Effects of Welding Parameters on Weld Zone Toughness and Hardness in 690 MPa Steel

Optimum preheat and interpass temperatures, as well as heat input, are established for welding 690-MPa quenched and tempered steel

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ABSTRACT. Specifications for the welding of high-strength steels are generally intended to control hydrogen cracking and provide adequate weld zone toughness for resistance to fatigue cracking and shock loading. The specifications should also allow welding to be undertaken safely and profitably.

The work described here was designed to identify the optimum match of welding parameters, notably preheat, interpass temperature and heat input, for the welding of a 690 MPa (100 ksi) microalloy quench and tempered steel.

The paper covers investigations into two aspects of weldability: toughness and hardness. The first part involved shielded metal arc (SMA) butt joint welding of carefully designed plates at a range of preheat and interpass temperatures and heat input values, to identify welding procedures that give maximum HAZ and weld metal toughness. The second is a laboratory study of bead-on-plate submerged arc welds to clearly identify the relationship between hardness and welding parameters.

The test procedure for the first investigation involved SMA welding at preheat and interpass (P and I) temperatures from –20°C to 220°C (–4° to 428°F) using heat input values of (approximately) 1.3, 2.9 and 4 kJ/mm (33, 74 and 102 KJ/in.) Charpy V-notch energy and fracture appearance transition curves were then generated with the Charpy notches being carefully located to give the lowest toughness values.

Results showed that the minimum preheat and interpass temperature for control of weld metal hydrogen cracking

was 60°C (140°F) and that low values of toughness in both weld and heat-affected zone consistently occurred in the weld root region. Low preheat techniques and one-sided welding should therefore be avoided for critical applications.

For weld metal, greatest toughness occurred at high preheat and interpass temperatures (160°C; 320°F) combined with low welding heat input (1.2 kJ/mm; 30 KJ/in). For high heat input welding, preheat and interpass temperature had little influence on toughness over the range of temperatures examined.

For heat-affected zone regions, levels of toughness obtained when using the high preheat/low heat input and low preheat/high heat input techniques were similar. It was found, however, that careful control of preheat and interpass temperature was essential, for each heat input value, because toughness can drop off rapidly on either side of the optimum interpass temperature. For some applications, optimum preheat and interpass temperatures were found to lie between 60° and 90°C (140° and 194°F).

In the second study, a series of head-on-plate submerged arc welds was deposited using a wide range of preheat and

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interpass temperatures, voltages, currents and travel speeds. In each case, the welding parameters were chosen so that the welding power input (V x I) could be held constant while varying heat input, or vice versa. For each weld, hardness readings were taken in both the weld deposit and HAZ at approximately 1 mm (0.04 in.) from the weld interface.

It was found that:

1) HAZ hardness readings (390–430 HV 30 for heat input values up to 2 kJ/mm) were consistently higher than weld metal hardness readings.

2) Heat input has a marginal effect on HAZ hardness up to about 2 kJ/mm (51 kJ/in.), however, above 2 kJ/mm the hardness drops off at a rate of approximately HV 30 for each increase of 1 kJ/mm (25 kJ/in.).

3) Weld metal hardness dropped continuously over the range of 0.5 to 4.5 kJ/mm (13 to 114 kJ/in.).

4) Both HAZ and weld metal hardness drops approximately 1 HV 30 for every 4°C (7.2°F) increase in preheat and interpass temperature.

The results of this work have been used to develop an optimized weld design for butt joint welding of 35–50 mm (1.4–2 in.) plate. This uses high heat input for all but the weld capping passes, where high interpass temperatures and low heat input techniques are employed.

Introduction

Preheat of weld preparations in high-strength steel is necessary for the control of hydrogen (cold) cracking, to avoid excessive hardness in weld heat-affected zones, and to provide adequate toughness for shock resistance. The required levels of preheat may be determined by any of a number of techniques, most of which are based upon empirical relationships between base metal composi-

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tion, weld restraint, microstructure and cooling rate. The WTIA Technical Note 1 (Ref.1), for example, provides a minimum preheat requirement to control cracking from a computation involving weld composition, plate thickness, hydrogen levels and heat inputs (HI).

One problem with these established relationships is that they were generally developed between 1950 and 1980, and therefore, relate to the more popular steels available during that period. For example, the influence of composition is commonly measured by calculating a carbon equivalent (CE) value according to a formula such as the International Institute of Welding (IIW) formula (Ref. 2):

$$CE_{(IIW)} = \%C + \frac{\%Mn}{6} + \frac{\%Cr + \%V + \%Mo}{5} + \frac{\%Ni + \%Cu}{15}$$

(1)

This simple formula does not take into account the influence of small quantities of the highly potent alloying elements such as Nb, B and N, which may be used in modern steels. Furthermore, the sensitivity of a steel to cracking may be influenced by factors other than composition, thickness and heat input. For example, the level of restraint across a weldment is influenced by the base metal strength, which may be dependent upon the prior thermal and mechanical treatments in addition to the chemical composition. Other factors that can have a significant influence over hardness and sensitivity to hydrogen cracking include the joint design, electrode hydrogen content and diffusible hydrogen in the base plate.

The carbon equivalent formulas were strictly developed for determining the hardenability of HAZs. Their adaptation to hydrogen cracking in welds and HAZs has developed out of engineering practice. Furthermore, these formulas are also deficient in that they apply only to the base metals for which they were developed.

With the introduction of modern microalloyed steels, the problem of HAZ cold cracking has been virtually eliminated, and now the weld deposits are critical because these are the regions of weldments most prone to cracking and embrittlement.

For these reasons, established rules for control of hydrogen cracking may be inappropriate for a new application, and it becomes highly desirable to undertake new qualification trials. Furthermore, control of cracking may not be the only requirement of a given welding procedure. In the fabrication of naval vessels, it is essential that the hull has adequate

Table 1 — Typical Composition of Steel and All-Weld-Metal Deposits

Typical Composition (wt-%)

Element	BIS 812 EMA	OX812EM	SMAW Filler Metal E 12018-M2	120-S1 SA Filler Metal and OP 121 TT® Flux
C	0.13	0.1	0.04	0.08
Si	0.29	0.28	0.20	0.34
Mn	0.87	0.93	1.55	1.74
P	0.013	0.011	0.010	0.009
S	0.002	0.0004	0.008	0.004
Cr	0.45	0.52	0.03	0.31
Ni	1.20	1.23	3.67	2.72
Mo	0.35	0.4	0.26	0.62
V	0.015	0.030	0.01	<0.01
Ti	0.009	0.005	—	0.01
Cu	0.19	0.22	Nil	0.02
Al	0.077	0.045	—	—
Nb	0.01	0.015	—	<0.01
B	0.0015	0.002	—	—
N	—	0.006	—	0.0081
Ca	≤3 ppm	—	—	<3 ppm
O	0.009	—	—	—
Fe	Bal	Bal	Bal	Bal

toughness to withstand shock loading, such as that which might be caused by exploding mines or torpedoes. This paper describes some of the background experimental work which was undertaken to develop welding procedures for use on a submarine, where toughness is essential.

