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Gradient Study of a Large Weld Joining Two Forged A 508 Shells of the Midland Reactor Vessel

Prepared by
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Prepared for
U.S. Nuclear Regulatory Commission

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Abstract

The low-carbon welds (WF67 and WF70) in the slab examined contained no abnormalities that would indicate fracture behavior different from that observed in bulk-material fracture tests. The A 508 material in the HAZ region, very close to the welds, contains small (~3 mm) regions adjacent to each layer of weld runs where grain coarsening and hardness elevation suggest reduction of cleavage initiation toughness. The degree of severity is largest where this local region coincides with a local elevation of carbide density in the A 508 material.

The A 508 HAZ region adjacent to the topmost weld run may be the region most likely to assist cleavage-fracture initiation because of its location: close to a free surface, small cracks, and the HAZ region beneath the cladding.

It was noted that the small cracks under the cladding have the appearance of prior austenite grain boundary separations that connect to austenite grain boundaries in the cladding. The extreme hardness of a narrow layer of cladding at the fusion boundary may be of interest in further studies of cladding toughness.

List of Figures

GRADIENT STUDY OF A LARGE WELD JOINING TWO FORGED A 508 SHELLS OF THE MIDLAND REACTOR VESSEL

G. R. Irwin
X. J. Zhang

A slab section through a large weld joining two forged A 508 shells was examined. The material is from the nozzle belt of the Midland reactor vessel. The examination searched for local regions where microstructure and microhardness indicated a potential for substantial reduction of fracture toughness. The slab dimensions were 457 mm (18 in.) by 318 mm (12.5 in.) in wall thickness by ~127 mm (~0.5 in.) in slab thickness. Only the central 152-mm (6-in.) section, as shown in Fig. 1, was examined. One face of the slab had been roughly cut, and a small central region was lost during smooth grinding. The clad (inner) surface is at the top in Fig. 1. The adjacent groove weld, made first, used WF67 weld metal. The contacting (outer) groove weld used WF70 weld metal. Other than small cracks under the cladding, no fabrication flaws or abnormalities were visible.

The compositions and heat treatment are given in Ref. 1.[*,†] Before welding, each shell had the following treatment: water quench, 866°C, 6 h; and temper, 649°C, 18 h. The stress relief after welding was 25.5 h at 607°C. The regions of primary interest are those where reheating from welding or cladding causes grain coarsening and elevation of hardness. Figures 2 and 3 (from Ref. 2) illustrate formation of these regions. Dimensions pertaining to the welds in Fig. 1 are shown in Fig. 3. Clearly the heat-affected zone (HAZ) regions of reduced toughness are relatively small.

A macrohardness survey was made across the WF67 weld and the adjoining A 508 materials. The position of this survey is indicated in Fig. 1, and the results are shown in Fig. 4. Large hardness elevations are indicated by single indent measurements within each HAZ. The hardness difference between the two A 508 shells, shown in Fig. 4, was verified by additional hardness measurements at four locations. The average hardness of A 508-R (to the right in Fig. 1) is HRa 53.3 (TS estimate, 84 ksi). The average hardness of A 508-L (to the left in Fig. 1) is HRa 57.3 (TS estimate, 96 ksi). These results correspond well to the tensile strength (TS) values reported by Combustion Engineering.[†] The carbon values reported for A 508-L and A 508-R were 0.24 and 0.20%, respectively.

With regard to variations of microstructure and hardness within the weld metals, Fig. 5(*a*) shows a typical boundary region produced by two weld runs within the WF70 weld. At the top of the figure, directional solidification results in relatively large columnar grains. The region of Fig. 5(*a*), containing microhardness indents is shown at larger magnification in Fig. 5(*b*). No significant change in hardness was found between the columnar grain region and the HAZ below the solidification boundary. Substantial variations of local region hardness do, however, occur somewhat randomly within large welds and within heavy-section nuclear vessel steels. A relationship of these variations to variations of cleavage initiation toughness is probable. However, the microstructure away from the A 508 HAZs in the materials of this report seem normal, and their fracture properties should be similar to those observed in bulk material fracture testing at similar levels of TS.

The region marked "A" in Fig. 1 contains the last weld bead applied against A 508-L material. The temperature cycle in its HAZ does not include reheating from a superimposed weld bead. Figure 6 shows the microstructure in that HAZ region and the locations sampled with microhardness indents. Figure 7 gives the hardness value (Hv) for each indent in graph form. Across ~2 mm from the fusion line, the average microhardness (Hv 270) corresponds to a TS estimate of 124 ksi. At 3 mm from the fusion line, the microhardness has dropped to about Hv 208 (TS estimate, 99 ksi). The prior austenite grain sizes in the hardened region range from 150 to 250 μm. It will be seen later that conditions of moderately larger severity are present in other weld-border HAZ locations. However, the length of this region, parallel to the direction of the welding, is large, and the hardness elevation would be enhanced elsewhere in HAZ locations where the local carbon content is elevated by carbide banding. In addition, the danger of a low-toughness region depends upon location. Locations similar to those of Fig. 6 are of special interest because of their closeness to a free surface, to small cracks under the cladding, and to the HAZ produced by the cladding process. Figure 8 shows the microstructure and location of microhardness indents for a HAZ region in A 508-L about

[*]Letter to G. R. Irwin, University of Maryland, College Park, from T. J. Theiss, Oak Ridge Natl. Lab., June 6, 1991.

[†]Combustion Engineering Chemical Analysis Report, to Oak Ridge Natl. Lab., October 1990.

