EVALUATION OF FLOW PROPERTIES IN THE WELDMENTS OF VANADIUM ALLOYS USING A NOVEL INDENTATION TECHNIQUE — A. N. Gubbi, A. F. Rowcliffe, E. H. Lee, J. F. King, and G. M. Goodwin (Oak Ridge National Laboratory)

OBJECTIVE

The aim of this work is to evaluate the flow properties of the fusion zone, heat affected zone, and base metal of gas tungsten arc and electron beam welds on V-Cr-Ti alloys

SUMMARY

Automated Ball Indentation (ABI) testing, was successfully employed to determine the flow properties of the fusion zone, heat affected zone (HAZ), and base metal of the gas tungsten arc (GTA) and electron beam (EB) welds of the V-4Cr-4Ti (large heat no. 832665) and the V-5Cr-5Ti (heat 832394) alloys. ABI test results showed a clear distinction among the properties of the fusion zone, HAZ, and base metal in both GTA and EB welds of the two alloys. GTA and EB welds of both V-4Cr-4Ti and V-5Cr-5Ti alloys show strengthening of both the fusion zone and the HAZ (compared to base metal) with the fusion zone having higher strength than the HAZ. These data correlate well with the Brinell hardness. On the other hand, GTA welds of both alloys, after a post–weld heat treatment of 950°C for 2 h, show a recovery of the properties to base metal values with V-5Cr-5Ti showing a higher degree of recovery compared to V-4Cr-4Ti. These measurements correlate with the reported recovery of the Charpy impact properties.[1,2]

INTRODUCTION

In ABI tests, a spherical indenter makes sequential indentation cycles with increasing loads at the same penetration spot on a polished horizontal metallic surface under suitable strain-controlled conditions, the details of which are given elsewhere.[3] The depth-penetration measurements with successively increasing loads are converted to the load-displacement data for each unloading sequence, which in turn, are analyzed by the data processing software program in the computerized ABI test system to determine the values of mechanical properties such as yield strength, true–stress/true–plastic strain curve, and Brinell hardness number (BHN), with proper input values of materials constants. The mechanical properties of the base metal, HAZ, and fusion zone have been measured by Haggag and Bell[4] from the resistance spot welds of 1020 ferritic steel and 2219 aluminum sheets using the ABI technique. In 1020 steel, there was an increase in strength of the weld zone and HAZ relative to the base metal due to martensite or bainite formation. On the other hand, in 2219 aluminum, the strength of the weld zone and HAZ relative to the base metal dropped due to dissolution of precipitates. In another study by Byun et al[5], the ABI test was sensitive enough to identify the local variation in material property in determining the mechanical properties of SA508C1.3 Reactor Pressure Vessel (RPV) steels. Farrell and co-workers[6] have tried to correlate the tensile properties obtained from the uniaxial tensile tests with those determined by the ABI tests on ferritic alloys and found that the two results agree reasonably well; one could evaluate the tensile properties from the ABI technique with a proper selection of material parameters used in the analysis of the results. A comparison of the tensile data derived from instrumented hardness testing with those from conventional tensile tests has been made for various alloys including aluminum, brass and stainless steel.[7]

Vanadium alloys with Cr and Ti contents ranging from 3 to 6 wt.% have been proposed as possible candidate materials for the first wall/blanket structure in a demonstration reactor.[8-11] Welding research, being carried out on vanadium alloys at Oak Ridge National Laboratory, has concentrated primarily on optimizing the parameters for obtaining GTA and EB welds with suitable mechanical properties. To supplement the welding research, an attempt has been made in the present work to characterize the variation in the mechanical properties of the fusion zone, HAZ and base metal of both GTA and EB welds in a nondestructive manner using an indentation technique. These data are extremely difficult to obtain using conventional tensile tests. A microprobe system, which is based on an automated ball indentation (ABI) technique, has been used to determine mechanical properties such as true stress–true plastic strain curve, yield strength, and Brinell hardness number.