Hulls of the new Australian Collins class of submarine are fabricated from a steel developed from the Swedish OX812EM formulation (composition and mechanical properties in Table 1). The welding procedures being used are developed from the high preheat/interpass temperature and low welding energy input techniques that were used for qualification of the high-strength steel plate (Ref. 3). These in turn were based upon recognized sound welding practice for the more highly alloyed HY100 steel. In the light of subsequent experience, it has become clear that these procedures should be reviewed because:

1) For some situations it is essential to use reduced preheat and interpass temperatures for the safety and comfort of welders. This includes certain areas

where space is confined and preheat temperatures greater than 100°C (212°F) are specified.

2) Reductions in preheat, or increases in the allowable heat input, can lead to considerable savings in both time and money. The commonly accepted cost of preheating to levels appropriate for HY100 steel in submarines is of the order of $A 20,000 (≈$U.S. 14,000) per 1000 kg (2200 lb) of hull constructed.

3) In some circumstances, reductions in the level of preheat applied to a joint can actually improve the performance of that joint. This occurs, for example, when a combination of excessive preheat and heat input leads to a wide zone of softening or overtempering. By choosing an appropriate combination of preheat and interpass (P and I) temperature and welding heat input, the weld zone toughness can be maximized.

It is therefore essential to determine the effect of preheat on weld zone properties.

The first part of this paper therefore describes a study into the effect of preheat and interpass temperature on the

Table 2 — Typical Mechanical Properties

0.2% proof stress (MPa)	750	780	800	760
UTS (MPa)	840	825	850	850
Elongation (A5, %)	18	18	19	21
Charpy impact energy (J)				
at −18°C	180	148	100	120
−60°C	160	80	—	—
−84°C	120	—	—	—
−51°C	—	—	73	87

Fig. 1 — Location of weld metal Charpy specimens. Notches are perpendicular to plate surface, and located in a region considered to give the lowest values for each of the three zones.

Fig. 2 — Location of base metal Charpy specimens. These are co-planer with the weld metal specimens and have notches just outside the fusion line.

Position: Uphill
Electrodes: Atom arc 12018-M2, 3.15 or 4.0 mm Dia.
Welding parameters:
  (All welds: Voltage: 23 V)
  Weld root:
    Travel Speed: 1 mm/s
    Current: 127 A
    Heat Input: 2.9 kJ/mm
  Weld middle:
    Travel Speed: 0.9 mm/s
    Current: 150 A
    Heat Input: 3.8 kJ/mm
  Weld top:
    Travel Speed: 1.9mm/s
    Current: 109 A
    Heat Input: 1.3kJ/mm

Fig. 3 — Welding procedure for each plate showing the approximate location of weld beads and the weld Charpy specimens.

toughness of critical shielded metal arc (SMA) weld zone regions (both weld metal and HAZ). The approach adopted in this work differs from that used by other experimenters, who use cooling rate as a primary measure of thermal cycle. Two measures of cooling rate have been used: cooling rate at a given temperature (Ref. 4), or the time taken to cool from 800° to 500°C (1472° to 932°F) ($\Delta t_{8/5}$, Ref. 5). For welding of thick plate, these equations are approximately proportional to the welding heat input (HI) (Ref. 6):

$$\Delta t_{8/5} = k(HI) \qquad (2)$$

In fact, the toughness of any weld zone may depend upon a large number of additional factors, such as the full thermal cycle (Ref. 6), the grain structure (equiaxed, columnar, etc., Ref. 7), weld restraint and the extent of weld dilution.

In this work, three values of heat input are used to undertake groove welding on a 50-mm (2-in.) thick plate and the preheat and interpass temperatures are varied. This approach provides data that can be directly translated to welding specifications, and it can be readily understood by the fabricator, who is familiar with the use of minimum preheat and interpass temperature to control hydrogen cracking.

An additional investigation was undertaken in order to study the effect of welding parameters on the hardness of various weld regions and on the concomitant weld dilution and depth of penetration. In this work a series of submerged arc welds was deposited on BIS 812 EMA steel (composition and mechanical properties in Tables 1 and 2) using a wide range of preheat and interpass (P and I) temperatures, voltages, currents and travel speeds. The submerged arc welding process was chosen for this work because it offers good control over all welding parameters, and is believed to be a more cost-effective process than SMA for

welding in the flat (1G) position. Submerged arc welding is extensively used for welding of the Collins submarines.

Experimental

For the first investigation, the toughness of various regions in a series of weldments was assessed using the Charpy test with an ISO striker (Ref. 8). In all cases the exact location of the notch was chosen to coincide with the microstructure that was estimated by the authors to give the lowest Charpy energy. In the case of weld deposits, the notch was generally parallel to coarse columnar grains. In the case of heat-affected zones, the notches were generally located close to the fusion boundary so that reheated, coarse-grained HAZ was tested. With the irregular shape of the fusion boundary and the relatively small volume taken up by each of the various reheated coarse-grained zones (Ref. 6), each Charpy notch generally coincided with a range of microstructures.

The range of preheat and interpass (P and I) temperatures under investigation extended from –20° to 220°C (–4° to 428°F). The explanation for this range is that –20°C lies well below the lowest temperature at which any practical welding is performed and 220°C is more than the maximum P and I temperature likely to be used. It was anticipated that cracking might occur at lower P and I temperatures (below 20°C; 68°F) and that some reduction in mechanical properties will begin to occur at temperatures approaching 220°C.

The Charpy test specimens had notches located perpendicular to the plate surface and oriented so that cracking was forced to travel in a direction parallel to the welding direction. Before cutting any notches, all specimens were lightly etched so that the exact location for each notch could be determined. The location of notches in weld metal Charpy specimens is shown in Fig. 1. The base metal Charpy specimens (Fig. 2) were parallel to the weld metal specimens and co-planer with them. These had notches close to the weld interface.

