Evaluation of Tensile Flow Properties of Weldments in Titanium Alloys

The impression test method was used to evaluate localized mechanical properties in the weld area, and the results were compared with conventional test data

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ABSTRACT. Mechanical property evaluation of weldments is a very difficult task because the failure often occurs in the base metal. Even when failures occur in weld metal, data are inconclusive because of unsymmetrical flow due to local differences in microstructure and chemistry leading to variations in properties. The impression tests, in which a cylindrical indenter of 1 to 2 mm (0.04 to 0.08 in.) diameter is penetrated into the specimen at constant speed, are used to study the behavior of weldments in titanium alloys. Results show that the yield strength, for example, may vary as much as 20% between the base metal and the fusion zone, and the work-hardening exponent may vary as much as 25%. These results are discussed in relation to mechanical properties measured by conventional tests.

Introduction

Measuring the strength and ductility properties of weldments is a very difficult and often impossible task. Standard methods, which use round or flat tensile specimens cut transverse to weldments, often fail in the base metal, yielding only the information that fusion zone and heat-affected zone strength exceeded that of the base metal. Even when failures occur in the fusion zone, data describing ductility are inconclusive because of unsymmetrical flow due to local differences in metal properties. All-weld-metal samples taken from weldments with very wide root openings are not conclusive because of directionality effects, which can be significant. These problems hamper welding development programs because conclusive data to compare different weld metal compositions, weld joint geometries and combinations of these are not easily obtainable.

One method of obtaining local mechanical properties of weldments is by impression tests. In this test, a cylindrical indenter with a flat end is penetrated into the specimen at a constant speed. The operating principle of impression methodology is that the flow properties of a small volume of material can be characterized by its resistance to indentation. These methods have existed for many years and considerable work has been done to develop them. Results have been conflicting in nature because the methods used for loading and data analyses have been inconsistent, and the response of materials to local loading and indenter geometry has been poorly understood (Refs. 1-7). Recent work (Refs. 8-10), however, has shown that by using consistent loading and data reduction methods, a correlation between material behavior in standard tests and the local response to impression can be developed. Using such correlations, it is possible to delineate the individual properties of fusion zone, heat-affected zone and base metal in a weldment.

Ductility in weldments is also of concern. Among the factors which influence necking or strain localization in metals under tension are the work-hardening properties and strain-rate sensitivity. Woodford (Ref. 12) made a correlation between strain-rate sensitivity and total elongation at rupture for a number of materials, and showed that some relation existed between the elongation and strain-rate sensitivity. Based on a nonlinear analysis for long-wavelength nonuniformities (Ref. 13), a method has been developed to estimate the elongation of base metal and fusion zone properties of a weldment in titanium, and it has been reported elsewhere (Ref. 14).

KEY WORDS

Titanium Alloys
Weld Strength
Weld Ductility
Impression Test
Work Hardening
Strain Rate
Strain Hardening
Tensile Flow
Ti-Alloy EB Welds
Ti-Alloy LB Welds

Experimental Procedure

The materials selected for this investigation were electron beam welds and laser beam welds of titanium and titanium alloys. The alloys were Ti-6Al-2V, with additions of 2, 4, and 6 Zr; Ti-6Al-4V; and unalloyed titanium. Rectangular block specimens with 40- × 25- × 12-mm (1.6- × 1- × 0.5-in.) dimensions were cut from the welds. The specimens were mechanically polished and lightly etched to highlight the weld metal and heat-affected zone regions. A typical macro-

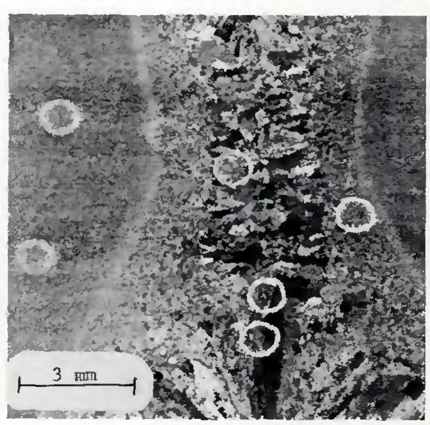

Fig. 1—Macrostructure of Ti-alloy weldment etched to highlight the weld region. The small circles are indentation marks from impression tests

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structure illustrating different weld zones with indentation marks resulting from impression tests is shown in Fig. 1.