EXPERIMENTAL PROCEDURE

Both GTA and EB welds were made on ~7mm–thick plates of the vanadium alloy with a nominal composition of 4 wt.% each of Cr and Ti and the rest vanadium, designated V-4Cr-4Ti (heat 832665) and the vanadium alloy with a nominal composition of 5 wt.% each of Cr and Ti and the rest vanadium (heat 832394, ANL designation BL63). The plates of both V-4Cr-4Ti and V-5Cr-5Ti used for GTA welding were in an annealed state with a fully recrystallized microstructure after a heat treatment of 1050°C for 2 h by the supplier (Teledyne Wah Chang, Albany, Oregon) whereas the plate of V-4Cr-4Ti used for EB welding was in warm–worked state. The details regarding the welding conditions used in both GTA and EB welds are given elsewhere.[1] Metallography samples from the GTA welds in as–welded and post–weld heat treated (vacuum-anneal of 950°C for 2 h) conditions, and EB welds in as–welded condition were mounted in bakelite (a hard material which eliminates the contribution from the compliance of the sample mounting material to ABI test results). The mounted specimens were polished and etched to reveal weld microstructure so that one could clearly distinguish the fusion zone, HAZ, and base metal.

Automated Ball Indentation Test:

The automated ball indentation tests were conducted on the fusion zone, HAZ, and base metal of each specimen by employing a fully computerized ABI system[12] using a tungsten carbide spherical indenter of 0.254 mm dia at a strain rate of ~8 x 10^{-3}/s. The indentation load and depth were monitored by a sensitive load cell and a linear variable displacement transducer (LVDT), respectively, which were fedback to the computer. Figure 1 shows a typical load vs. indentation depth curve from the base metal region of the post-weld heat treated GTA weld of V-4Cr-4Ti. Each ABI test consists of seven load-unload sequences, and the computer software carries out a regression analysis of the partial elastic unloading of each sequence. The plastic indentation depth for each load–unload cycle is determined by extrapolating the calculated line to the zero load. This plastic depth for each load–unload cycle is used in obtaining the true stress and true plastic strain. Values of yield strength and BHN were also estimated and included by the computer in the results.

The detailed procedure followed in the analysis of ABI test data is given elsewhere.[3] A brief description of the various equations and steps involved are given here. In an ABI test both inhomogeneous (Lüders) and homogeneous (work hardening) material behavior occur simultaneously during the test. Using the values of indentation load and indentation depth obtained from the ABI test, flow stress and strain are determined by the computer program based on elastic and plastic theories. For each loading cycle in the ABI test, the total indentation diameter d_t is calculated from the total indentation depth h_t using the relationship

$$d_t = 2\sqrt{h_t D - h_t^2} \qquad (1)$$

The true plastic strain ε_p and true stress σ_t are given by

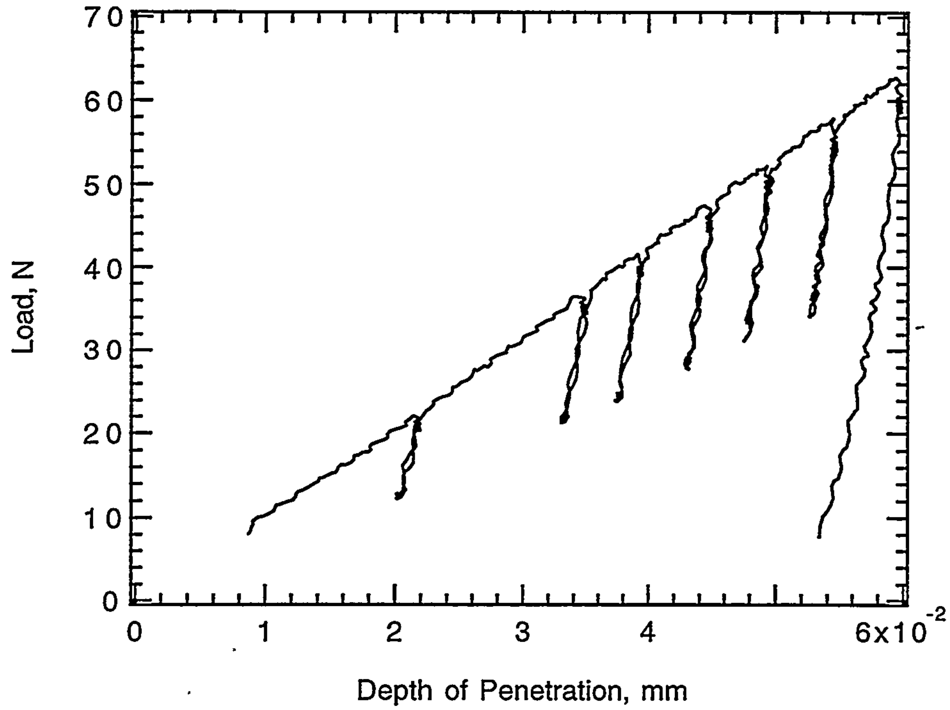

Figure 1. A typical plot of load as a function of depth of penetration of indenter from the base metal region of the post–weld heat treated V-4Cr-4Ti GTA weld.