The design of each test plate (Fig. 3) has been carefully contrived to give examples of the broad range of weld deposits that may occur in real welds. For example, the all-weld-metal Charpy V-notch specimens are located at examples of low heat input, high heat input and high dilution regions of the weld deposit. The corresponding base metal Charpy specimens are located at examples of (approximately) 5, 1 and 2 thermal cycles, respectively.

The identification code for each test

series has two letters. The first indicates whether the notch is located in the weld (W) or heat-affected zone (H) and the second shows whether the specimens are located at the top (T), middle (M) or root (R) of the weld. As a guide to the system employed, example codes for three test series are as follows: WT: weld metal, top; WM: weld metal, middle; HR: heat-affected zone, root.

For each combination of P and I temperature and Charpy specimen location, nine specimens were prepared. The test temperature for each Charpy specimen was chosen so that a transition curve could be generated for each location/preheat combination. Compositions and mechanical properties of both base metal and undiluted weld metal are provided in Table 1.

During the welding of plate A (at –20 °C), the weld deposit showed extensive cracking that was later identified as hydrogen cracking — Fig. 4. Since it was not possible to take Charpy specimens from this plate, welding was terminated at this preheat level.

Cracking also occurred in the weld deposit of the plate welded at room temperature (23°C; 73°F), but this cracking was not widespread and there was sufficient metal remaining to obtain the required number of Charpy specimens at each location of the weld.

For each set of Charpy tests the following temperatures were recorded:

1) The temperature of 28 J fracture energy.

2) The temperature of 47 J fracture energy.

3) The temperature of 100 J fracture energy.

4) The fracture appearance transition temperature (FATT).

The fracture appearance transition temperature (FATT) is the temperature at which the fracture appearance is approximately half dull and slanted (indicating ductile fracture) and half shiny and flat (indicating brittle fracture). It is measured by constructing full transition curves for fracture appearance and reading off the temperature corresponding to 50% fibrosity.

It was intended to record the upper shelf energy, however, this was not achieved for any of the curves generated. In most cases, 100 J was not achieved in the transition curves and the number of datum points for this parameter is therefore limited.

Because scatter was anticipated to be great in some of the test results, two additional temperatures were recorded for each of the plots. These were the FATT and 47 J temperatures for curves constructed along the lower bound of results.

These were designated WFATT and W47 J, respectively, in this work.

Bead-on-plate welding used in the second investigation was undertaken with the submerged arc process, since this is widely used in submarine manufacture and offers good control over the welding parameters. Composition and properties of the 120S electrode used for this work are presented in Table 1. Preheat and interpass temperatures selected for this work ranged from –10° to 170°C (14° to 338°F), currents from 138 to 422 A and travel speeds from 2.5 to 12.4 mm/s (6 to 29 in./min). The welding parameters were selected so that welding power input (V x I) could be held constant while varying the heat input, or vice versa.

Hardness readings were taken in both the weld deposit and heat-affected zone (HAZ), with the HAZ hardness readings being taken approximately 1 mm (0.04 in.) from the weld interface as illustrated in Fig 5. At each location, three hardness readings were taken and the value reported was the average of these three readings.

Results

Effect of Welding Parameters on Weld Zone Toughness

In analyzing results of the first investigation, it is considered desirable to have the ductile/brittle transition at the lowest
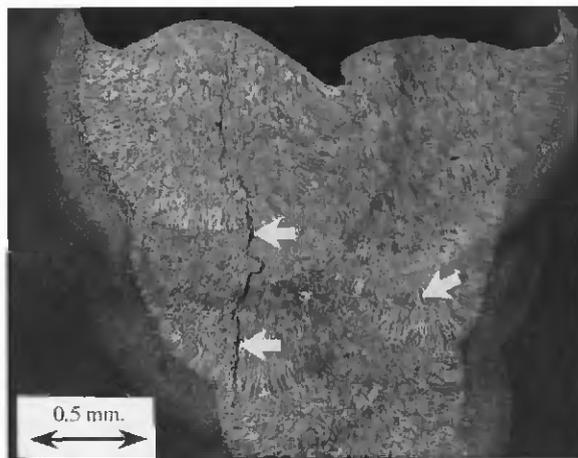

Fig. 4 — Macrograph showing extensive weld metal hydrogen cracking (arrowed) in plate welded at –20°C. 40% Fry's reagent.

temperature. Therefore, the best results for a given set of prescribed Charpy energy valves are those which give the lowest transition temperatures, as illustrated in Fig. 6. Results are presented in Figs. 7–13 and summaries of the important findings are provided in Figs. 14 and 15. In some instances the WFATT and W47J transition temperatures are high (i.e., close to zero) showing that the toughness of these regions is not good. It should be borne in mind, however, that these results represent the worst obtained from the worst regions of each of the six zones under investigation.

In Fig. 7 the results for HAZ top, middle and root are presented. For HAZ top results there is a clear drop in the temperature at P and I values centered on 100°C (212°F). This suggests that 100°C P and I temperature provides the toughest weld metal at this location. The HAZ
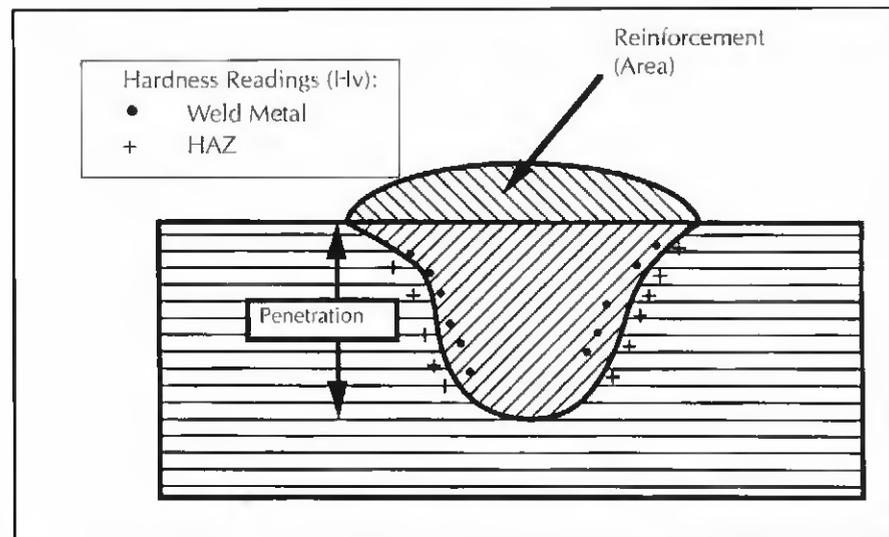