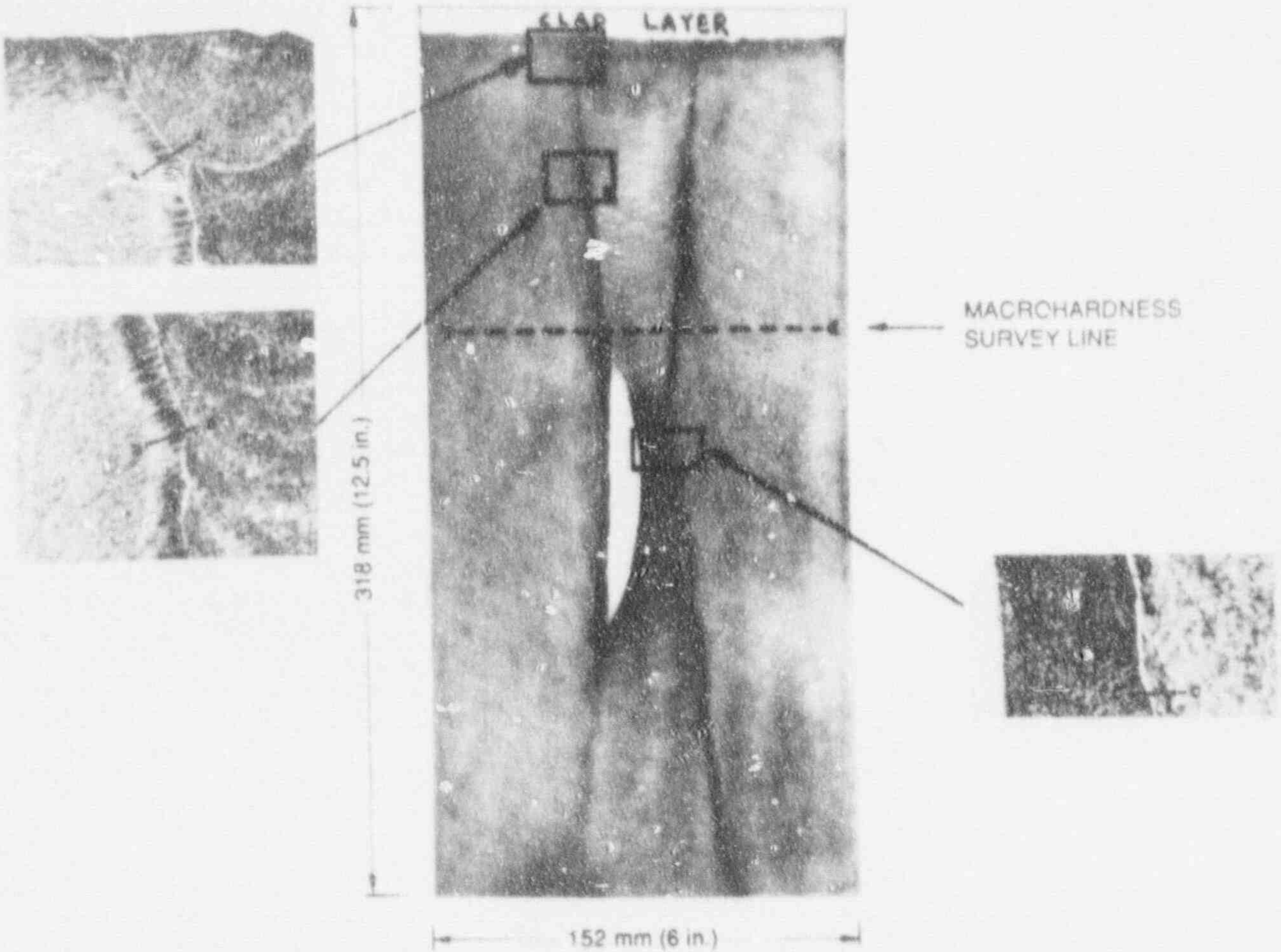

Figure 1 Dimensions and macrostructure of slab section studied. Special attention regions are indicated

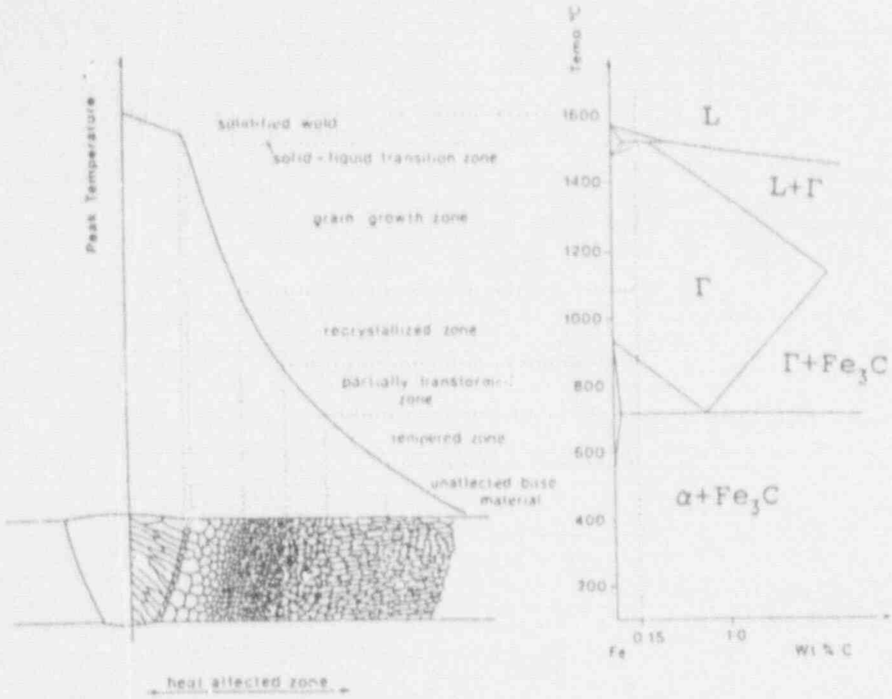

Figure 2 Schematic diagram of various subzones of typical HAZ (from Ref. 2)