$$\varepsilon_p = 0.2\frac{d_p}{D} \qquad (2)$$

and

$$\sigma_t = \frac{4P}{\pi d_p^2 \delta} \qquad (3)$$

where d_p is the plastic chordal indentation diameter, D is the indenter diameter, P is the indentation load, and δ is a function of the plastic zone development beneath the indenter and is given by 2.87α. Here α is known as constraint factor whose value is proportional to the strain rate sensitivity of the test material. For vanadium, it was assumed as 1.15. The plastic indentation diameter d_p is obtained iteratively by a complex equation[3], and the derived true stress–true plastic strain data are fitted to the well–known power law equation

$$\sigma_t = K\varepsilon_p^n \qquad (4)$$

where n is the strain hardening exponent, and the K is the strength coefficient. The values of n and K determined from the fit are a part of ABI test results.

Determination of 0.2% yield strength is not straight forward as one cannot simply extrapolate the true stress–true plastic strain data due to the fact that strain hardening exponent could be different at strain as low as 0.2% compared to higher strains. The computer program of the ABI test system performs a linear regression analysis to ABI data points from all loading cycles to fit Meyer's law and obtains material yield parameter A . Meyer's law is given by

$$\frac{P}{d_t^2} = A\left[\frac{d_t}{D}\right]^{m-2} \tag{5}$$

where m is Meyer's coefficient and A is the stress at [d_t / D] equals unity. Figure 2 shows a representative plot where [P / d_t^2] is plotted as a function of [d_t / D] and the material yield parameter A determined from the extrapolated linear regression fit. The yield strength σ_y is then calculated by using the relationship

$$\sigma_y = \Omega A \tag{6}$$

where Ω is another material constant (for vanadium alloys it was taken as 0.25).

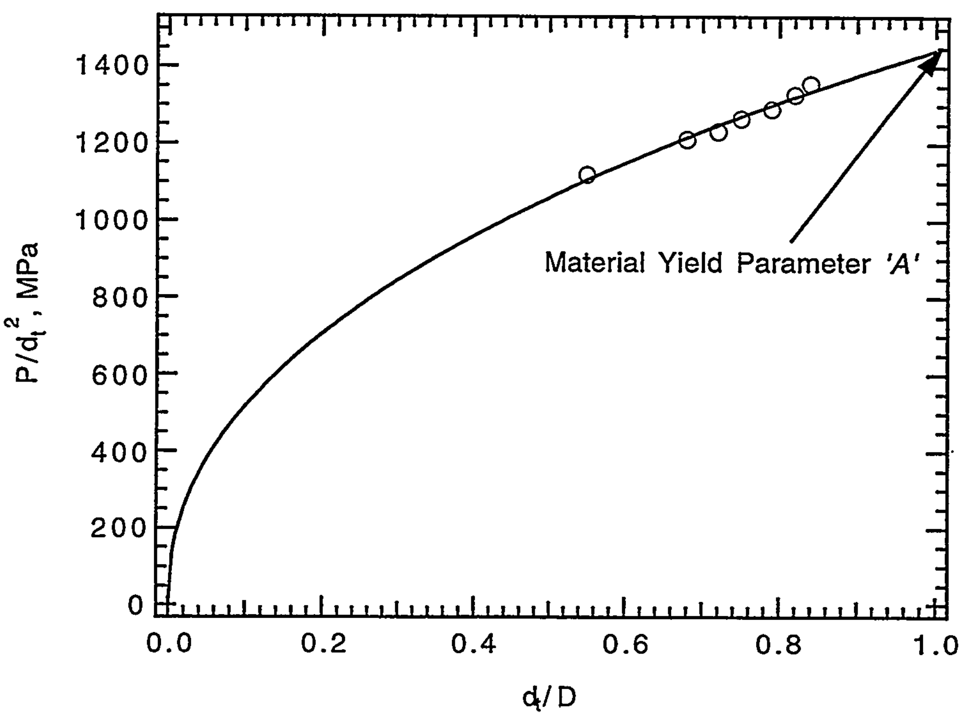

Figure 2. A typical plot of [P / d_t^2] as a function of [d_t / D] from the base metal region of the post–weld heat treated V-4Cr-4Ti GTA weld showing the calulation of material yield parameter A..

