by 52 MPa per unit of heat input. All of the tensile properties measured readily meet the requirements of Ref. 1.

Approximately 20 CVN impact specimens of size, location and notch orientation as specified in Ref. 1 were taken

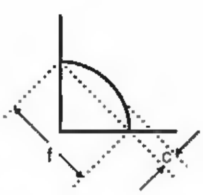
Table 1—Deposition Characteristics in H/V Fillet Welds

Operating Range	Current (A)	Consumption Rate (kg/h)	Deposition Rate (kg/h)	Deposition Efficiency (%)
Minimum	117	1.68	1.52	91
Optimum	190	3.40	3.28	96
Maximum	290	5.82	5.57	96

Table 2—Bead Profiles for 1.2 mm Diameter Wire

Bead Profiles for 1.2 mm Diameter Wire

Weld Position	Leg Length (mm)	Penetration (mm)	Bead Profile (c/f)
H/V Fillet (190 A, 26 V)	7.0	0.8	0.07
Vertical Stringer (110 A, 22 V)	5.0	0.6	0.12
Vertical Weave (115 A, 22 V)	10.0	0.5	0.09



from each test plate. These were tested at a series of temperatures over the range +20 to –80°C (+68° to –112°F) with triplicate tests at each temperature. Table 5 lists the mean CVN values obtained plus the standard deviations.

The mean CVN values for each heat input are plotted against test temperature in Fig. 2, indicating that, while there is some spread in the mean values at any particular temperature, only minor trends with heat input can be discerned. In

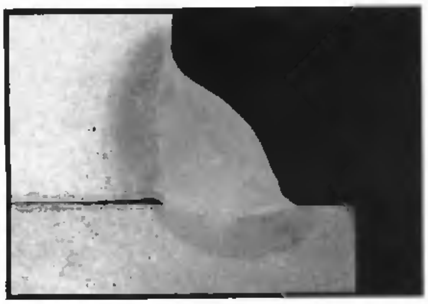


Fig. 1—Section through an uphill vertical (3F position) fillet weld made using a stringer bead technique (6X).

considering these results, the variability between individual CVN values, as quantified by the standard deviation values in Table 5, should be taken into account. The overall outcome is that the CVN results showed little sensitivity to heat input except that the lowest heat input appears to give slightly better values in the transition and upper shelf regions. Using this curve, the approximate temperatures for CVN values of 100 J and 35 J are –40°C (–40°F) and –80°C (–112°F) respectively for all heat inputs.

V-butt test plates were welded in the 2G, 3G and 4G positions (see Table 3 for weld parameters) and subjected to the types of mechanical tests specified in Ref. 4. This involved CVN testing of the weld metal (in this instance a single temperature of –40°C was chosen), plus a transverse tensile test and both face and root bend tests of the weldments. The transverse tensile test was considered satisfactory if the failure was in the base metal, while the bend tests were considered satisfactory if no crack exceeding 3 mm was present on the outer surface after bending through 120° around a former of 30-mm radius.

The results of these tests are listed in Table 6 for each welding position. This table shows that the results of the transverse tensile and bend tests were all satisfactory. The mean CVN values at –40°C were in the range 80 to 100 J which is similar to the range of values obtained at this temperature in the all-weld-metal tests (see Table 5), and suggests that the impact properties are insensitive to welding position, as well as heat input.

Composition and Microstructure of Welds

Weld metal chemical composition was measured using optical emission spectroscopy for all elements except O and N, which were measured using a fusion technique. Table 7 lists the results obtained from both the all-weld and the positional test plates. The only significant changes in composition in the all-weld test plates were a decrease in Mn level, and possibly in Si level, with increase in heat input. Weld metals from the 2G and 3G position test plates were of similar composition, while that of the 4G test plate was lower in Mn and Si. There did not appear to be any major differences in the levels of elements other than Mn and Si between any of the test plates. Weld metal O values were 0.041 to 0.045% and therefore showed little variation between test plates. All but one weld metal N value was between 0.0036 and 0.0058%. The exception was the 1G weld at 1 kJ/mm which gave a slightly higher N value (0.0076%). Measurements were also made of the diffusible hydrogen in deposits. These were found to be in the range 2–4 ml of hydrogen per 100 g of weld metal.