The apparatus for impression tests is shown schematically in Fig. 2. A flat end cylindrical punch of 1-mm (0.04-in.) diameter, machined from tungsten carbide rod, was used as the indenter. Tests were conducted at room temperature in a closed loop MTS hydraulic testing machine. Load signals from the test machine and the corresponding displacement of the indenter, as measured by an LVDT attached between the load cell and the sample, were recorded simultaneously during the test by an x-y recorder. An arbitrarily chosen penetration speed of 8.5×10^{-4} mm/s, which is equivalent to a true strain rate of 2.38×10^{-3} s^{-1}, was used.

Results and Discussion

The welding methods chosen produced very small weld zones, and there was no sharp boundary between the heat-affected zone and the fusion zone and base metal. Impression tests of the heat-affected zone were carried out arbitrarily at the edge of the base metal. Moreover, the heat-affected zone was not homogeneous; therefore, the results obtained were representative of the locations where the impression tests were carried out rather than of the true heat-affected zone.

By comparing the flow curves obtained in impression tests, and flow curves obtained from compression tests conducted on a 6-mm (0.24-in.) diameter cylinder of the same alloys, correlations were established between the true stress-true strain behavior. The following relations between compression and impression test results were determined (Ref. 9):

$$\sigma_c = \sigma/\alpha \qquad (1)$$

$$\epsilon = \beta \cdot \delta/d \qquad (2)$$

where σ is the true stress, σ_c is the compression stress, δ is the indenter displacement, d is the indenter diameter, ϵ is the conventional true strain, and α and β are material constants. In previous work (Ref. 9) involving unalloyed titanium, the factors α and β were determined to be 3.5 and 2.8, respectively.

The data for true stress, σ, in impression, and normalized penetration, δ/d, obtained by averaging results of five impression tests, were transformed into true stress, σ, and true strain, ϵ, using Equations 1 and 2. Figure 3 is a plot of true stress, σ, versus normalized penetration, δ/d, on a linear scale for the as-welded conditions. The reproducibility of the impression tests is very good in both base metal and fusion zone. The results from the heat-affected zone material had considerable variation, and are not shown in the figure. This scatter results from the inhomogeneity of the heat-affected zone.

Figure 4 is a logarithmic plot of the true stress, σ, in impression vs. normalized penetration, δ/d. The results in Fig. 4 are straight lines, which model the flow character of the different zones of the weldment according to the power law:

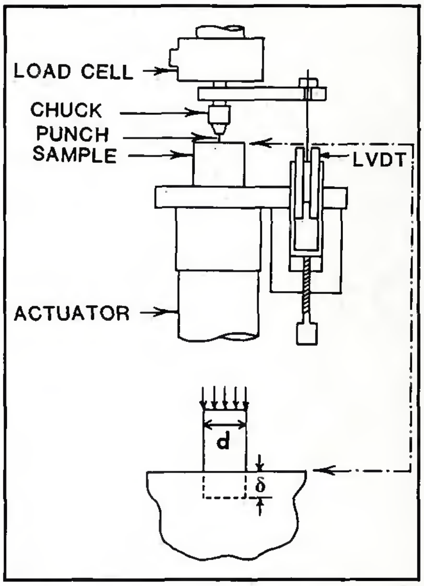


Fig. 2—Arrangement of apparatus for conducting impression tests

$$\sigma = K\left(\frac{\delta}{d}\right)^n \qquad (3)$$

where K is the strength coefficient and n is the strain-hardening coefficient. The values of the strain-hardening coefficient are determined from impression test curves by fitting the power law equation to the measured values of true plastic strain and true stress.

The yield strength is computed from Equations 1 and 2 at the point value where $\epsilon = 0.2\%$. The ultimate tensile stress is computed using Considere's con-