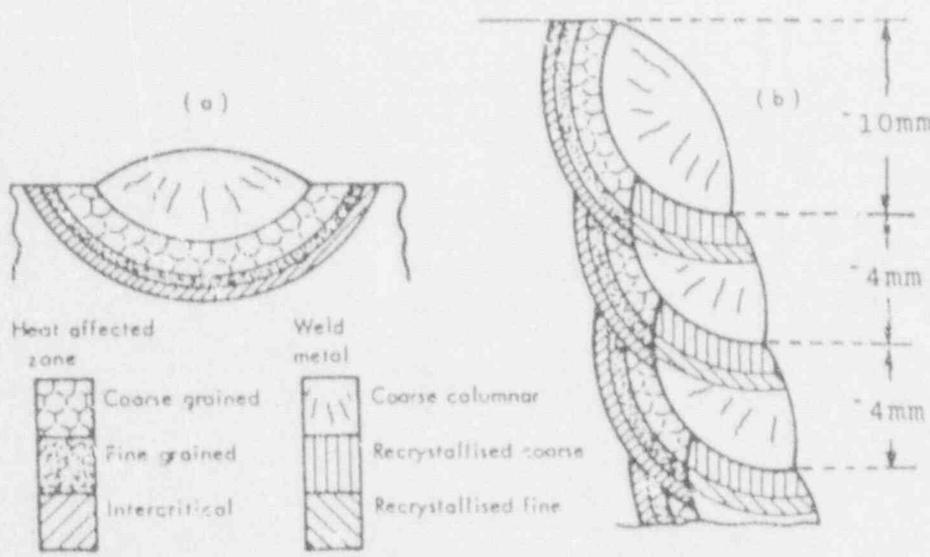

Figure 3 Schematic comparison of HAZ microstructure for single- and multiple-weld bead runs (from Ref. 2)

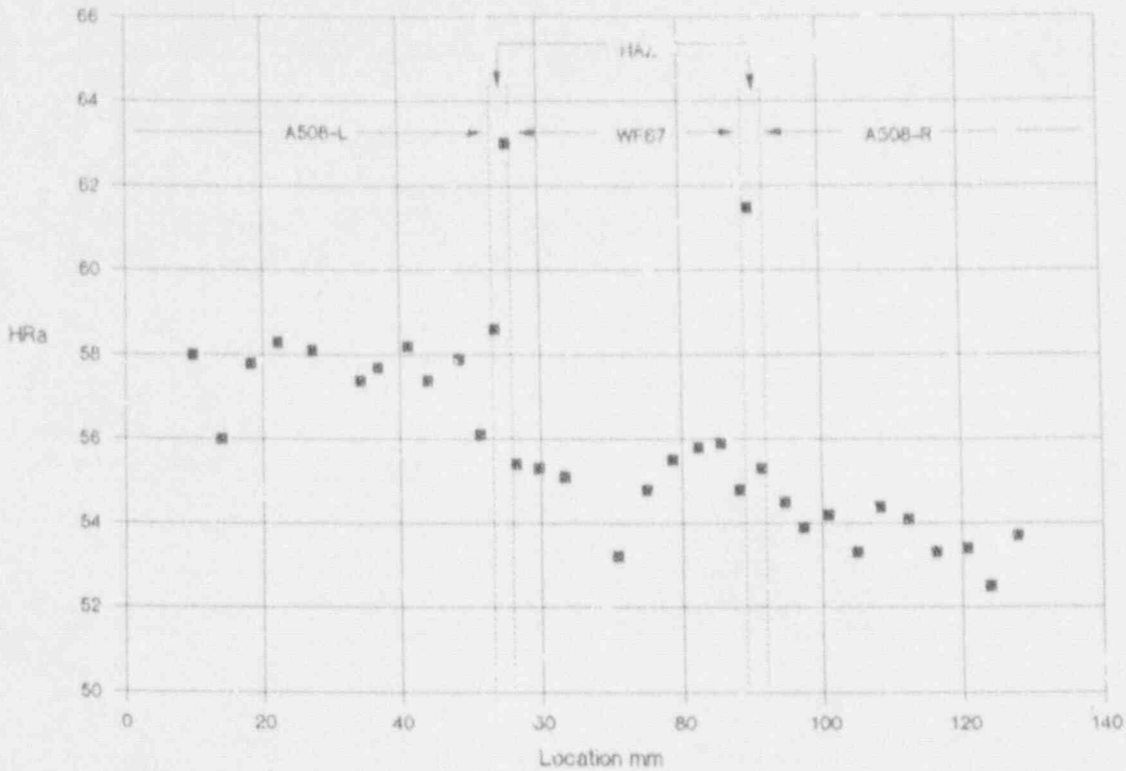

Figure 4 Macrohardness survey across WF67 and adjacent regions of A 508 steel. The hardness indents were near (above and below) straight line (see Fig. 1). The abscissa indicates positions parallel to that line

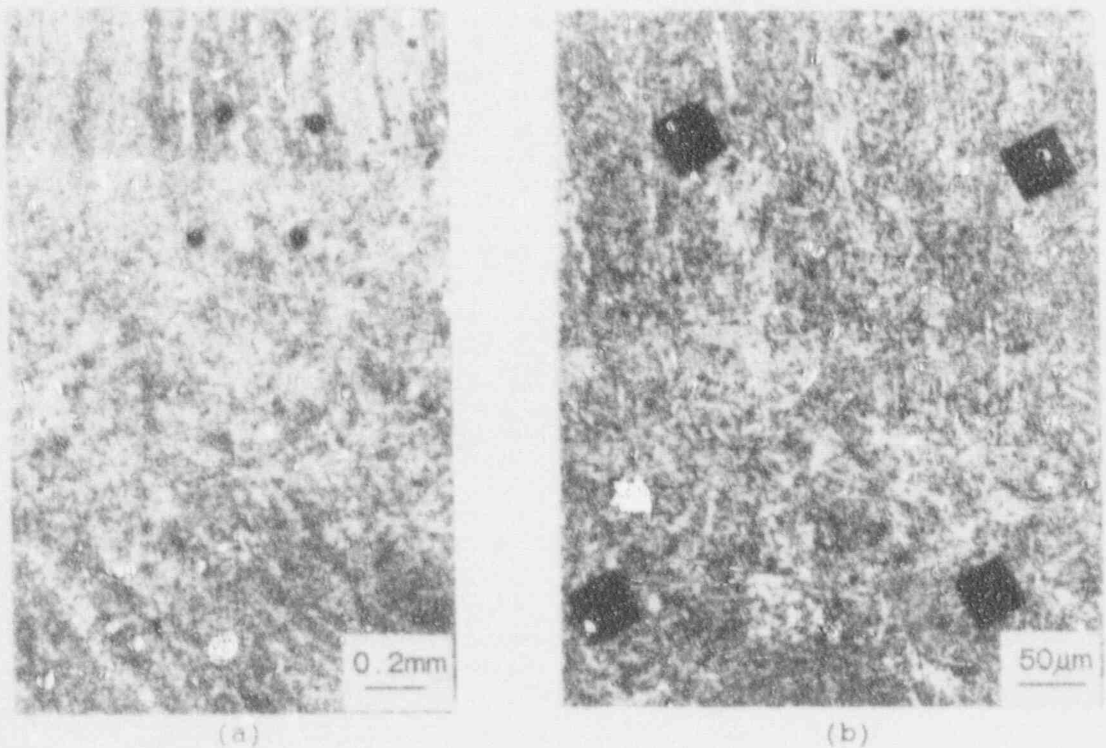

Figure 5 (*a*) Typical fusion line region of two weld bead runs within WF70 weldment showing change of microstructure across fusion line; (*b*) enlarged view of region of (*a*) sampled with microhardness indents