Examination of the as-deposited microstructure of the all-weld test plates, using optical microscopy, showed that the proportion of intragranularly nucleated components (*i.e.*, acicular ferrite and intragranular polygonal ferrite) decreased with heat input. This is illustrated in Fig. 3 which shows typical as deposited regions at the three heat inputs. To quantify these differences, point counting was conducted, involving 1000 points in each case, on the final pass at each heat input. The method described in Ref. 6 was used to find area fractions of acicular ferrite (AF), intragranular polygonal ferrite (PF(I)), grain boundary ferrite (PF(G)) and ferrite with second phase (FS). The results are listed in Table 8, and show that AF decreased markedly with heat input, particularly at high heat input, while PF(I), PF(G) and FS increased at the high heat input. In addition, the percentage area of reheated material was

Table 3—Parameters Used in the Preparation of Weld Test Plates

Parameters Used in the Preparation of Weld Test Plates

Weld Position	Average Input (kJ mm^{-1})	Number of Welding Runs	Average Current (A)	Average Voltage (V)	Average Welding Speed (mm/min^{-1})
1G	1.1	19	175	28	310
	1.2	18	180	28	290
	1.8	15	275	32	325
	2.6	9	260	33	225
2G	1.1	13	185	26	305
3G	1.2	13	120	22	170
4G	1.4	13	180	26	310

Notes:
1) Heat input has been corrected for effects of pulsing; 2) Semi-automatic welds; 3) Electrode extension estimated to be 15–20 mm.

Table 4—All-Weld-Metal Tensile Properties

Heat Input (kJ/mm)	Welding (Current/Voltage)	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)
1.1 (±0.1)	175 A/28 V	600	635	26
1.8 (±0.1)	275 A/32 V	535	583	29
2.6 (±0.2)	260 A/33 V	474	557	32

Table 5—All-Weld-Metal CVN Impact Properties

Heat Input (kJ/mm)	CVN Impact (J) Average & (Standard Deviation)					
	20°C	0°C	–20°C	–40°C	–60°C	–78°C
1.1 (±0.1)	180 (10)	181 (7)	165 (27)	86 (10)	69 (20)	34 (6)
1.8 (±0.1)	171 (15)	139 (9)	115 (5)	125 (17)	44 (19)	26 (9)
2.6 (±0.2)	163 (16)	151 (6)	120 (2)	90 (12)	46 (6)	38 (12)

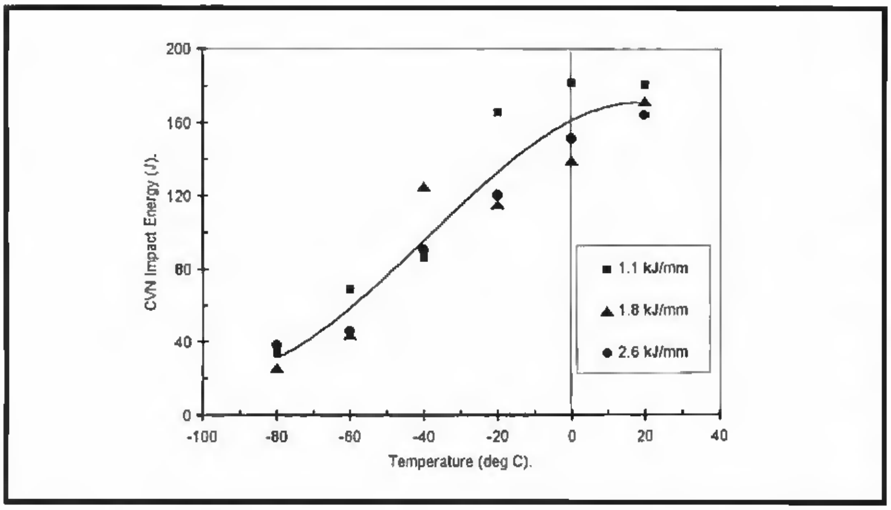


Fig. 2—Variation of CVN impact energy with temperature for weld metal in all-weld-metal test plates made at the heat inputs shown.