Fig. 5 — Illustration showing the approximate location of hardness readings in the bead-on-plate submerged arc welds. The weld reinforcement area and weld penetration are also illustrated.
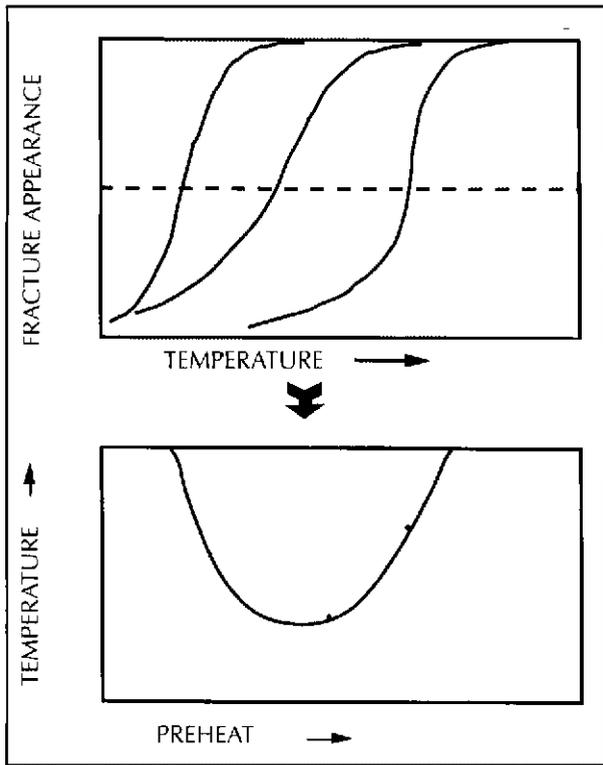
Fig. 6 — Technique for analyzing Charpy test results. The transition temperature (in this case FATT) is measured from the Charpy transition curve and plotted against preheat. The greatest toughness occurs at the lowest point on the curve (in this case at a slightly lower preheat temperature than that used for A).

Fig. 7 — Charpy energy and fibrosity values for the three HAZ regions. Definitions of the various codes are provided in the text.

middle results in Fig. 7 are inconsistent in that the energy results also show that best toughness can be obtained by using 100°C preheat; whereas, the two fracture appearance curves give the lowest temperatures (i.e., best results) at 60°C P and I temperature. Results for the HAZ root region are also inconsistent with 5 of the 6 curves[1] showing a significant decrease in toughness at 100°C P and I. The 100°C P and I temperature work should therefore he repeated to check for consistency.

Results for weld metal (Fig. 8) showed less pronounced changes in toughness as a consequence of varying P and I temperature. The 'weld top' results show that best results are obtainable at 180°C while the 'weld middle' results show very little change in the transition

curves as a consequence of changing preheat temperature. The 'weld root' results showed a slight toughness improvement at 60–100°C.

In order to identify more clearly the trends indicated with all of these results, they have been replotted in Figs. 9 to 13 using third-order polynomial regression analysis to produce smooth, best-fit curves for each location (weld top, HAZ middle, etc.). This approach is approximate only and the results of this work would need to be verified experimentally, using the same welding procedures.

The 28 J energy results (Fig. 9) showed considerable scatter and the regression coefficients were generally low (of the order of 0.6–0.8). This indicates that the measure of toughness is unreliable and low confidence should be given to the results. It is noteworthy, however, that the best results were obtained at the weld surface when about 165°C (329°F) preheat was applied.

The results for 47 J and W47 J (Figs. 10 and 11) gave higher levels of confidence (regression coefficients about 0.7–0.95) and were self consistent. It is thus concluded that these measures give an improved indication of the relative toughness of the various welding procedures. The results show that best toughness in the HM, HR and WR positions may be obtained by using about 80°C (176°F) P and I temperature.

The FATT results (Figs. 12, 13) gave high confidence levels (coefficient of 0.85–0.95), and the results were also reasonably consistent. Best toughness in the HR, HM and HT positions was obtained at about 70°C (158°F), while the best toughness overall was again obtained at the weld top with a P and I temperature of about 150°C (302°F).

The 100 J results were inconclusive due to the shortage of data and the wide scatter of results.

The best toughness results for each region are presented in Figure 14. The temperatures given here are the lowest points on the preheat vs. temperature graphs presented in Figs. 9 to 13. For weld metal, this graph clearly shows that the low heat input/high P and I temperature technique used at the weld surface gives significantly better results than the high heat input/low P and I temperature technique used at the weld middle and that both of these techniques give better results than those achieved at the high dilution, weld root region.

In the heat-affected zone, it is apparent that toughness at the weld center is similar to that at the surface, while the
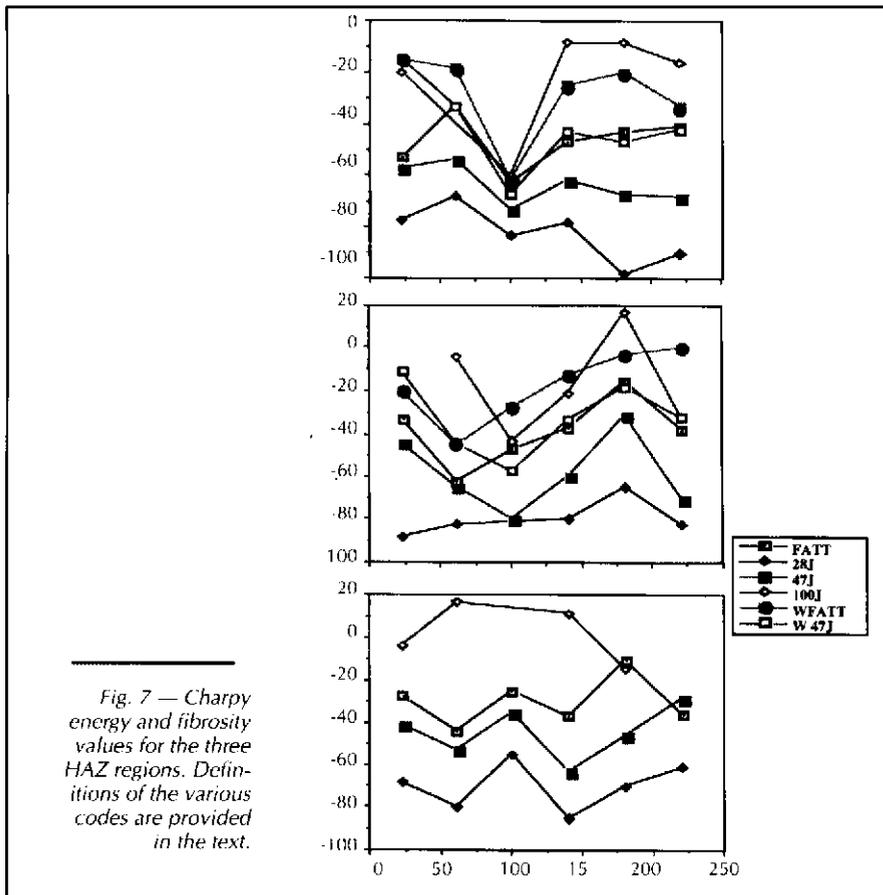
1. 100 J Charpy energy was not achieved for the 100°C preheat plate.