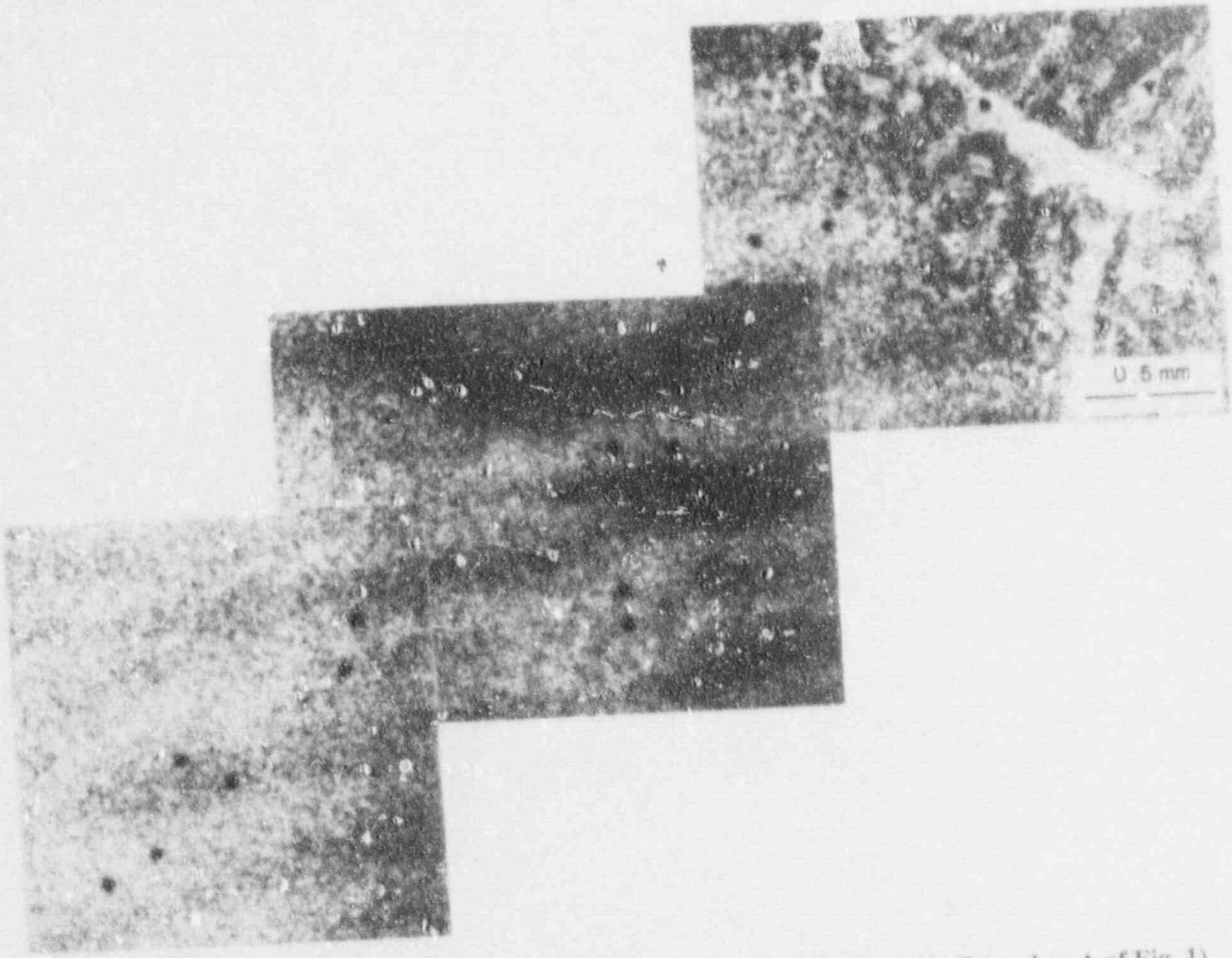

Figure 6 Microstructure and microhardness indents near line across A 508-L HAZ (see box A of Fig. 1)

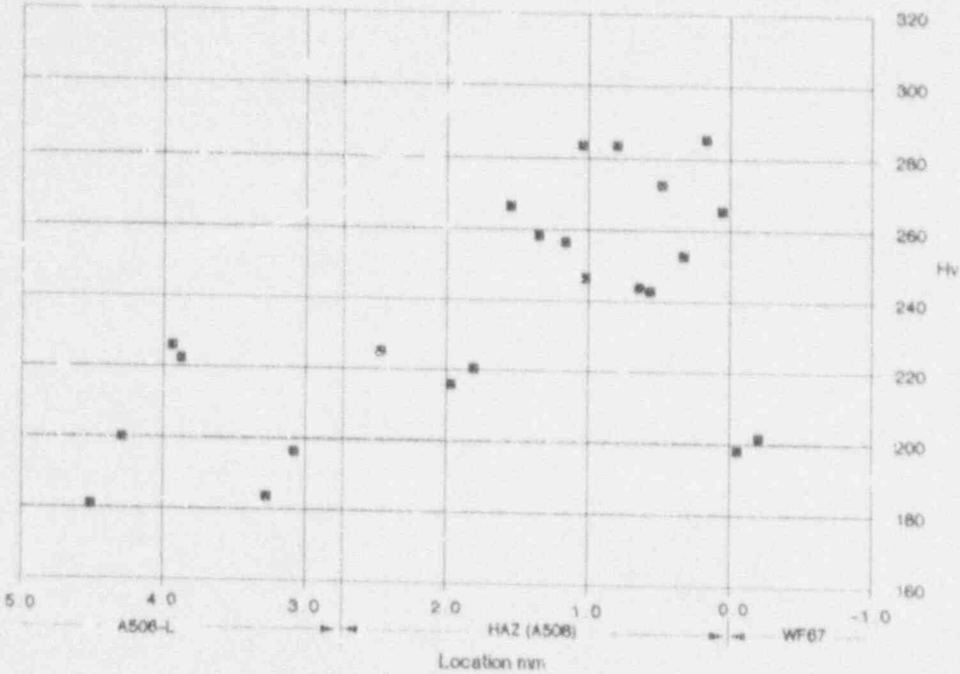

Figure 7 Microhardness results for indents in Fig. 6 in graph form. The abscissa is distance from fusion boundary parallel to straight line through set of indents

