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J-CONTROLLED CRACK GROWTH AS AN INDICATOR OF HYDROGEN-STAINLESS STEEL COMPATIBILITY

by

M. R. Dietrich, G. R. Caskey, Jr.,
and J. A. Donovan

E. I. du Pont de Nemours & Co.
Savannah River Laboratory
Aiken, South Carolina 29808

Accepted for presentation and publication
Third International Conference on
Effects of Hydrogen Materials
Jackson Lake Lodge, WY
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Author(s); M. R. Dietrich, G. R. Caskey, and J. A. Donovan

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J-CONTROLLED CRACK GROWTH AS AN INDICATOR OF HYDROGEN-STAINLESS STEEL COMPATIBILITY*

M. R. Dietrich,** G. R. Caskey, Jr., and J. A. Donovan†

E. I. du Pont de Nemours & Co.
Savannah River Laboratory
Aiken, South Carolina 29808

ABSTRACT

The J-integral was evaluated as a parameter to characterize fracture of stainless steels and as a measure of hydrogen damage. C-shaped specimens of Type 304L, 316, and 21-6-9 stainless steels were tested in high pressure helium and hydrogen. The critical force for crack initiation (Jm), and tearing resistance (dJ/da) were decreased by hydrogen in all three alloys. The J-integral appears useful as a measure of hydrogen compatibility because it is sensitive to both test environment and microstructure.

* The information contained in this article was developed during the course of work under Contract No. DE-AC09-76SR00001 with the U. S. Department of Energy.

** Babcock & Wilcox Research Center,
Lynchburg, Va.

† Mechanical Engineering Department
University of Massachusetts
Amherst, Ma. 01003

Introduction

A wide variety of mechanical tests have been applied to the study of hydrogen compatibility of metals. Crack velocity, threshold stress intensity, and fracture toughness are valid measures of hydrogen compatibility with high strength and low ductility alloys. Concepts of linear elastic fracture mechanics are inadequate to characterize fracture properties of stainless steel in either inert or hydrogen environments, because stainless steels are ductile and have relatively low strength. The J-integral (1, 2) was developed for fracture accompanied by large scale plasticity. Thus the J-integral provides a basis for characterization of crack initiation, stable crack growth, and plastic instability of stainless steels.

This report describes an investigation at the Savannah River Laboratory into utilization of the J-integral as a parameter to describe initiation of ductile cracks in Type 304L, 316, and 21-6-9 stainless steels. The tearing resistance (dJ/da), describing stable crack growth, also was estimated from the load-deflection data.

Measurement of J-Integral

"C"-shaped fracture specimens (3) approximately 3.8 mm thick and 25.4 mm outer diameter were machined from high energy rate forged (HERF) bar stock. Type 316, 304L, and 21-6-9 stainless steels were studied. Orientations of the specimens and the V-notch with respect to the forging flow line patterns are shown in Figure 1. Fatigue cracks approximately 2.5 mm long were generated at a maximum stress intensity of $K = 44$ MPa $\sqrt{m}$. The specimens were tested in high pressure (69 MPa) helium or hydrogen in the as-received HERF condition or in high pressure hydrogen after prior exposure to deuterium at 69 MPa pressure for seven days at 520 K.

The J-integral was evaluated by determining the area under the load-deflection curve out to the maximum load. The usual methods of detecting crack propagation were not applicable to the high pressure test apparatus. Therefore, the critical force at the maximum load (Jm) was determined rather than the critical force to initiate a ductile crack (Jc). Correction to Jm due to the combined bending and tensile loading on the 'C' shape specimens could increase J by about ten percent but was not made because of the larger uncertainty in the load and deflection at crack initiation (4).

Tearing resistance (dJ/da) has been suggested to characterize stable crack growth and as a parameter for predicting plastic instability (5). In the present study dJ/da was measured at the maximum in the load-deflection curve. The data are internally consistent but may not be directly comparable to dJ/da evaluated in other studies.

Hydrogen Effects on Fracture

The test environment and deformation pattern caused by the HERF processing affected the J-integral at maximum load and the tearing resistance of the three austenitic stainless steels. Generally, Jm was less for tests in hydrogen than for tests in helium. The tearing resistance was lower for tests in hydrogen than in helium in Type 304L and 21-6-9 stainless steels in all orientations (Figures 3b and 4b). The results for Type 316 stainless steel differed from the above in several ways: 1) Jm was the same in hydrogen and helium when the notch was parallel to the flow lines, 2) Jm was less in helium than hydrogen when the notch was at 45° to the flow lines, and 3) the tearing resistance was the same in both environments (Figure 2b).