Fig. 8 — Charpy energy and fibrosity values for the three weld regions.

Fig. 9 — Temperature of 28 J energy for each location in the weldment at particular preheat/interpass temperatures. Curves are third-order polynomial regression lines for each weld zone. Optimum temperature is the lowest point in each plot.

root region toughness is considerably lower than either of these two locations.

In absolute terms the best toughness to be obtained in this work occurred at the weld surface when using low heat input and high preheat welding procedures. The FATT for weld metal at 180°C (356°F) P and I temperature was –69°C (–92°F).

Optimum Preheat and Interpass Temperatures

A summary of the optimum P and I temperatures as determined by the FATT and 47 J is provided in Fig. 15. For the low heat input weld deposits at the weld surface, best toughness was achieved by using 150° to 180°C (302° to 356°F) P and I temperatures, while for the WR, HM and HR positions the best properties were obtained with preheat/interpass temperatures of 60° to 90°C (140 to 194°F). For the reduced heat input, HT position, the greatest toughness was obtained over a wide range from 80° to 150°C (176° to 302°F). There was no clear advantage with the use of any par-

ticular preheat/interpass temperature at the high heat input WM position.

Effect of Welding Parameters on Weld Zone Hardness

Results of the work on weld zone hardness are presented as a series of graphs showing the different relationships found to exist (Figs. 16, 17). It was found that HAZ hardness readings (390–430 HV 30 for heat input values up to 2 kJ/mm) were consistently higher than the weld metal hardness readings. Descriptions of the relationships are presented below.

Effect of Heat Input and Power Input on Weld Metal Hardness

The relationship between hardness and heat input is illustrated in Fig. 16 for each of the preheat values used. For HAZ regions the effect of heat input is marginal, up to about 2 kJ/mm, however, the hardness drops off significantly between 2 and 4.5 kJ/mm. For –10°C, the hardness drops about 117 HV 30 between 1.5 and

4.5 kJ/mm. This represents a drop of 39 HV 30 for every increase of 1 kJ/mm (25 kJ/in.). At 170°C preheat the hardness drops from a lower peak (385 HV 30) at 1.5 kJ/mm to a similar hardness (295 HV 30) at 4.5 kJ/mm. This represents a drop of 30 HV 30 for each increase of 1 kJ/mm.

For weld zones, the drop in hardness was continuous over the range of heat input values tested (0.5 to 4.5 kJ/mm), however, as illustrated in Fig. 17B, the drop in hardness was greater between 1 and 2.5 kJ/mm than for heat input values over 2.5 kJ/mm (3.5 kJ/mm).

The effect of power input on hardness was found to be small and the spread of all results was narrow (up to about 10 HV 30 at 1.5 kJ/mm).

Hardness vs. Preheat

By plotting hardness against current for each value of P and I temperature, it is possible to read off hardness values for 200, 300 and 400 A and develop a plot of hardness against preheat as shown in Fig. 17. Heat input for this work was about 2 kJ/mm. To obtain this, each in-

Fig. 10 — Temperature of 47 J energy for each location.

Fig. 11 — Lower bound temperature of 47 J energy for each location (as in Fig. 7).

crease in current was matched by an equivalent reduction in travel speed, or vice versa. Evidently, hardness drops roughly linearly as P and I temperature is increased. In the HAZ, there was little difference between the three current values, and the average hardness dropped steadily from 420 HV 30 at –20°C P and I temperature to 385 HV 30 at 120°C. This represents a drop in hardness of approximately 1 HV 30 for every 4°C increase in P and I temperature.

In the weld deposit, hardness readings at –10°C PandI temperature were significantly higher (335 HV 30) for the 400-A welds than for the 200- and 300-A welds (about 303 HV 30). The hardness values converged, however, as PandI temperature was increased and the average hardness of all three current values was about 270 HV 30 at 170°C P and I temperature. In this case, the drop in hardness was about 1 HV 30 for every 3°C (5.4°F) increase in P and I temperature for the 200-

A welds and 1 HV 30 for every 4.4°C (8°F) P and I temperature increase for the 300- and 400-A welds. The high hardness readings at –10°C P and I temperature was associated with formation of bainite and martensite in the weld zone — Fig. 18.

Effect of Current on Depth of Weld Penetration

Depth of joint penetration is impor-

Fig. 12 —Fracture appearance transition temperatures for each weld zone.

Fig. 13 — Lower bound of fracture appearance transition temperatures. Lowest points on each plot represent optimum preheat temperature.

tant in the development of welding procedures. For a constant heat input of 2 kJ/mm, Fig. 19 shows that the depth of joint penetration increased in a parabolic manner from 1 mm at 100 A to about 6 mm at 400 A.

Heat Input vs. Reinforcement

For each deposited weld bead, the area of reinforcement was measured by tracing the weld outline on transparent graph paper and counting squares to give the area of weld above the level of the plate. Results are plotted in Fig. 20.

There was a roughly linear relationship between heat input and reinforcement, with the approximate relationship being:

[reinforcement area (mm^2)] =
[25 × heat input (kJ/mm)] − 10   (3)

Discussion

The experimental technique used here produced consistent results for the 47 J, W47 J, FATT and WFATT parameters. Considerable scatter occurred with the 28 J parameter, and there was insufficient data to obtain reliable information from the 100 J energy parameter.

Welding of the plate that had been cooled to −20°C proved unsatisfactory due to development of significant weld metal hydrogen cracks. This cracking occurred due to both the very low temperature of the plate and the existence of water, in the form of frost, on the plate surface. The fact that cracking predominantly occurred in the weld metal shows that the weld is more sensitive to cracking than this base metal.