Table 6—Positional V-Butt Weld Test Plate Results

Position	Welding Current/Voltage	Root Bend	Face Bend	Transverse Tensile (MPa)	CVN @ –40°C (J) & (Std. Dev.)
Horizontal (2G)	185 A/26 V	passed	passed	483 base metal	82 (15)
Vertical (3G)	120 A/22 V	passed	passed	498 base metal	87 (11)
Overhead (4G)	180 A/26 V	passed	passed	480 base metal	101 (37)

Table 7—Weld Metal Composition

Test Plate Type	Weld Pos.[a]	Heat Input (kJ/mm)	Composition (wt-%) C	Mn	Si	Al	O	N
all weld	1G	1.1	0.08	1.49	0.55	0.006	0.043	0.0076
all weld	1G	1.8	0.08	1.39	0.48	0.006	0.046	0.0058
all weld	1G	2.6	0.09	1.36	0.51	0.007	0.045	0.0036
V-butt	2G	1.1	0.09	1.59	0.57	0.007	0.043	0.0040
V-butt	3G	1.2	0.10	1.58	0.55	0.007	0.041	0.0042
V-butt	4G	1.4	0.10	1.36	0.49	0.010	0.042	0.0050

Note: Each weld metal contained approximately 0.008% S and 0.013% P.

found by measuring the percentage of as-welded material in macrographs of the central regions of the welds, and then taking into account that the remainder was reheated. The values obtained are listed in Table 8. These measurements suggest that the proportion of reheated material was relatively constant in the lower heat input plates but slightly higher in the high heat input one.

Figure 4 consists of macrographs of sections through the test plates welded in the 2G, 3G and 4G positions. These indicate that sound welds with adequate side wall penetration are achieved in each position. They also suggest that more reheated material is present in the vertical weld—Fig. 4B. The as-deposited microstructure of the positional welds varied little between test plates and a typical example is shown—Fig. 5. This microstructure is of similar appearance to that of the lowest heat input all-weld test plate—Fig. 3A.

Discussion

A few reports have now appeared describing the combination of pulsed welding and standard, basic flux cored wires (Refs. 2, 7, 8). All of these indicate that operating behavior can be improved compared with that obtainable with conventional power sources, but the majority express some reservations concerning the practicality of truly all-position welding. To our knowledge, this is the first report dealing with the use of pulsed welding with specifically formulated basic flux cored wires.

The initial fillet welding trials indicated controlled metal transfer occurred over a broad welding current range and that 2F position fillets were of good

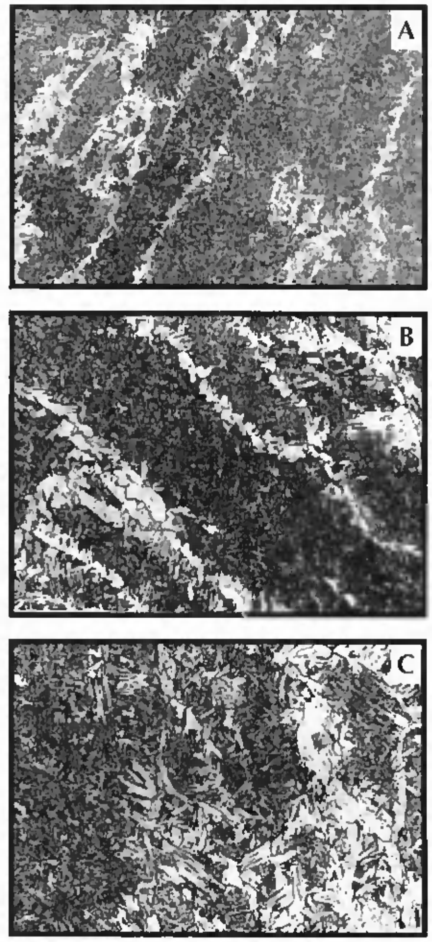


Fig. 3—Optical micrographs of as-deposited areas of all-weld-metal test plates welded at various heat inputs (200X). A—1.1 kJ/mm. B— 1.8 kJ/mm. C—2.6 kJ/mm.

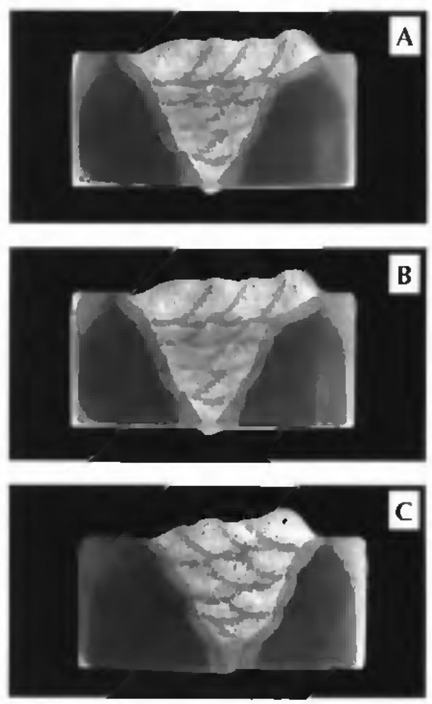


Fig. 4—Macrographs of sections through V-groove welds in various positions. A—2G. B—3G. C—4G (Plate thickness 20 mm.)