Regardless of the test environment, notch orientation relative to the HERF flow pattern affected Jm. The lowest values of Jm were for notches parallel to the flow lines, an effect that was especially pronounced in Type 316 stainless steel where inclusions were aligned along the forging pattern. Values of Jm were about the same for crack orientations 90 or 45° to the flow lines for Types 316 and 21-6-9 stainless steels (Figures 2a and 4a). Jm for Type 304L stainless steel was greatest when the crack was at 45° to the flow lines (Figure 3a).

Tearing resistance was unaffected by orientation of the crack relative to the flow lines for all tests in helium (Figures 2b, 3b, and 4b). Only small changes in tearing resistance with orientation were observed for tests in hydrogen.

Charging the specimens with hydrogen prior to testing in a hydrogen environment caused changes in both Jm and dJ/da which were alloy and orientation dependent. Hydrogen exposure of Type 316 stainless steel decreased Jm and dJ/da (Figure 2). For Type 304L stainless steel Jm was decreased for orientations of 90 and 45° but dJ/da was not altered significantly (Figure 3). In contrast, hydrogen exposure increased Jm for Type 21-6-9 stainless steel although dJ/da was unaffected (Figure 4). The increase in Jm is possibly due to microstructural changes that occurred during hydrogen charging.

Fracture modes were altered by the test environment but were independent of the crack orientation relative to the flow lines. All three alloys failed by microvoid coalescence when tested in helium as shown in Figure 5a. When tested in hydrogen, the fracture mode of Type 21-6-9 stainless steel changed to intergranular separation (Figure 5b), whereas the failure mode of Type 304L stainless steel changed to a brittle tearing mode (Figure 5c). The failure mode of Type 21-6-9 stainless steel charged with hydrogen and tested in hydrogen was a mixture of tearing and intergranular separation. Some intergranular separation was observed also in Type 316 stainless steel charged with hydrogen and tested in hydrogen.

Measures of Hydrogen-Stainless Steel Compatibility

Susceptibility to hydrogen damage may be evaluated by comparing Jm values for tests in helium with tests in hydrogen for the three types of steel. Type 304L stainless steel ranks better than Types 316 and 21-6-9 steel on this basis, regardless of which specimen orientation is chosen for the comparison. On the other hand, the relative ranking of Types 316 and 21-6-9 stainless steels depends upon specimen orientation. In addition, the data for Type 316 stainless steel is biased by the high inclusion content of these specimens. The Type 304L and 21-6-9 stainless steel specimens are much cleaner.

Tensile ductility has been used extensively as a measure of hydrogen damage (7). Based on plastic strain to failure (reduction in area), Type 304L stainless steel is more susceptible to hydrogen damage than Type 21-6-9 stainless steel in direct opposition to the ranking based on Jm. These measures of hydrogen damage are biased differently, however, with respect to deformation and fracture. Jm depends on flow stress and plastic strain up to the point where crack advance is assumed to begin. Plastic strain to failure, on the other hand, is affected strongly by the ability of the alloy to neck down without breaking and is effectively sampling a region of deformation not included in Jm. Furthermore, compact tensile specimens such as the C-shaped specimens of this study are not susceptible to unstable plastic tearing, whereas tensile specimens can be driven to tearing instability by internal microcracks in the necked region (5).

There is agreement in ranking of Type 304L and 21-6-9 stainless steels between tensile ductility and tearing resistance, dJ/da. In both cases, Type 21-6-9 steel is less susceptible to hydrogen damage. In this comparison both parameters are influenced by the deformation and crack growth processes that succeed the onset of crack growth on load maximum.

The method for determining Jm and dJ/da employed in this study was a variation of the procedure suggested by Paris (5). The results are in good agreement with results on Type 304L and 316 stainless steels reported elsewhere (8). Our results are an initial evaluation of J-integral methods for developing valid ductile fracture parameters for studies of hydrogen degradation of tough alloys such as the austenitic stainless steels. Further work is needed on experimental and analytical procedures as well as continued investigation of microstructural effects introduced by mechanical and thermal processing.

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2. J. A. Begley and J. D. Landes: ASTM STP 514, pp. 1-23, 1972.

3. C399, Standard Method of Test for Plane Strain Fracture Toughness of Metallic Materials, 1979 Annual Book of ASTM Standards, ASTM, 1979.