The relatively high crack resistance of this base metal, when compared to the more traditional HY 100 and Q2N steels, can be explained by its leaner alloy content. The weld deposit, however, is identical to those deposits used for the HY 100 and Q2N steels and the alloy content is high. In practical terms, therefore, the lowest levels of preheat that can be tolerated without incurring a risk of hydrogen cracking is governed by the crack sensitivity of the weld deposit. To gain benefit from the reduced crack sensitivity of the new, low alloy steels, it is therefore necessary to develop welding electrodes and welding procedures that give an equivalent improvement in crack resistance.

Results for the other levels of preheat show that, of the six regions studied, best toughness can be achieved in the weld deposit when low heat input, 180°C P and I temperature is used. Furthermore, the toughness at HAZ surface (HT) was
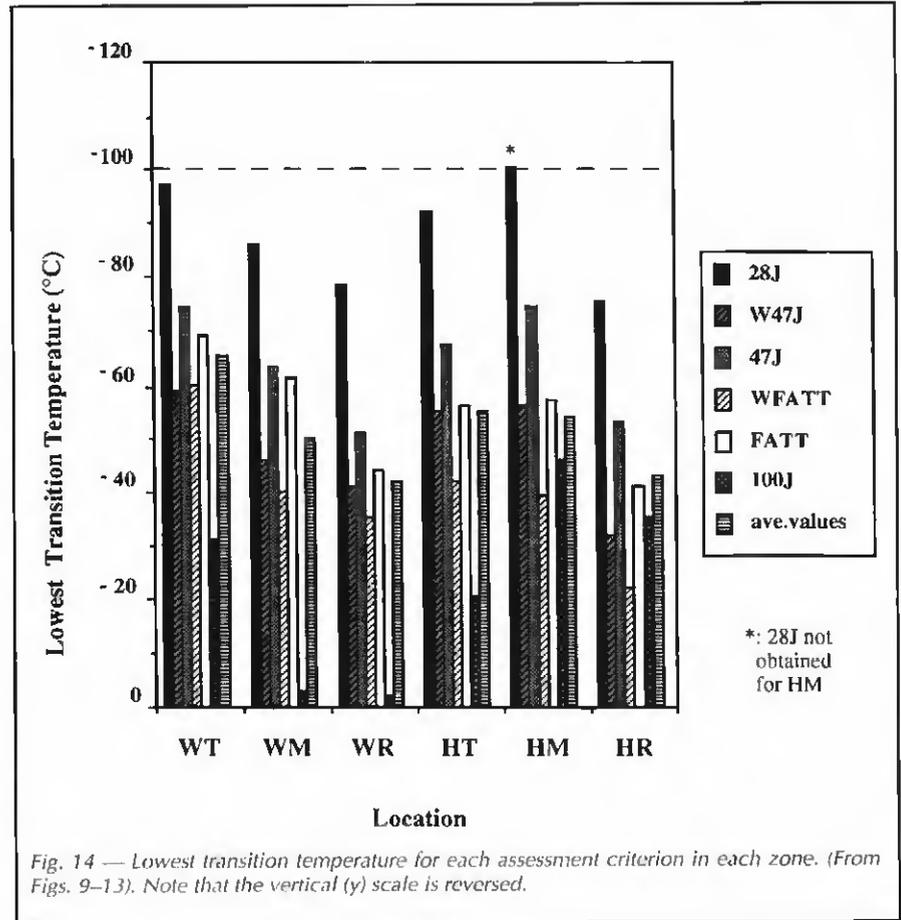
Fig. 14 — Lowest transition temperature for each assessment criterion in each zone. (From Figs. 9–13). Note that the vertical (y) scale is reversed.
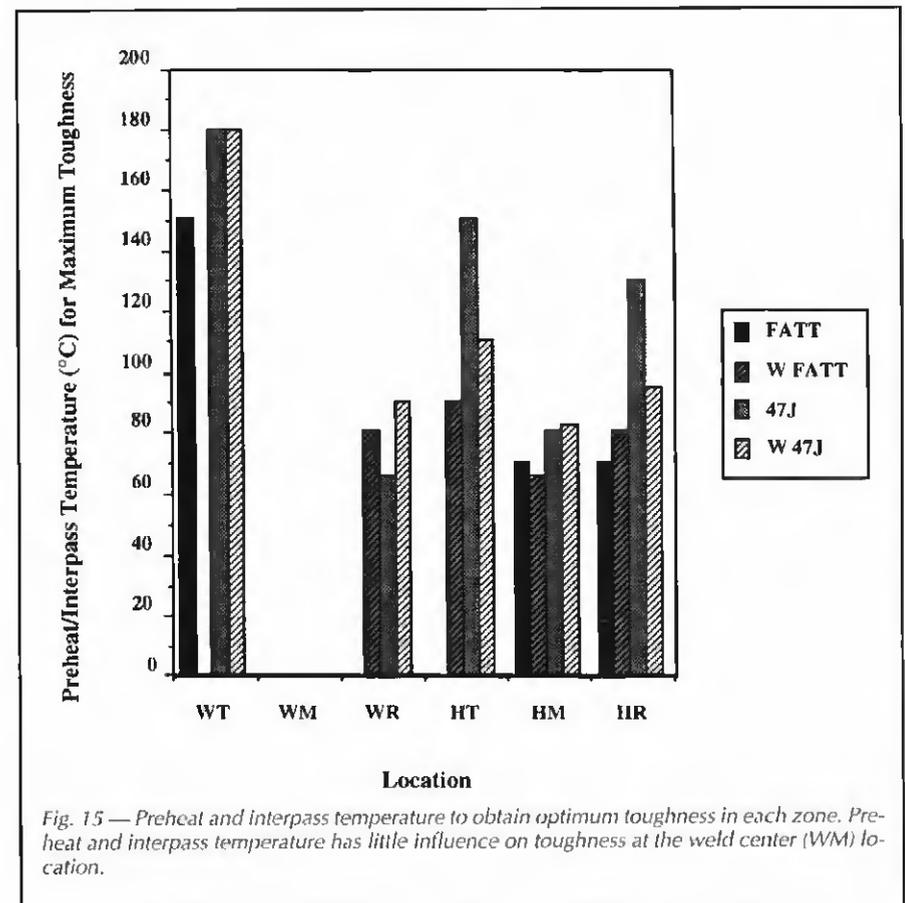
Fig. 15 — Preheat and interpass temperature to obtain optimum toughness in each zone. Preheat and interpass temperature has little influence on toughness at the weld center (WM) location.

Fig. 16 — Hardness for different values of heat input and interpass temperature. A — HAZ; B — weld metal.