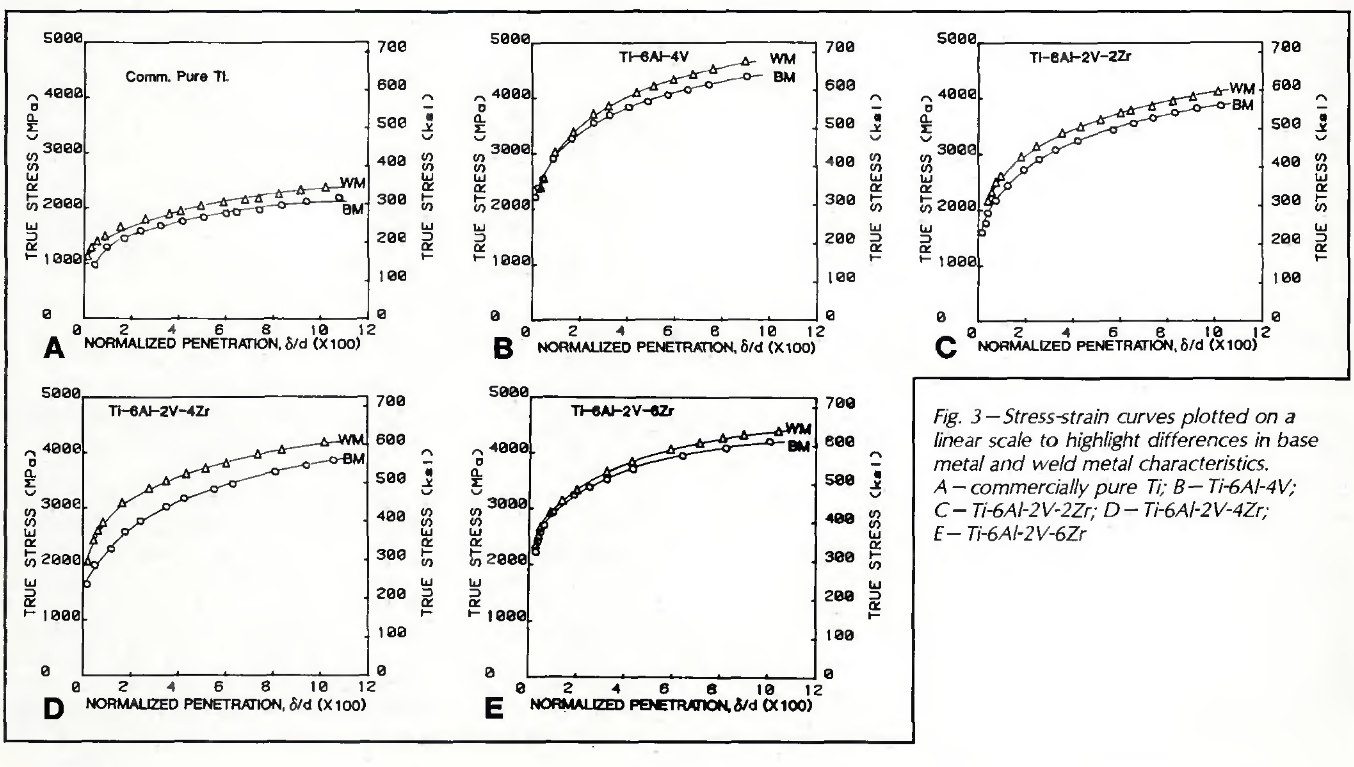


Fig. 3—Stress-strain curves plotted on a linear scale to highlight differences in base metal and weld metal characteristics. A—commercially pure Ti; B—Ti-6Al-4V; C—Ti-6Al-2V-2Zr; D—Ti-6Al-2V-4Zr; E—Ti-6Al-2V-6Zr