RESULTS AND DISCUSSION

GAS TUNGSTEN ARC WELDS

Table 1 lists the mechanical property parameters obtained from the ABI test results on the GTA and EB welds of V-4Cr-4Ti (Heat 832665). ABI tests were done at two different locations in each region of the post–weld heat treated GTA weld to examine the repetitiveness of the test and the results are included in

Table 1. Parameters of Mechanical Properties obtained from ABI test results on Welds of V-4Cr-4Ti (Heat 832665)

WELD MATERIAL	YIELD STRENGTH (MPa)	Strength Coeff. K (MPa)	BHN (kg/sq.mm)	Strain Hardening Exponent (n)
GTA As-Welded				
Base Metal	360	604	132	0.083
Heat Affected Zone	424	719	159	0.084
Fusion Zone	445	761	167	0.086
PWHT 2h/950°C				
Base Metal 1	383	636	143	0.082
Base Metal 2	365	642	139	0.090
Heat Affected Zone 1	373	665	140	0.091
Heat Affected Zone 2	402	649	146	0.077
Fusion Zone 1	407	686	150	0.083
Fusion Zone 2	410	686	152	0.082
EB As-Welded				
Base Metal	489.5	842	183	0.087
Heat Affected Zone	418.5	684	151	0.079
Fusion Zone	430.9	719	158	0.082

Table 1. It can be seen that the mechanical properties evaluated from different locations in the same region are similar (except for HAZ, may be due to some microstructural change), which shows the consistency in results of ABI testing for the same region. Figure 3 shows typical true stress–true plastic strain curves, derived from ABI test analyses, from the fusion zone, HAZ and base metal of the as–welded GTA weld on V-4Cr-4Ti. The numbers in parentheses in Fig. 3 are the Brinell hardness values and it can be seen that the HAZ and fusion zone are at least 20% harder than the base metal, with the fusion zone being the hardest. Also, the calculated yield strengths for the HAZ and fusion zone are ~18 and 24% higher, respectively, than that for the base metal.

Similarly, Figure 4 exhibits typical true stress–true plastic strain curves from the fusion zone, HAZ, and base metal of the GTA weld on V-4Cr-4Ti after a post–weld anneal of 950°C for 2 h. The dashed line in Fig. 4 shows the flow curve obtained from a second location of the base metal which is very similar to that obtained from the first location. This shows consistency in ABI test results for the same region. The GTA weld after 950°C–anneal shows a recovery in the hardness of the fusion zone and HAZ but still 10%

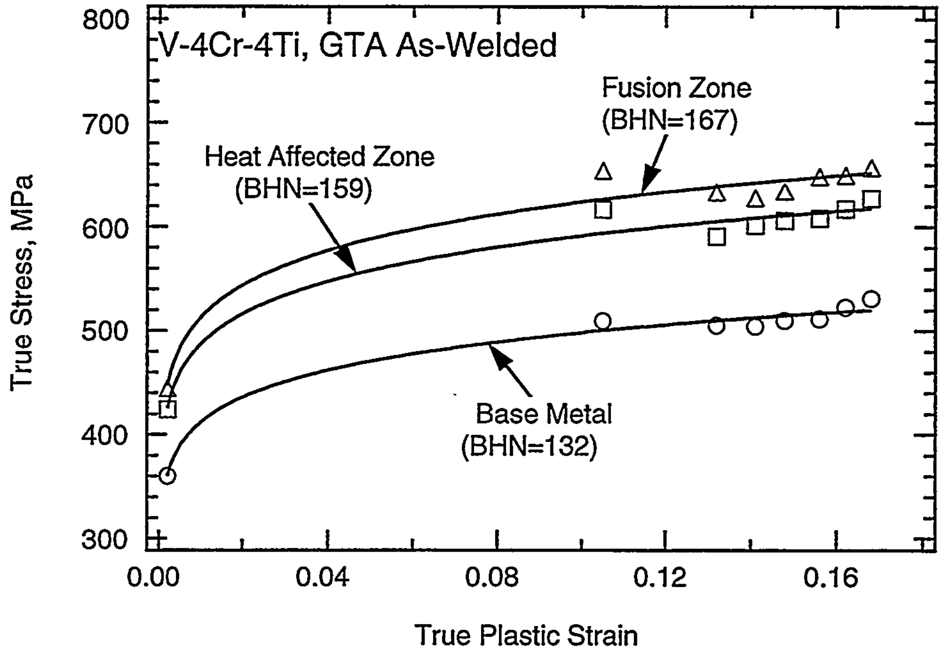

Figure 3. True stress–true plastic strain curves from the fusion zone, HAZ, and base metal of the as-welded V-4Cr-4Ti GTA weld.