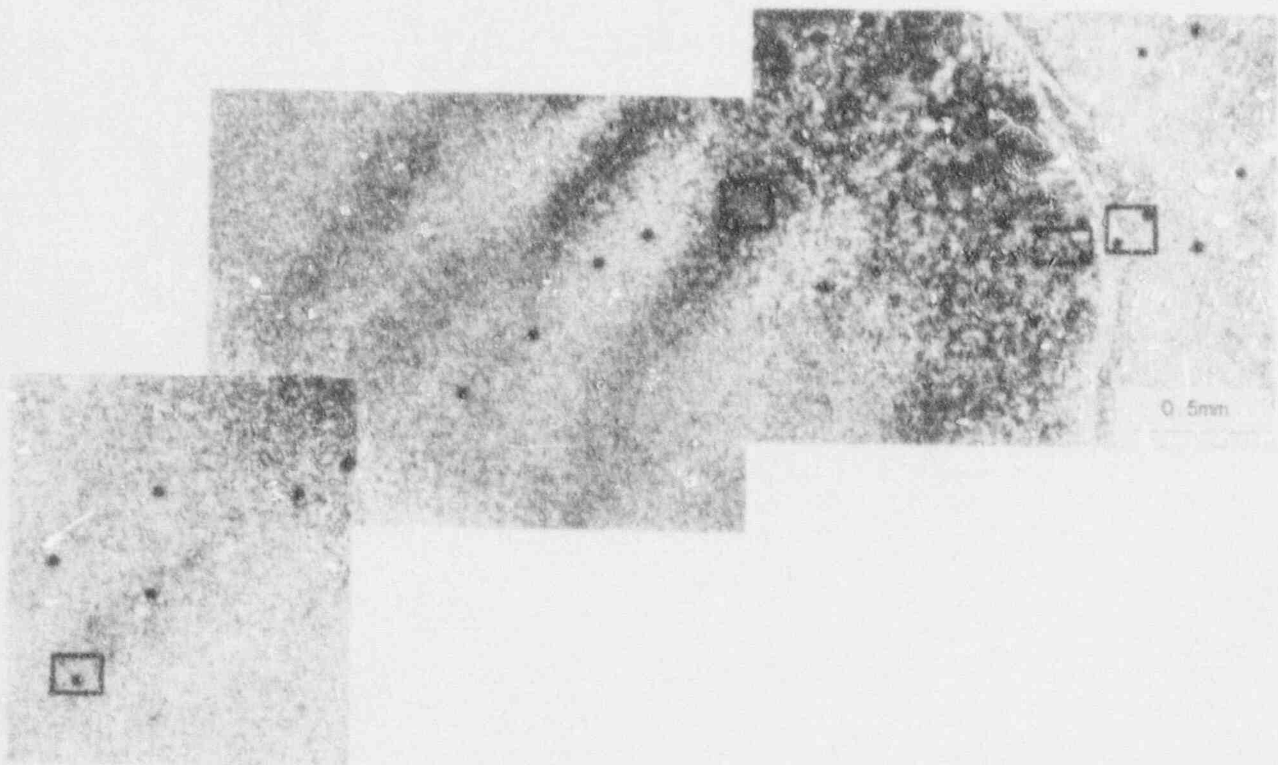

Figure 8 Microstructure and microhardness indents for HAZ region (see box B in Fig. 1)

50 mm below the cladding. In this region the hardness elevation is enhanced by a local increase of carbide density. Figure 9 shows the hardness values obtained from the microhardness indents visible in Fig. 8. The indent pairs enclosed by rectangles in Fig. 8 are shown at higher magnification in Fig. 10(*a*)–(*d*). The two indents in Fig. 10(*a*) span the fusion boundary. The lower-left indent in Fig. 10(*c*) has the hardness value Hv 252. Figure 9 indicates a substantial hardness elevation extending 2.5 mm from the fusion boundary. Within 1.5 mm from the fusion boundary, the hardness of Hv 300 corresponds to a TS estimate of 138 ksi. Figure 10(*b*) is typical of that region. The microstructure shown in Fig. 10(*b*) and the hardness of Hv 204 are typical for the unaffected A 508-L material.

Reheating from welding or cladding and postprocess stress relief change the microstructure and properties in HAZ regions. Depending upon the heat cycle due to welding or cladding, large austenite grains and various products of decomposition of austenite (such as acicular ferrite, bainite, and martensite) form; these produce elevations of hardness. In the materials of this study, a long-time, high-temperature, stress-relief treatment was performed that changed the microstructure further and reduced the hardness elevation in HAZ regions. The microstructure across a wide range in the HAZ then became a mixture of ferrite matrix and carbide particles. The local hardness within a HAZ region is determined by the size and shape of ferrite grains and the size, amount, and distribution of carbide particles. The largest increases of hardness in HAZ regions occur within regions where carbide banding causes enhanced carbide density. Regions darkened by enhanced carbide density are evident in Fig. 10(*a*)–(*c*).

Figure 11 shows a HAZ region in A 508-R adjacent to the WF70 weld. Because A 508-R has a lower TS than A 508-L, some decrease of hardness elevation in its HAZ region might be expected. However, the region selected for a microhardness survey, as shown in Fig. 11, contains a region of elevated carbide density, indicated by darkening of the microstructure. The hardness values are shown in graph form in Fig. 12. Within the dark region of Fig. 11, microhardness values in the range of 280 to 300 Hv were obtained.