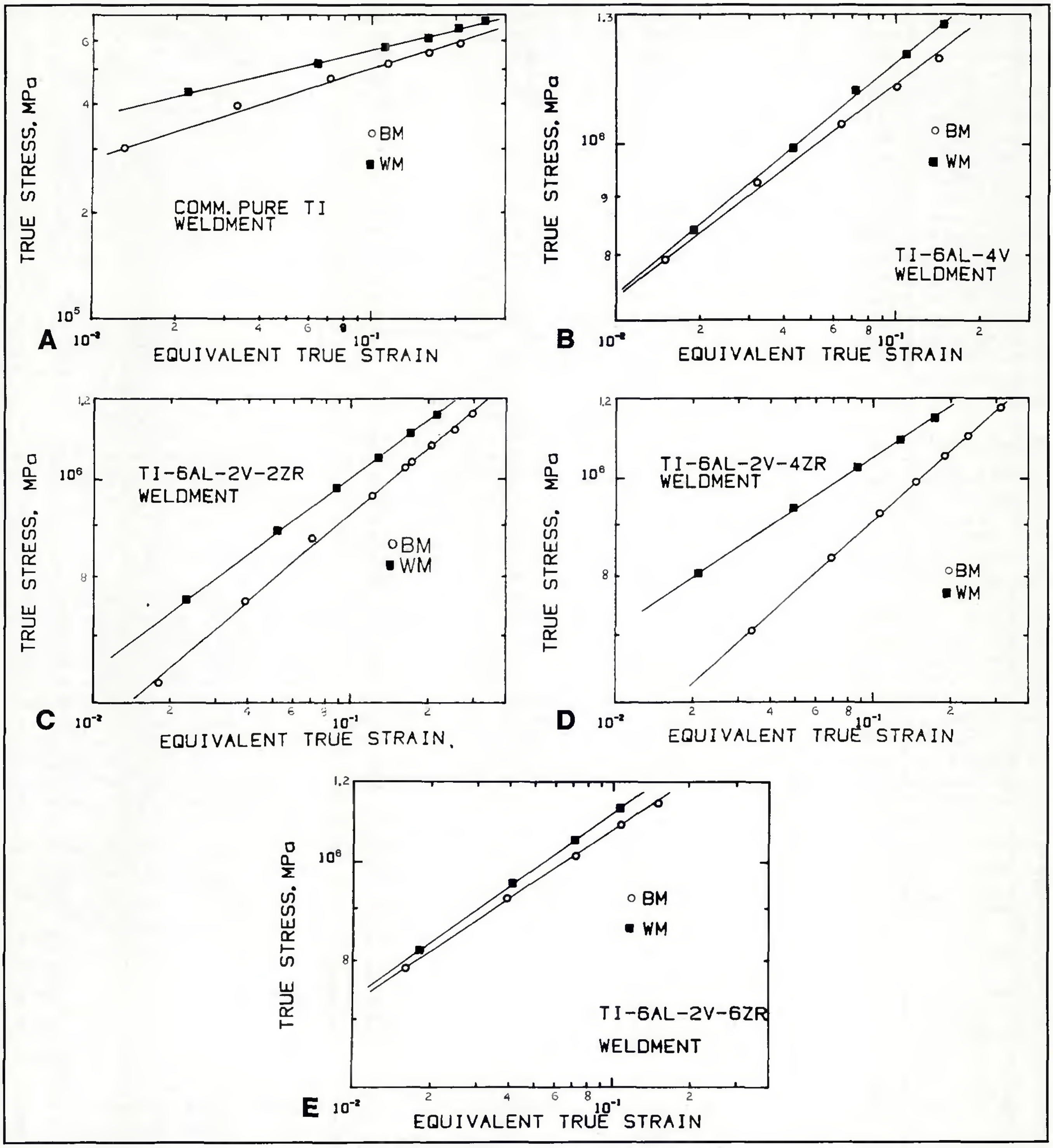


Fig. 4—Flow curves (strain-hardening region only) measured by impression test methods for a straight line on a logarithmic plot, showing that they follow a power law relation. A—commercially pure Ti; B—Ti-6Al-4V; C—Ti-6Al-2V-2Zr; D—Ti-6Al-2V-4Zr; E—Ti-6Al-2V-6Zr

struction (Ref. 11), as shown in Fig. 5. In this construction, a plot of true stress vs. engineering strain, the point of tensile instability on the flow curve is the point of tangency of a line drawn from the point where engineering strain = −1 and true stress = 0. In this plot, the true ultimate strength is the tangent point, and the engineering ultimate strength is the intersection of the tangent line with the stress axis. The engineering ultimate strength is the value reported.

Yield strength values of base metal and fusion zone regions for all test samples were determined from the curves in Fig. 3, and the results, together with other properties, are shown in Table 1. Yield strengths of the titanium alloys measured by impression test methods are consistently lower than the yield strengths measured by conventional tensile tests, except in the case of unalloyed titanium, where the values are approximately the same. This is due to the fact that the correlation factors, α and β, used for titanium alloys were obtained experimentally, using commercially pure titanium, and may not apply for the two-phase alloys of this investigation. Because compression tests were not conducted for