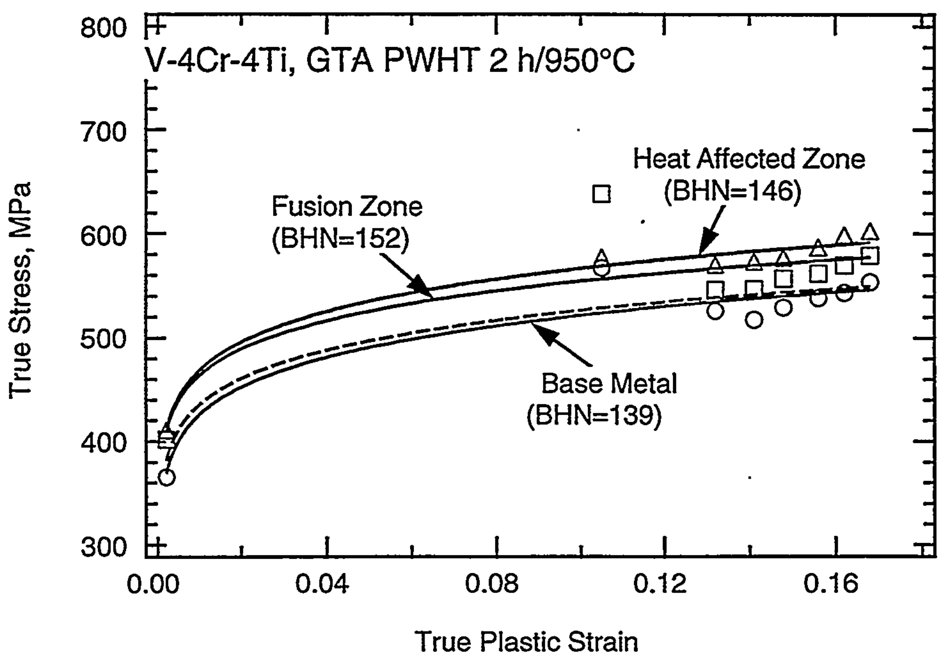

Figure 4. True stress–true plastic strain curves from the fusion zone, HAZ, and base metal of the post-weld heat treated (at 950°C for 2 h) V-4Cr-4Ti GTA weld.

or more higher than that of the base metal. The yield strength also drops for the two zones but both zones are still stronger than the base metal by as much as 10%. This recovery of mechanical properties observed in ABI tests correlates well with the results from impact properties[2] obtained by the testing of sub–size Charpy specimens of the GTA welds and the base metal. The base metal of V-4Cr-4Ti exhibited a DBTT of around –190°C whereas the as–welded GTA weld showed a much higher DBTT of ~+250°C. But, after a post–weld heat treatment of 950°C for 2 h, the DBTT dropped to +75°C, which is still higher than that for the base metal.

The key parameters of the mechanical properties delivered by the ABI test results on the GTA and EB welds of V-5Cr-5Ti (Heat 832394) are tabulated in Table 2. The true stress–true plastic strain curves, obtained from the ABI analyses, from the fusion zone, HAZ, and base metal of the GTA weld on V-5Cr-5Ti in as–welded condition are plotted in Figure 5. Similar to the observations made for the as–welded GTA weld of V-4Cr-4Ti, here also it is clear that the curves for the HAZ and fusion zone are higher than that for the base metal of V-5Cr-5Ti. From the Brinell hardness numbers given in parentheses, the HAZ and fusion zone are harder by 7% and 16%, respectively, than the base metal. In the same token, the calculated yield strengths for the HAZ and fusion zone are higher than that for the base metal by 8 and 16%, respectively.

Table 2. Parameters of Mechanical Properties obtained from ABI test results on Welds of V-5Cr-5Ti (Heat 832394)

WELD MATERIAL	YIELD STRENGTH (MPa)	Strength Coeff. K (MPa)	BHN (kg/sq.mm)	Strain Hardening Exponent (n)
GTA As-Welded				
Base Metal	430	746	159	0.089
Heat Affected Zone	465	783	170	0.084
Fusion Zone	499	835	185	0.083
PWHT 2h/950°C				
Base Metal	381	674	143	0.092
Heat Affected Zone	387	666	147	0.087
Fusion Zone	403	693	151	0.088
EB As-Welded				
Base Metal	405	690	153	0.086
Heat Affected Zone	472	794	177	0.084
Fusion Zone	470	778	175	0.082