The reheating cycle applied to the A 508 material by the cladding process appears to introduce grain coarsening and hardness elevation comparable in severity to those found in HAZ regions adjacent to the welds. Figure 13(*a*) shows microstructure and microhardness indents in a region that includes the fusion boundary between A 508-L and the cladding. A portion of the Fig. 13(*a*) surface, close to the fusion boundary, was repolished and etched to increase visibility of austenite grain boundaries in the cladding. The result is shown in Fig. 13(*b*). The small cracks under the cladding in the A 508 material appear to be separations on prior austenite grain boundaries and may often connect to austenite grain boundaries in the cladding, as indicated in Fig. 13(*b*). The results of the hardness indents, shown partially in Fig. 13(*a*), are given in graph form in Fig. 14. The elevation of hardness across 2.5 mm in the A 508-L material is similar to that found in the HAZ adjacent to the weld. The extreme hardness elevation in a very narrow (~0.02 mm) region of cladding at the fusion boundary corresponds to a TS estimate high enough to suggest brittle behavior. However, the small cracks beneath the cladding formed without visibly penetrating through this narrow, high-hardness region. A similar narrow, high-hardness region was found in the cladding over the low-carbon WF67 weld. Reheat of the weld by the cladding process did not produce a HAZ of significant severity, and no small cracks were observed in that region.

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2. K. Easterling, *Introduction to the Physical Metallurgy of Welding*, Butterworths, 1983.

*Available for purchase from National Technical Information Service, Springfield, VA 22161.

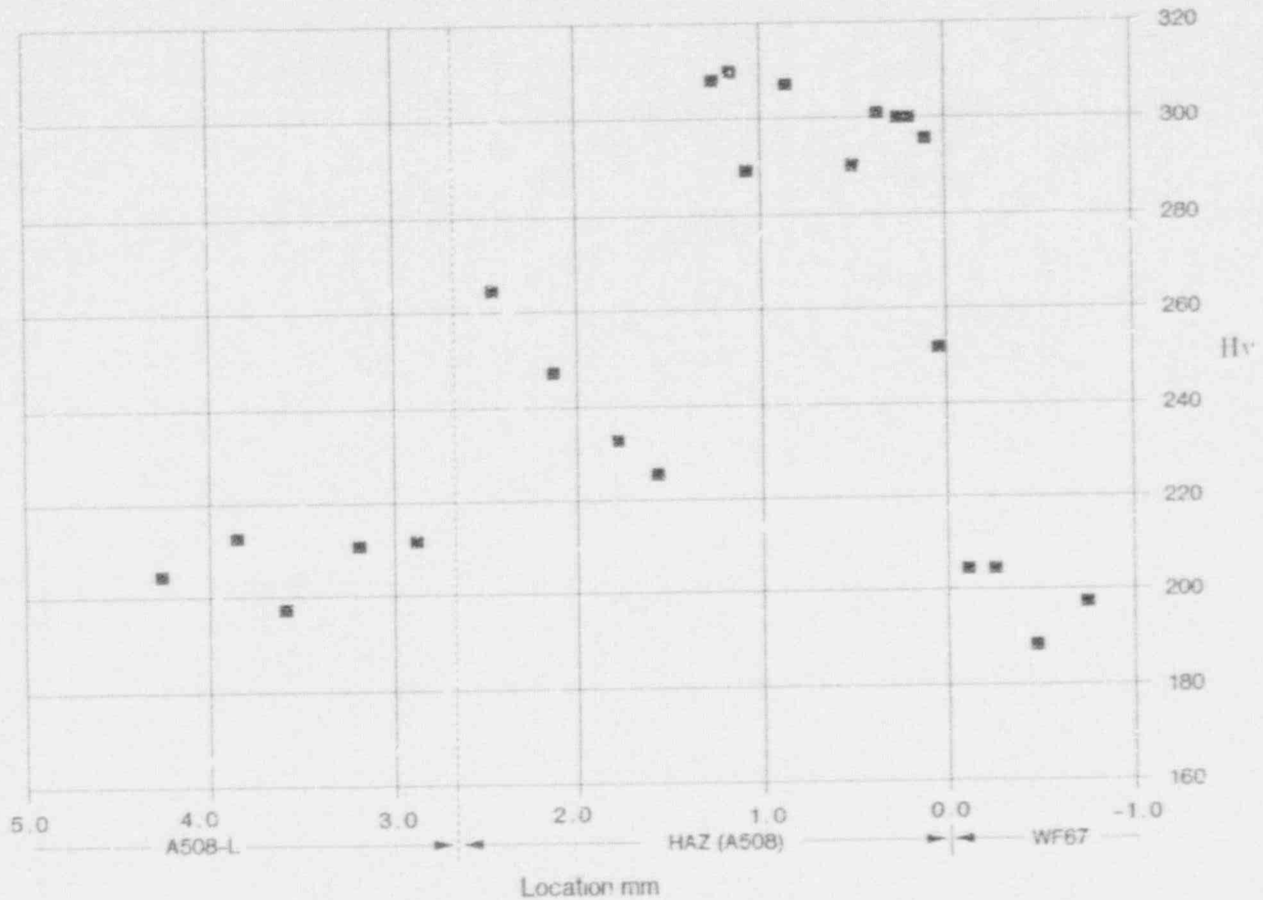


Figure 9 Microhardness results for indents shown in Fig. 8 in graph form. The abscissa is distance from boundary parallel to straight line through set of indents