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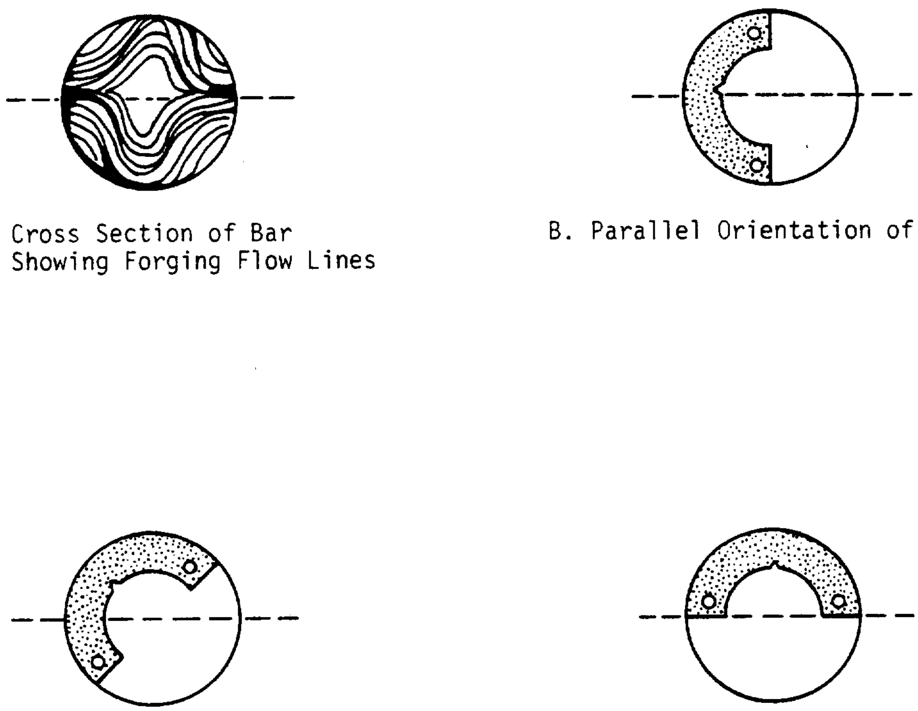
7. M. R. Louthan, Jr., G. R. Caskey, J. A. Donovan, and D. E. Rawl: Mater. Sci. & Eng., 10, pp. 357, 1972.

8. W. H. Bamford and A. J. Bush: ASTM STP 668, pp. 553-577, 1979.



A. Cross Section of Bar
Showing Forging Flow Lines

B. Parallel Orientation of Notch

C. 45° Orientation of Notch

D. 90° Orientation of Notch

Fig. 1. Forging Flow Lines of HERF Stainless Steel
and Notch Orientations Relative to Flow Lines