Figure 6 is a composite plot comprising the true stress–true plastic strain curves from the fusion zone, HAZ and base metal of the GTA weld on V-5Cr-5Ti after a post–weld heat treatment of 950°C for 2 h. A nearly complete recovery in the hardness values and yield strengths of the HAZ and fusion zone to the base metal values is observed. Also, the stress–strain curves of the HAZ and base metal overlap each other and the curve for the fusion zone approaches that of the other two regions. This recovery of mechanical

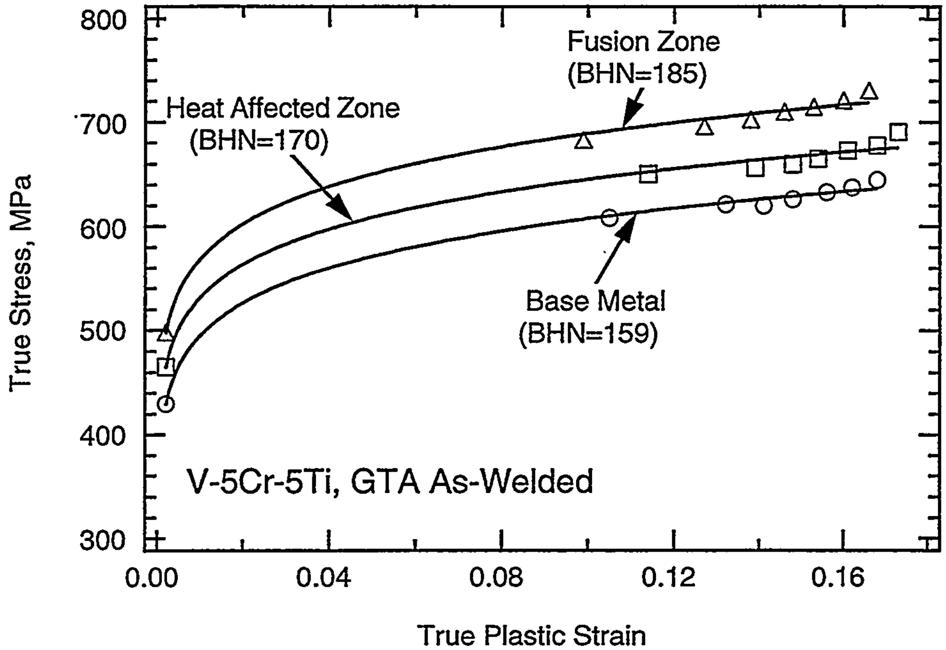

Figure 5. True stress–true plastic strain curves from the fusion zone, HAZ, and base metal of the as-welded V-5Cr-5Ti GTA weld.

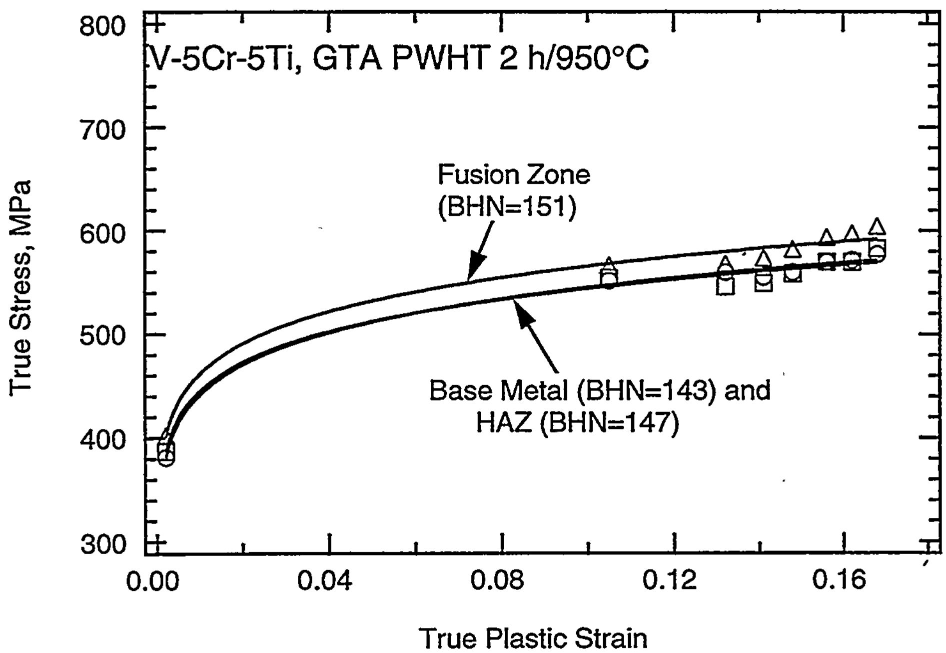

Figure 6. True stress–true plastic strain curves from the fusion zone, HAZ, and base metal of the post-weld heat treated (at 950°C for 2 h) V-5Cr-5Ti GTA weld.

properties observed in ABI analyses agrees very well with the impact properties[1] obtained by the testing of sub–size Charpy specimens of the GTA welds and the base metal of V-5Cr-5Ti. The DBTT for the as–welded GTA weld was determined to be around 250°C and a post–weld heat treatment of 950°C for 2 h reduced the DBTT to 0°C, which was below that (+75°C) for the base metal.