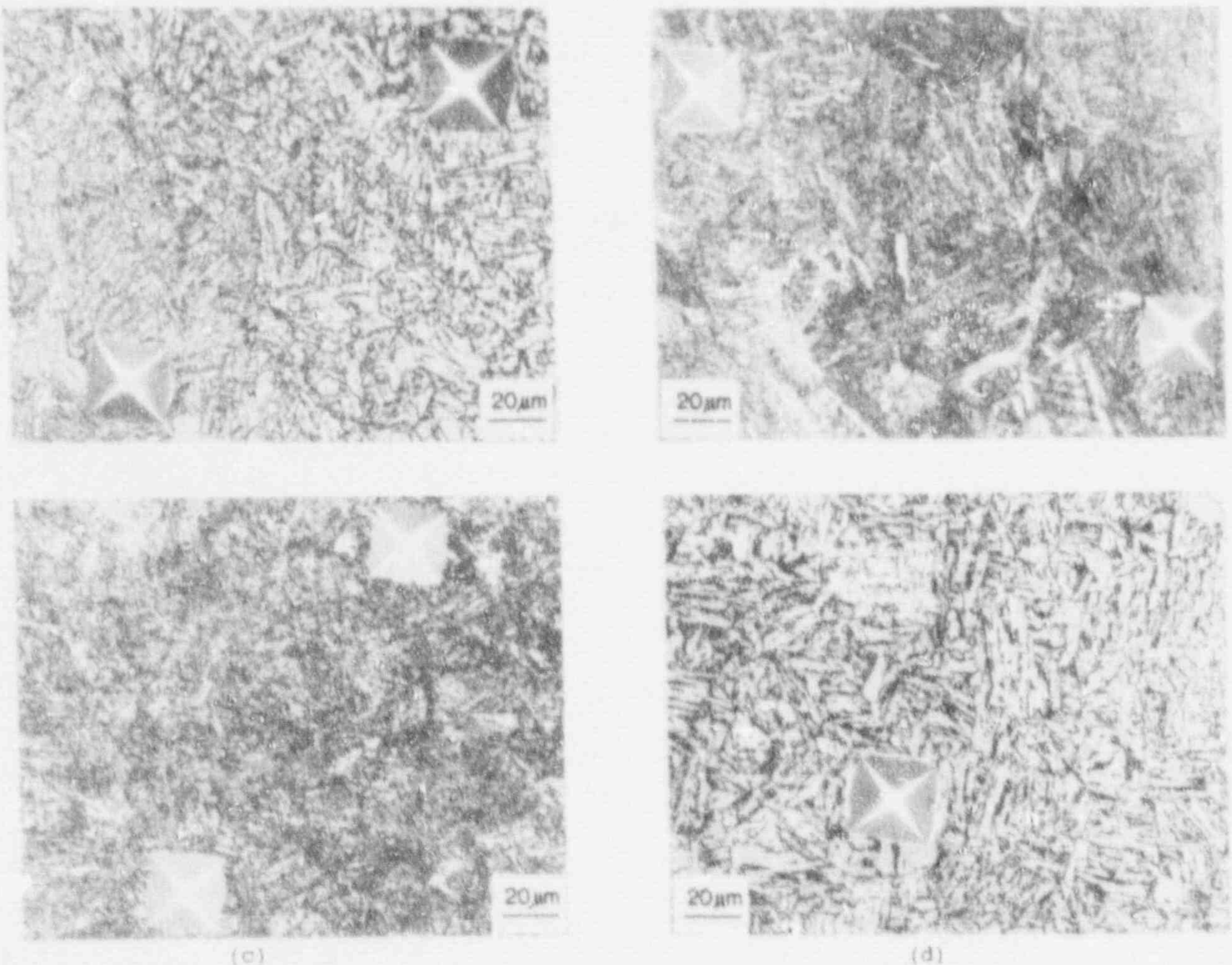


Figure 10 Four higher magnification views showing change of Fig. 8 microstructure with distance from fusion boundary. Regions shown are indicated in Fig. 8. (*a*) Includes fusion boundary; distance from boundary increases in (*b*), (*c*), and (*d*)

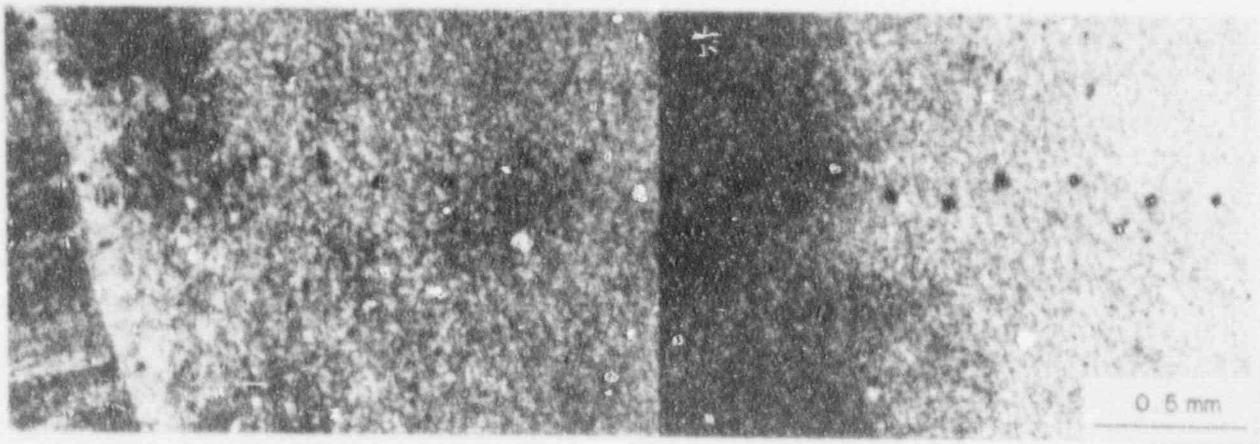


Figure 11 Microstructure and microhardness indents across A 508-R HAZ adjacent to WF70 weld. Location is within box C of Fig. 1