Fig. 17 — Relationship between hardness and preheat for current values of 200, 300 and 400 A. All welding was undertaken at 2 kJ/mm.

Fig. 18 — Micrograph of weld metal deposited at –10°C preheat and 400 A welding current. Higher hardness readings in this weld deposit was associated with the formation of martensite and bainite.

Depth of Penetration Vs. Current

Fig. 19 — Effect of current on depth of joint penetration at 2 kJ/mm.

similar to that at the HAZ middle and the HAZ top transition curve was about 10°C higher in temperature than the weld top (WT) transition curve.

Practical experience with the explosion bulge testing of this OX 812 EM and similar steels, such as BSI 812 EMA, has shown that the early results were marginal and that a sharp ductile/brittle transition occurred at about −22°C (−7.6°F) (Ref. 9). When low heat input/high P and I welding procedures were used with an identical electrode to that described here, it was also found that brittle failure often occurred along the HAZ. Thus, the 10°C temperature shift in Charpy energy found here probably represents the difference between marginal HAZ performance and satisfactory weld performance in the explosion bulge test. To obtain similar weld performance in submarine construction, it is considered essential that similar low heat input/high P and I temperature techniques be used. Protection of the HAZ may be achieved by using a "top hat" procedure similar to that used in experimental explosion bulge testing (Ref. 10). In this way a tough weld deposit can be used to protect a marginal HAZ.

The work has shown that the HAZ toughness is equivalent when both P and I high temperature/low heat input and P and I low temperature/high heat input techniques are used. The advantages of using low P and I temperature and high heat input include considerable savings in time, expense and improved operator safety and comfort. Use of high heat input welding techniques also boosts productivity considerably. If HAZ properties are considered in isolation, it is therefore considered desirable to use high heat input/low P and I temperature techniques. As indicated by Figs. 9–13, however, it is important that the actual preheat and interpass temperatures are tightly controlled because HAZ performance drops off rapidly either side of the optimum temperature.

Welding with increased heat input and lower P and I temperature slightly reduces the weld zone impact performance as shown in Fig. 13 (WM). This may be tolerable, however, in the weld fill passes where the demand for toughness is not as great as near the weld surface. Moreover, improved operator comfort may result in better weld quality.

At the weld root, toughness is low in both the weld and HAZ regions despite the fact that intermediate weld heat input values were used. In the weld deposit, this low toughness is partly due to the high dilution of base metal. Furthermore, in both the weld metal and HAZ, root mechanical properties can be adversely
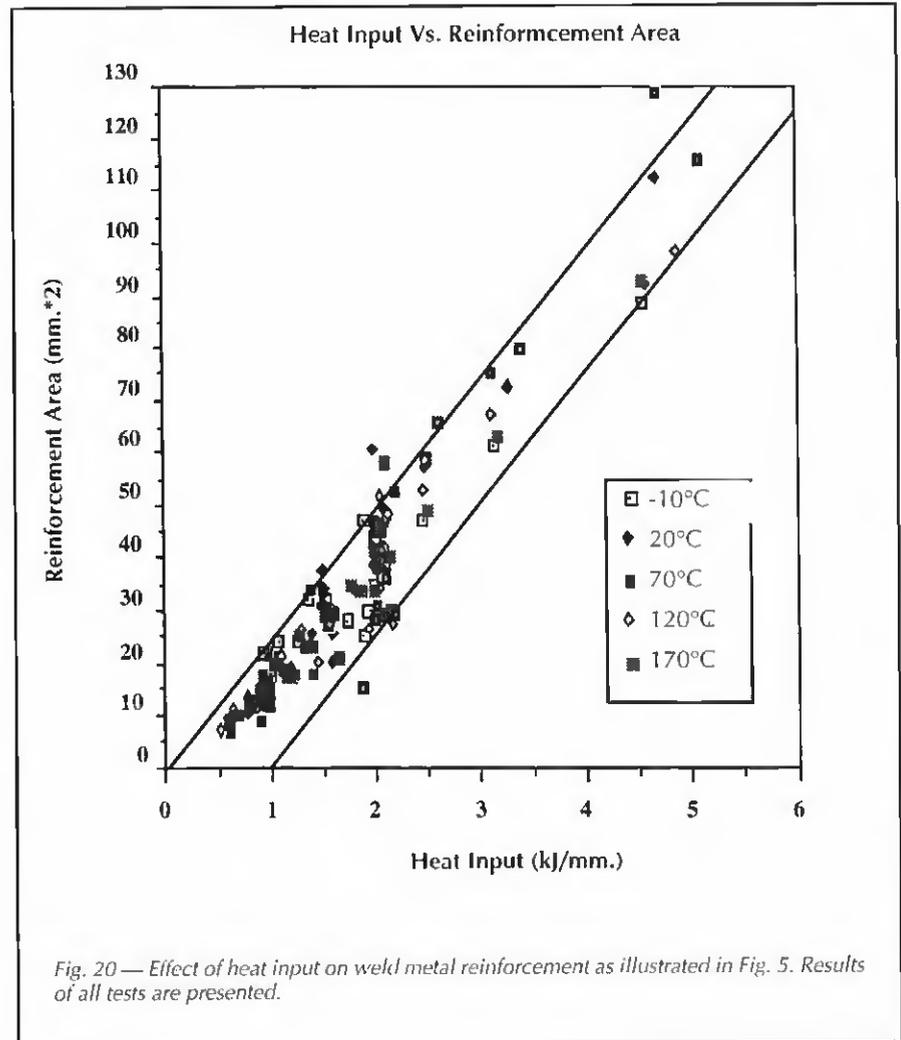