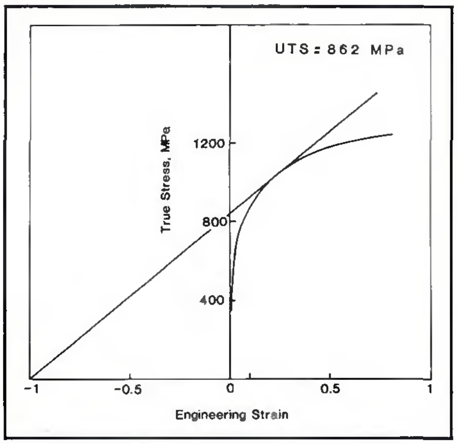
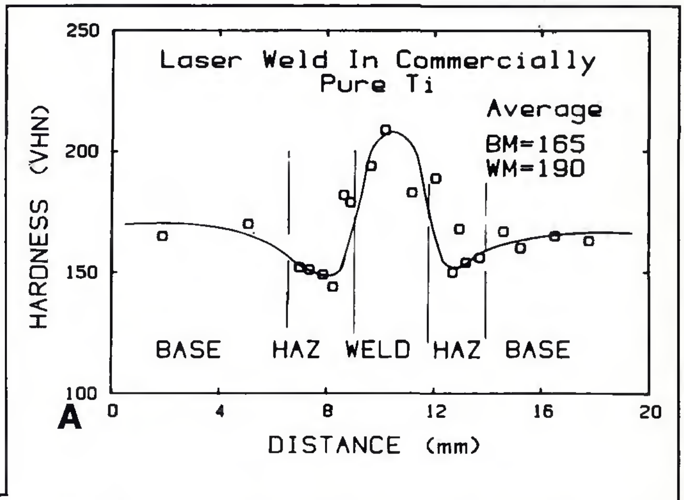


Fig. 5 — Illustration of method for computing ultimate tensile strength using Considere's construction