The much higher DBTT (compared to the base metal) obtained from the Charpy impact testing of the GTA welds in both V-4Cr-4Ti and V-5Cr-5Ti in as–welded condition is thought of primarily due to the oxygen in solution which was picked up during welding[2] in a dynamically evacuated glove box environment, and also from the dissolution of Ti (O, N, C) precipitates . An increase in strength (as well as the hardness) can be attributed to the combined effects of dissolved oxygen (resulting in solution–strengthening) and thermal stresses developed during weld solidification. The recovery in DBTT after 950°C–anneal in the two alloys is attributed to the precipitation of oxygen in the form of oxides.[2] This precipitation combined with the thermal stress relief due to annealing results in the softening of the fusion zone as well as the HAZ.

ELECTRON BEAM WELDS

Figure 7 depicts typical true stress–true plastic strain curves derived from ABI test analyses from the base metal, HAZ, and fusion zone of the EB weld on V-4Cr-4Ti. Here, the flow curve for the base metal region lies above the flow curves for the HAZ and fusion zone; in contrast, results from the GTA weld (which was done on a plate annealed at 1050°C for 2 h with a fully recrystallized microstructure) showed that the curve for the base metal was always lower than that for the HAZ and fusion zone, see Figs 3 and 4. This is not surprising as the plate used for EB welding was a warm–worked plate which had a deformed, elongated grain structure with the hardness higher than that for both HAZ and fusion zone, see numbers given in parentheses in Fig. 5. For comparison, the true stress–true plastic strain curve from the recrystallized base metal region of GTA weld has been shown in dashed lines in Fig. 5. Both HAZ and fusion zone exhibit similar yield strengths (see Table 1) with a slight difference in the flow curves.

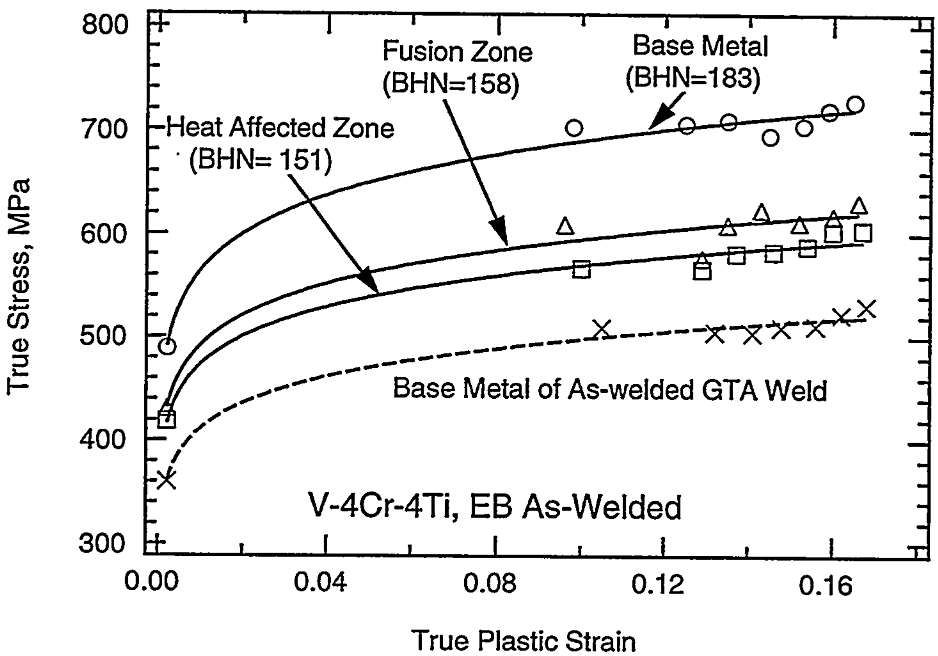

Figure 7. True stress–true plastic strain curves from the fusion zone, HAZ, and base metal of the EB weld of V-4Cr-4Ti.