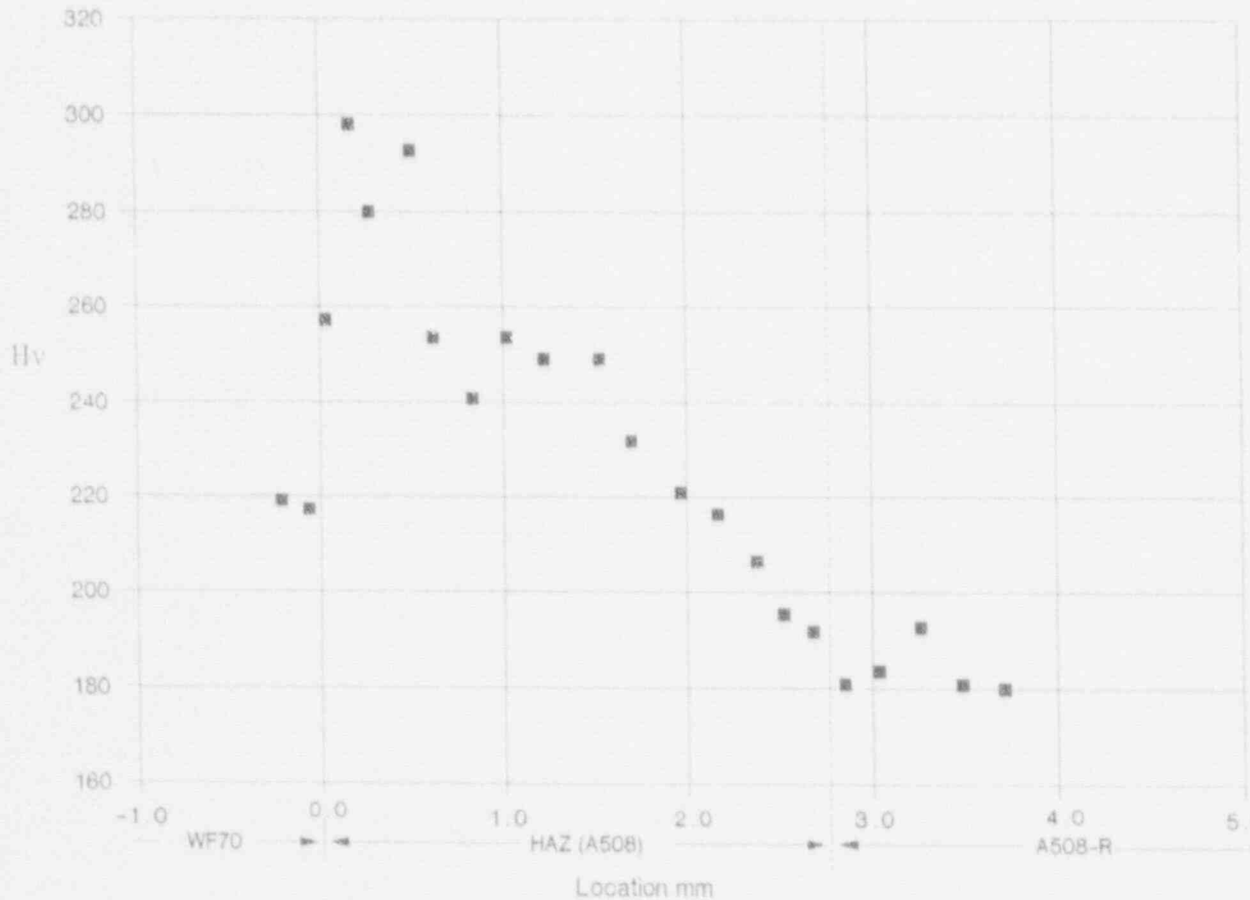
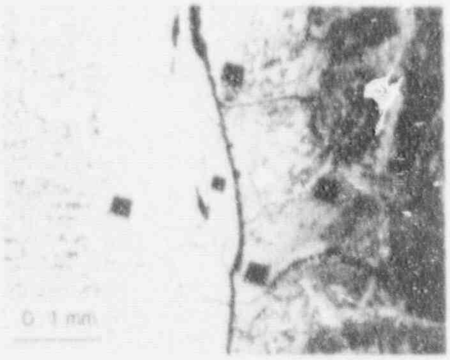


Figure 12 Results from microhardness indents in Fig. 11. Abscissa shows distance of indent from fusion boundary parallel to straight line through measurements group

(a)



(b)

Figure 13 (*a*) Microstructure, small cracks, and microhardness indents near fusion boundary between cladding and A 508-L material in box C of Fig. 1; (*b*) portion of (*a*) after repolishing and etching to enhance grain boundaries in cladding

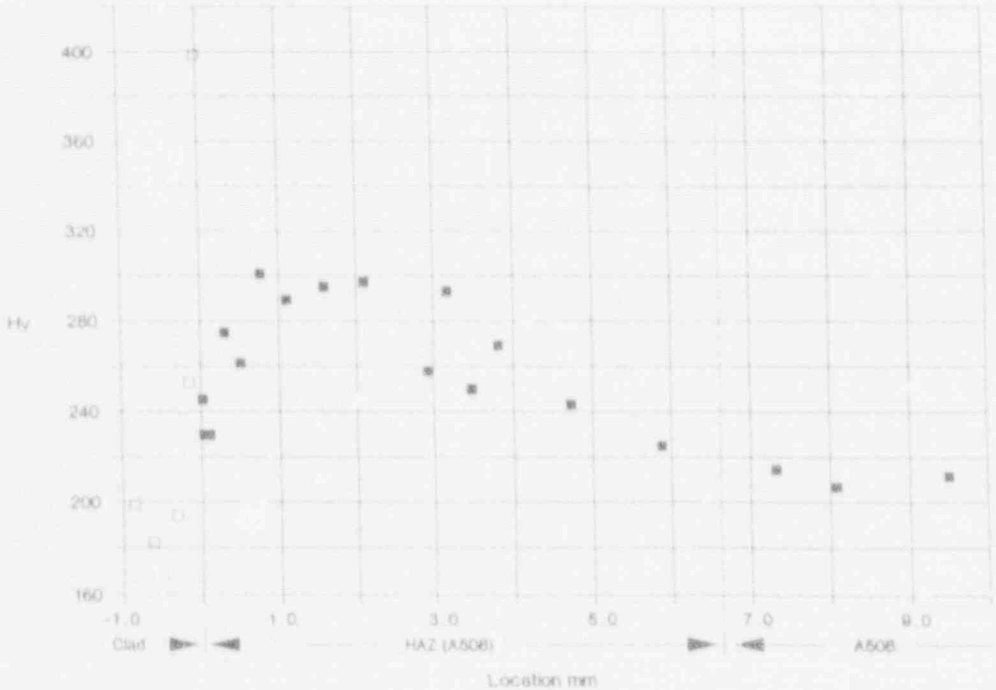


Figure 14 Microhardness results from Fig. 13(*a*) in graph form. Abscissa shows normal distance from fusion line

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