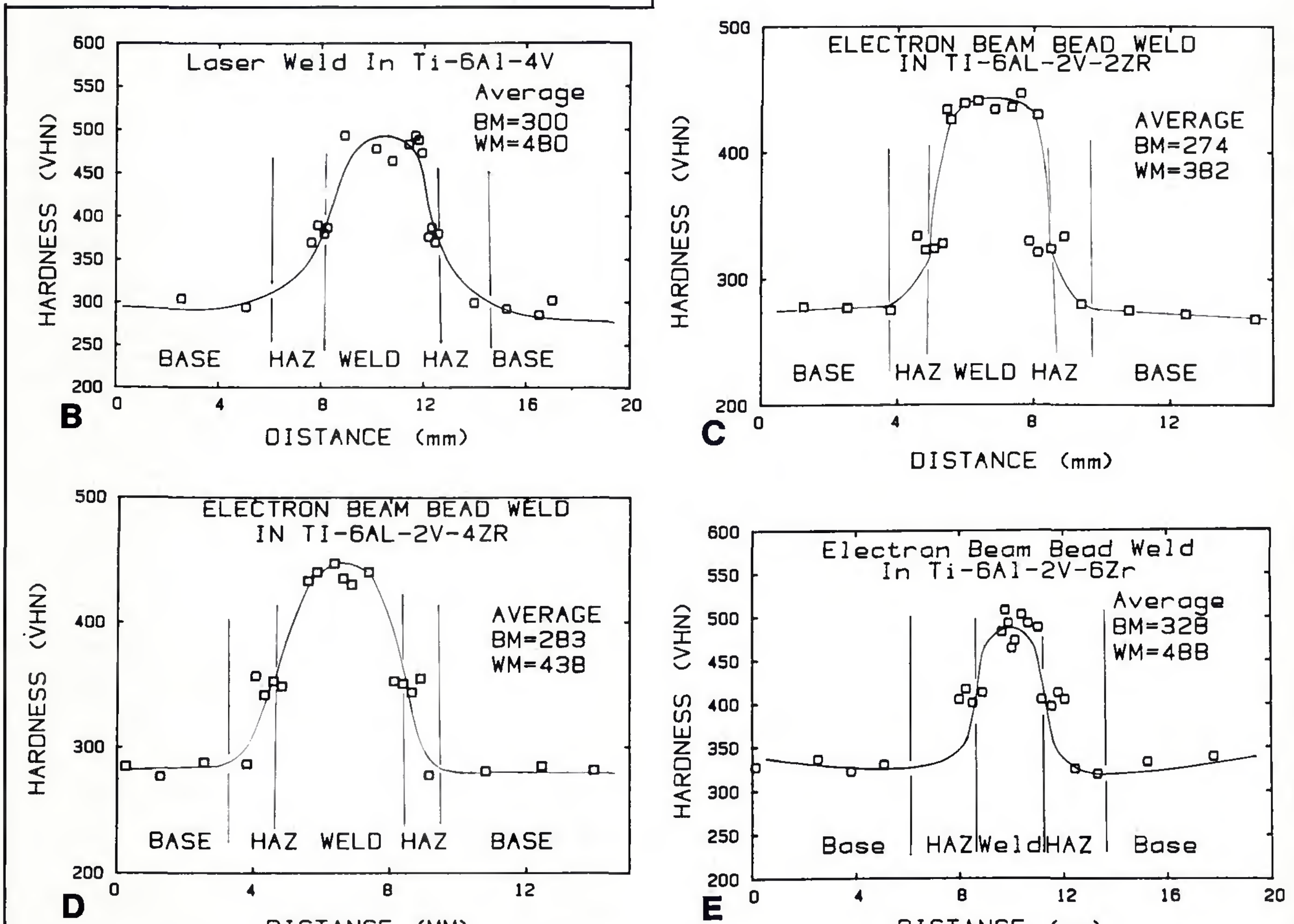


Fig. 6 — Vickers hardness transverse across weldments. A — laser beam weld in commercially pure Ti; B — laser beam weld in Ti-6Al-4V; C — electron beam weld in Ti-6Al-2V-2Zr; D — electron beam weld in Ti-6Al-2V-4Zr; E — electron beam weld in Ti-6Al-2V-6Zr

the alloys of this study, it was necessary to use the values of α and β listed above for comparisons of the properties of the subject materials. This approach permits a relative measure of the mechanical properties of the base metal, heat-affected zone and weld metal to be made. The yield strength varies as much as 20% between the base metal and weld metal, and the yield strength in the base metal is consistently lower than the yield strengths of the weld metal. (This result is consistent with the concept that the faster cooling rate of the weld metal during welding results in higher-strength material.) An additional factor to be considered in the comparisons is that values of yield and ultimate strength in two-phase titanium alloys are probably different; therefore, close agreement of the results is not expected.

Values of ultimate strengths determined using Considere's construction for base metal and the fusion zone are shown in Table 1. Ultimate strength values of base metal for all samples measured by impression test are consistently higher than ultimate strength values measured by conventional tensile test methods as shown in Table 2, except in the

Table 1—Mechanical Properties of Titanium Weldments from Impression Tests

	0.2% Yield Stress (MPa)		Ultimate Stress (MPa)		Strain-Hardening Coefficient	
	Base Metal	Weld Metal	Base Metal	Weld Metal	Base Metal	Weld Metal
Ti-6Al-2V-2Zr[(a)]	628	722	878	935	0.216	0.190
Ti-6Al-2V-4Zr[(a)]	697	750	862	956	0.227	0.168
Ti-6Al-2V-6Zr[(a)]	771	794	971	1006	0.161	0.164
Ti-6Al-4V[(b)]	781	829	1023	1090	0.177	0.198
Commercially pure Ti[(b)]	345	406	486	534	0.227	0.188

(a) Electron beam weld.
(b) Laser beam weld.

Table 2—Base Metal Tensile Test Results

	0.2% Offset Yield Stress (MPa)	Ultimate Tensile Stress (MPa)
Ti-6Al-2V-2Zr	748	821
Ti-6Al-2V-4Zr	791	864
Ti-6Al-2V-6Zr	818	897
Ti-6Al-4V	793	965
Commercially pure Ti	344	413

Table 3—Vickers Hardness of Titanium Weldments

	Base Metal	Weld Metal
Ti-6Al-2V-2Zr	274	382
Ti-6Al-2V-4Zr	283	438
Ti-6Al-2V-6Zr	328	488
Ti-6Al-4V	300	480
Commercially pure Ti	165	190

case of Ti-6Al-2V-4Zr, where the ultimate strengths are approximately the same. Differences in the results of impression tests and conventional tensile tests are attributed to the correlation factor. Further work is in progress to examine the reasons for the disparity in the correlation factors obtained by impression and compression tests. As with comparisons of yield strength values, ultimate tensile strength values of the base metal are lower than the comparable values in weld metal.

The strain-hardening coefficient varies as much as 25% between base and weld metal, and in general, the base metal has a higher value than that of the weld metal, with the exception of Ti-6Al-4V.

The results for yield strength and ultimate strength shown in Table 1 indicate a decreasing value from fusion zone to base metal. These results were consistent with results of Vickers hardness measurements taken across the welds, as shown in Fig. 6 and Table 3.

Conclusions

1. An impression test method was used to determine the local mechanical properties, including yield strength, ultimate strength, and strain-hardening coefficients, for weldments in several titanium alloys. Results show that the yield strength may vary by as much as 20% between the base metal and the fusion zone, and work hardening may vary by as much as 25%.

2. The results were found to be consistent with results of conventional tension and hardness tests.

3. Measurements which delineate the properties of individual zones cannot be made by conventional metallurgical tests using larger samples. The impression test method is relatively easy and can be used to evaluate the mechanical properties of individual zones.

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