Table 8—Weld Metal Microstructure, Flat Position, All Weld Test Plates

Heat Input (kJ/mm)	As-deposited Microstructure (Area %) AF	PF(I)	PF(G)	FS	Reheated Area (%)
1.1	64	4	20	12	56
1.8	58	6	24	12	57
2.6	43	9	27	20	63

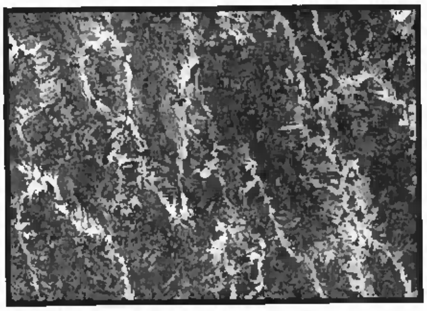


Fig. 5—Optical micrograph of typical as-deposited region of V-groove test plates (200X). (This example is from 3G position test plate.)

profile and penetration. The 3F position fillets, produced at the lower end of the welding current range using both stringer bead and weave techniques, also had good bead profile and penetration. In fact, the measured bead convexity ratios (Table 2) were significantly lower than those for standard basic flux cored wires and pulsed welding (Ref. 2).

The production of sound butt welded test plates in the 2G, 3G and 4G position, which gave entirely satisfactory mechanical properties (Fig. 3 and Table 6), provides further evidence that this combination of special basic flux cored wires with pulsed welding can be considered a practical all-position process.

Previous studies of weld metal mechanical properties from standard basic flux cored wire have shown that temperatures for 35 J CVN values were typically –60 to –80°C (–76° to –112°F) (Ref. 9), and that tensile properties were typically 630 MPa tensile strength and 29% elongation (Ref. 10). Assessment of such standard basic flux cored wires with pulsed welding has suggested that pulsed welding resulted in only marginal changes in mechanical properties compared with conventional power sources (Ref. 2). The present all-weld results show that CVN impact results are at least equivalent to those from standard basic flux cored wires as are the tensile properties. In addition, these results show that impact properties from the special wire and pulsed welding are insensitive to either heat input or welding position. This confirms the previous observation that weld metal from basic flux cored wires is insensitive to heat input over a similar heat input range (Ref. 9), but no previous assessment over a full range of welding positions appears to have been made.

There is broad agreement that, in general, low temperature impact properties of weld metal improve with the proportion of AF in the as-welded regions as shown in Ref. 11. The present results appear not to follow this trend as, although the proportion of AF decreases markedly with heat input, the impact results are largely unaffected. This decrease in AF is accompanied, at least at the high heat input, by an increase in the FS and PF(G) proportions, which are normally deleterious to impact properties. An explanation for this unexpected behavior may be the relatively high proportion of reheated material that is present. The proportion of reheated material is highest in the high heat input weld, which contains the lowest proportion of AF. Examination of reheated regions showed that, as heat input increased, the ferrite became more thoroughly equiaxed, though of marginally larger grain size.

It is possible then, that the less desirable as-welded microstructure at high heat input was balanced by a higher proportion of reheated material with more equiaxed structure, leaving low temperature impact properties unaffected. In addition, even the as-deposited areas in the region of the test plates from which mechanical test specimens were taken, are possibly affected by subsequent weld passes as discussed in Ref. 12.

Conclusions

1) The combination of a specially formulated basic flux cored wire, using the conventional CaF_2-CaO-SiO_2 slag system but containing a reduced proportion of slag forming ingredients, with pulsed welding using an optimized pulse program has proven to be a practical, all-position welding process.

2) The weld metal mechanical properties and hydrogen levels from the basic flux cored wire/pulsed welding combination are at least equivalent to those expected from standard basic flux cored wires and in addition are insensitive to heat input and welding position.

3) The proportion of acicular ferrite in as-welded regions decreased markedly with increase in heat input but, despite an expectation that this would lead to degraded low temperature impact properties, these properties were unaffected.

4) It appears that the proportion and microstructural details of reheated regions have played a significant role in determining low temperature impact properties.

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