Fig. 20 — Effect of heat input on weld metal reinforcement as illustrated in Fig. 5. Results of all tests are presented.
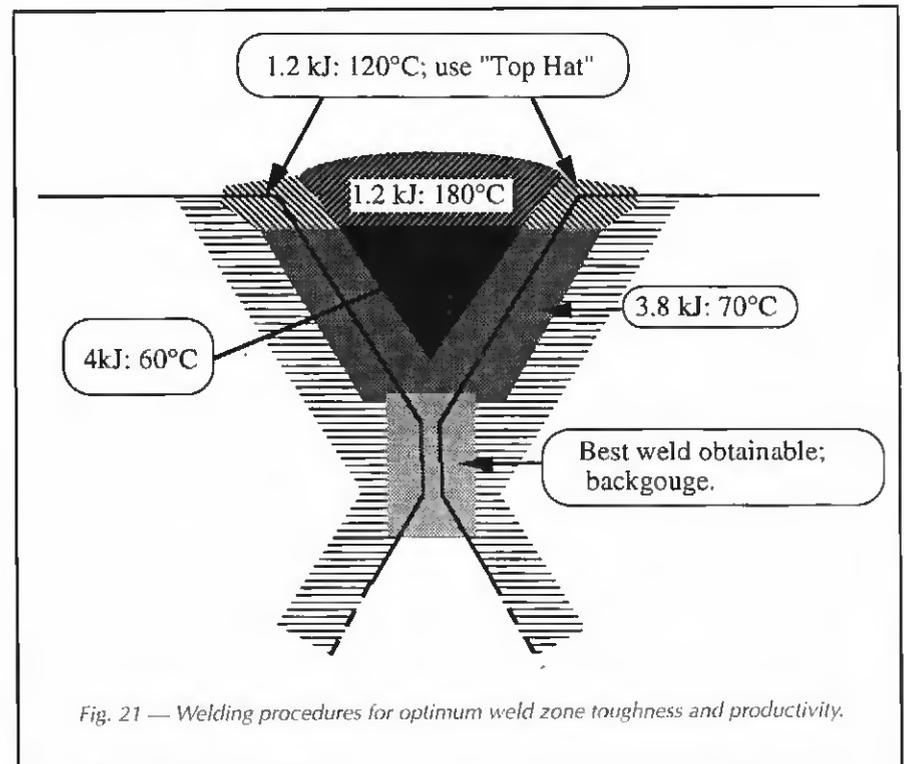

Fig. 21 — Welding procedures for optimum weld zone toughness and productivity.

affected by the difficulty of access and the arc blow problems that often occur.

In practical weldments it is essential that the surface have adequate toughness since most failures initiate at the surface. It is therefore important that one-sided welding be avoided since this practice places an inherently brittle weld root zone at the finished surface. It is preferable to have the weld root close to the center of a joint and, in critical applications, to completely remove this root by gouging before welding of the second side. In addition to removing brittle weld regions, back gouging also removes any defects that might be present at the root, and opens out the root regions to facilitate welding of the second side.

The work on hardness of submerged arc weld zones in these steels gives guidance about the selection of appropriate welding parameters to control the hardness, penetration and dilution of welds.

Optimum Joint Design

In the development of welding procedures, it is essential to avoid cracking and provide an adequate level of toughness in the weld zone. Furthermore, it is desirable to allow high-productivity techniques to be used so that profitability is maintained. On the basis of these investigations the design of an optimum butt joint has been developed which gives good weld zone properties while maximizing productivity. This design is presented in Fig. 21 and features a weld root at the joint center where lower toughness properties can usually be tolerated.

The fill passes are undertaken using high heat input/low preheat techniques to optimize productivity while ensuring adequate toughness. At the center of the fill passes heat input/P and I temperature is unimportant so long as sufficient preheat is provided to avoid hydrogen cracking. At regions close to the weld interface, however, preheat/interpass temperatures must be held close to 70°C for maximum HAZ toughness.

At the weld surface, where toughness is most important, medium P and I temperature/low heat input welding procedures should be used at the weld toe with higher preheat and interpass temperatures (180°C) being used towards the

center capping passes.

From a practical viewpoint, it is recognized that welding operators would have difficulty keeping to such complex weld designs and that the monitoring and inspection of such welds would be difficult. With the increasing use of robotics and computer-controlled welding equipment, however, complex welding procedures such as these should be readily obtained.

Conclusions

1) For the SMA welding of 50-mm-thick, high-strength OX 812 EM steels, maximum overall weld zone toughness was obtained by using low heat input (1.3 kJ/mm) welding procedures in conjunction with preheat and interpass temperatures of about 180°C.

2) Optimum HAZ toughness in OX 812 EM steels was obtained at both high and low welding heat inputs under stated conditions; however, it was found that the appropriate preheat and interpass temperature must be maintained throughout welding. For maximum productivity and improved operator comfort, it is recommended that high heat input (3.8 kJ/mm) welding be used in conjunction with preheat and interpass temperatures close to 70°C.

3) Weld root toughness was low in both the weld metal and heat-affected zone. One-sided welding of these steels should therefore be avoided and, for critical applications, it is recommended that weld roots be backgouged and filled to remove this inherently brittle region.

4) For submerged arc welding of BIS 812 EMA steels,

a) HAZ hardness readings were significantly higher than weld metal hardness readings.

b) Heat input had a marginal effect on HAZ hardness up to about 2 kJ/mm; however, above 2 kJ/mm, the hardness dropped off at a rate of approximately 30 HV 30 for each increase of 1 kJ/mm.

c) Weld metal hardness dropped continuously over the range of 0.5 to 4.5 kJ/mm.

d) Both HAZ and weld metal hardness dropped approximately 1 HV 30 for every 4°C increase in preheat and interpass temperature.

References

1) Welding Technology Institute of Australia, Technical Note 1, *The Weldability of Steels.*

2) IIW Doc IX-535-67, 1973.

3) Phillips, R. H., Dixon, B. F., and Ritter, J. C. 1989. Qualification of new steel for Australian submarine construction. *Proceedings of the 37th Annual Welding Conference* , pp. 50–67, Welding Technology Institute of Australia , Sydney.

4) Holsberg, P. W., and Wong, R. J. 1990. Welding of HSLA-100 steel for naval applications. Conference Paper R. A. Patterson and K. W. Mahin (Ed.), pp. 219–239, Detroit, ASM International, Materials Park, Ohio.

5) Uwer, D., and Degenkolbe, J. 1976. Thermal cycles in arc welding, calculation of cooling times. IIW Document IX-987-76.

6) Davis, C. L., and King, J. E. 1994. Cleavage initiation in the intercritically reheated coarse-grained heat-affected zone: part 1: fractographic evidence. *Metallurgical and Materials Transactions A,* 25A, pp.563–573.

7) Evans, G. M. 1992. Effect of heat-input on the microstructure and properties of C-Mn all-weld metal deposits. *Welding Journal* 61: 125-s to 132-s.

8) Specification ISO 148. 1983. *Steel Charpy Impact Test (V-Notch).*

9) Ritter, J. C., and Phillips, R. H. 1984. The mechanics and metallurgy of explosion bulge testing. *Proceedings of the 42nd Annual Conference of the Welding Technology Institute of Australia,* Melbourne, Australia, Vol 2, Paper 30.

10) Ritter, J. C., and Dixon, B. F. 1987. Improved properties in welded HY-80 steel for Australian warships. *Welding Journal* 66(3): 33–44.