A similar family of stress–strain curves for the EB weld on V-5Cr-5Ti is presented in Fig. 8. The HAZ and fusion zone show almost identical flow curves with their yield strengths being similar (see Table 2). Both regions are much stronger and harder (refer to Brinell hardness numbers in parentheses in Fig. 6) than the base metal region.

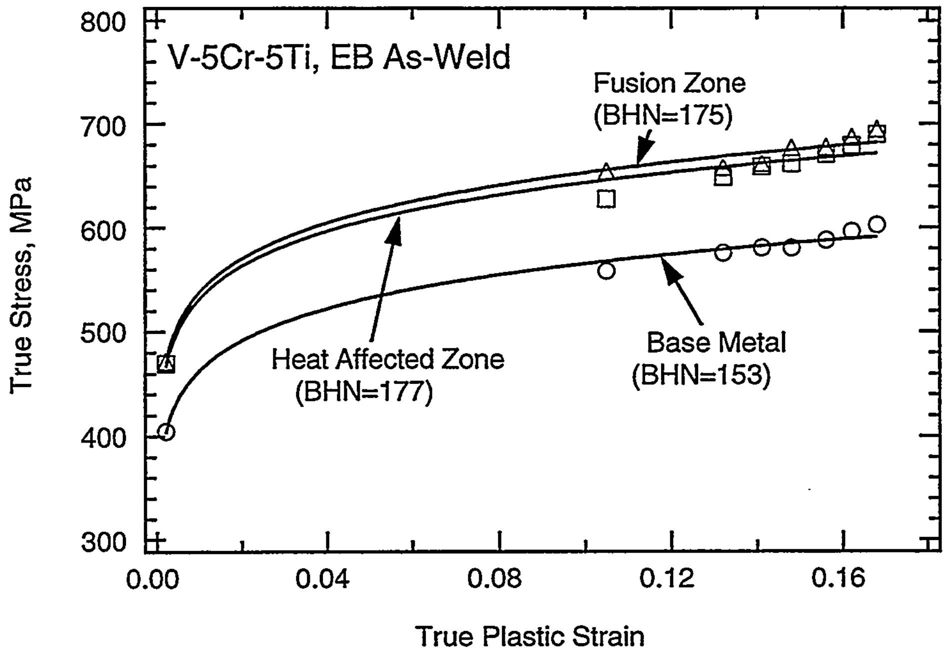

Figure 8. True stress–true plastic strain curves from the fusion zone, HAZ, and base metal of the EB weld of V-5Cr-5Ti.

Charpy impact testing of the sub–size specimens of EB weld on V-4Cr-4Ti showed a DBTT of –100°C (with DBTT for base metal being around –190°C)[2] and similar tests on EB weld of V-5Cr-5Ti showed no transition with predominantly ductile fracture mode and high values of absorbed energy (with DBTT for base metal being around +75°C)[1]. The lower DBTTs obtained for the EB welds compared to that for the as–welded GTA welds of the two alloys (inspite of the ABI results showing similar strengthening and hardening of the HAZ and fusion zone for the two weld processes) is probably due to much finer grain size[2] in the case of EB welds compared to that of GTA welds.

SUMMARY AND CONCLUSIONS

Automated ball indentation tests were successfully used to evaluate the gradients in the mechanical properties of the fusion zone, heat affected zone, and base metal from the GTA and EB welds on the large heats of the V-4Cr-4Ti (Heat 832665) and V-5Cr-5Ti (Heat 832394) alloys. The following observations were made from the investigation.

(1) Automated ball indentation tests were sensitive enough to distinguish the variations in the properties of the fusion zone, heat affected zone, and base metal in both GTA and EB welds of V-Cr-Ti alloys.

(2) The gas tungsten arc welds from the V-4Cr-4Ti and V-5Cr-5Ti alloys showed much stronger and harder heat affected zone and fusion zone compared to the base metal. A recovery in the mechanical properties of the two zones after a post–weld heat treatment at 950°C for 2 h agrees quite satisfactorily with the recovery observed in the Charpy impact properties in other studies.[1,2]

(3) The electron beam welds from the V-4Cr-4Ti and V-5Cr-5Ti alloys showed the mechanical properties of the heat affected zone and fusion zone to be significantly different from the base metal properties. The V-4Cr-4Ti alloy showed a higher stress–strain curve for the base metal due to it being a warm–worked plate whereas the V-5Cr-5Ti alloy exhibited much stronger and harder heat affected zone and fusion zone with both zones being almost similar in properties.

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