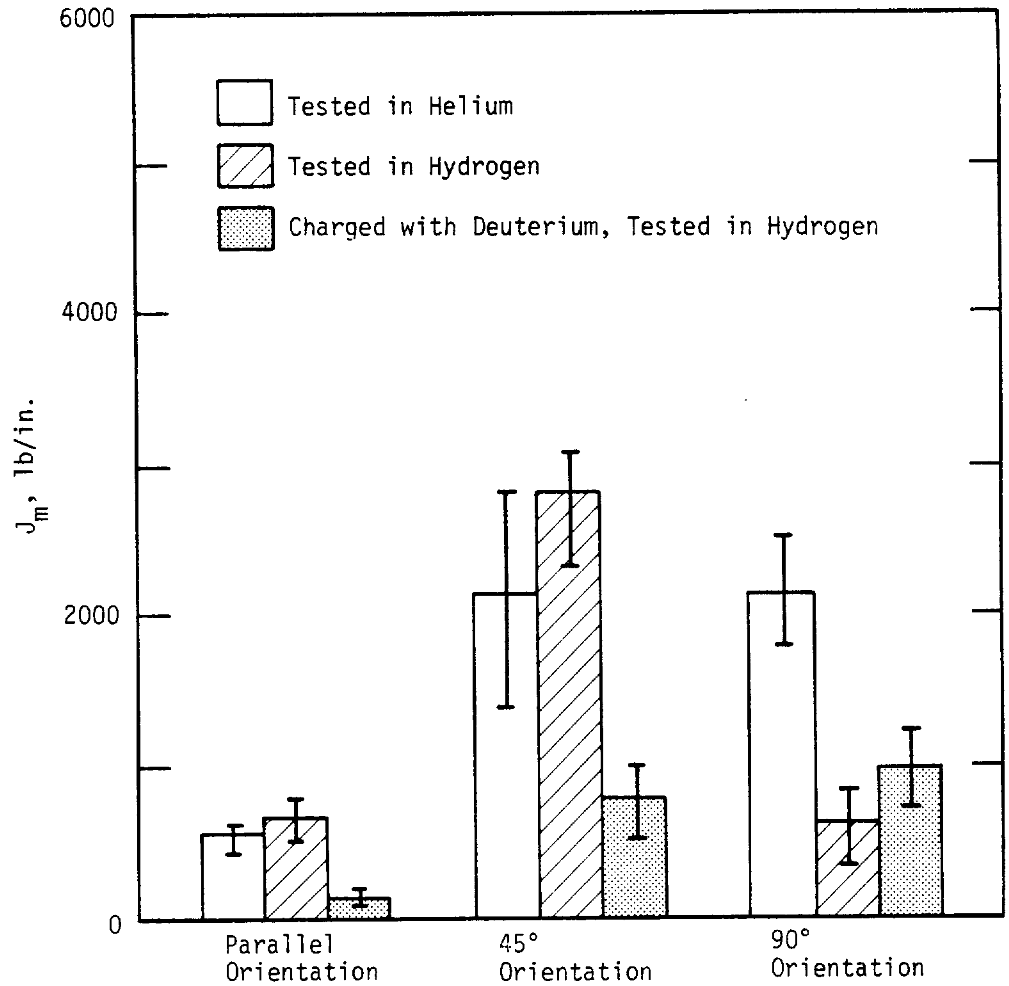


Fig. 2a. Fracture Parameters for Type 316 Stainless Steel

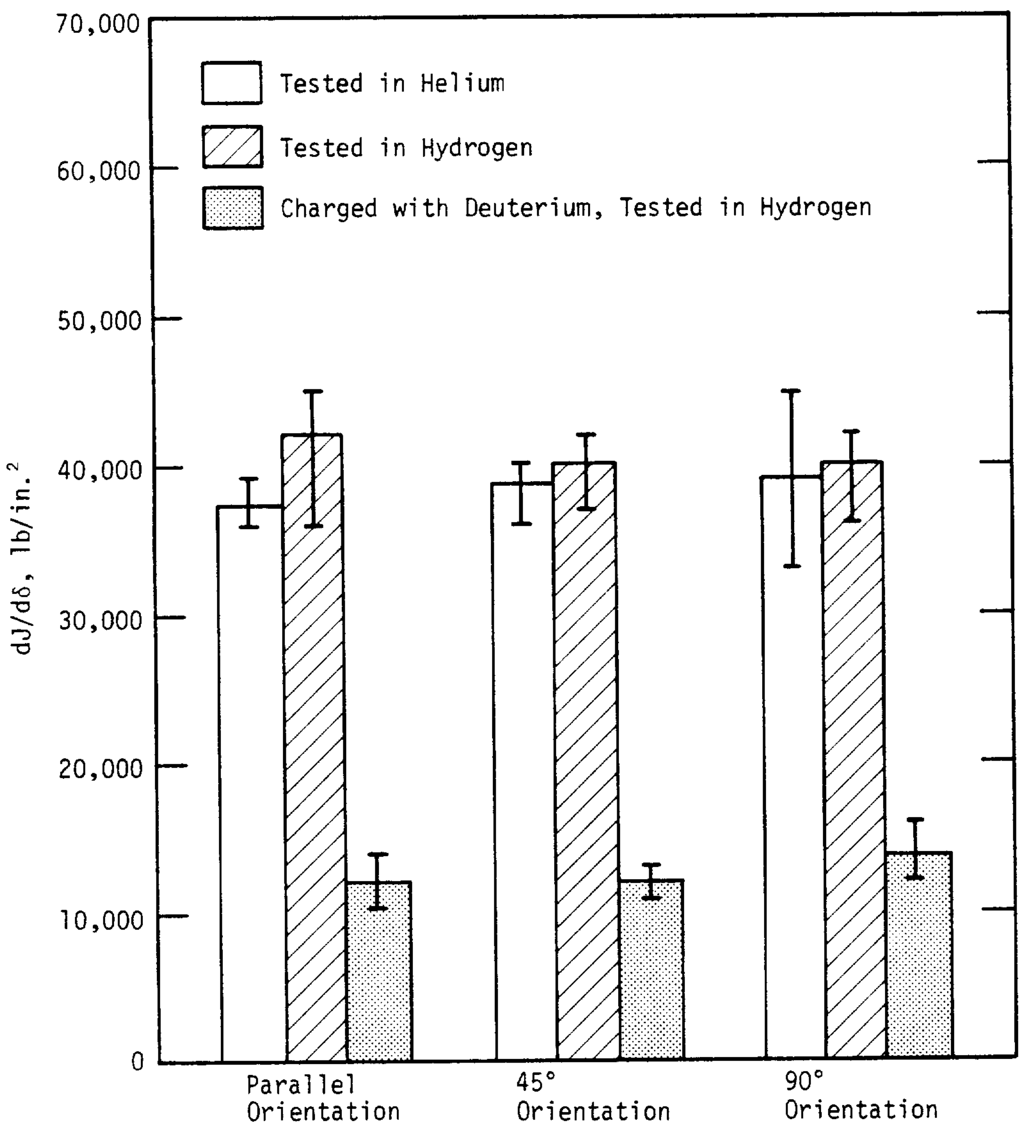


Fig. 2b. Fracture Parameters for Type 316 Stainless Steel

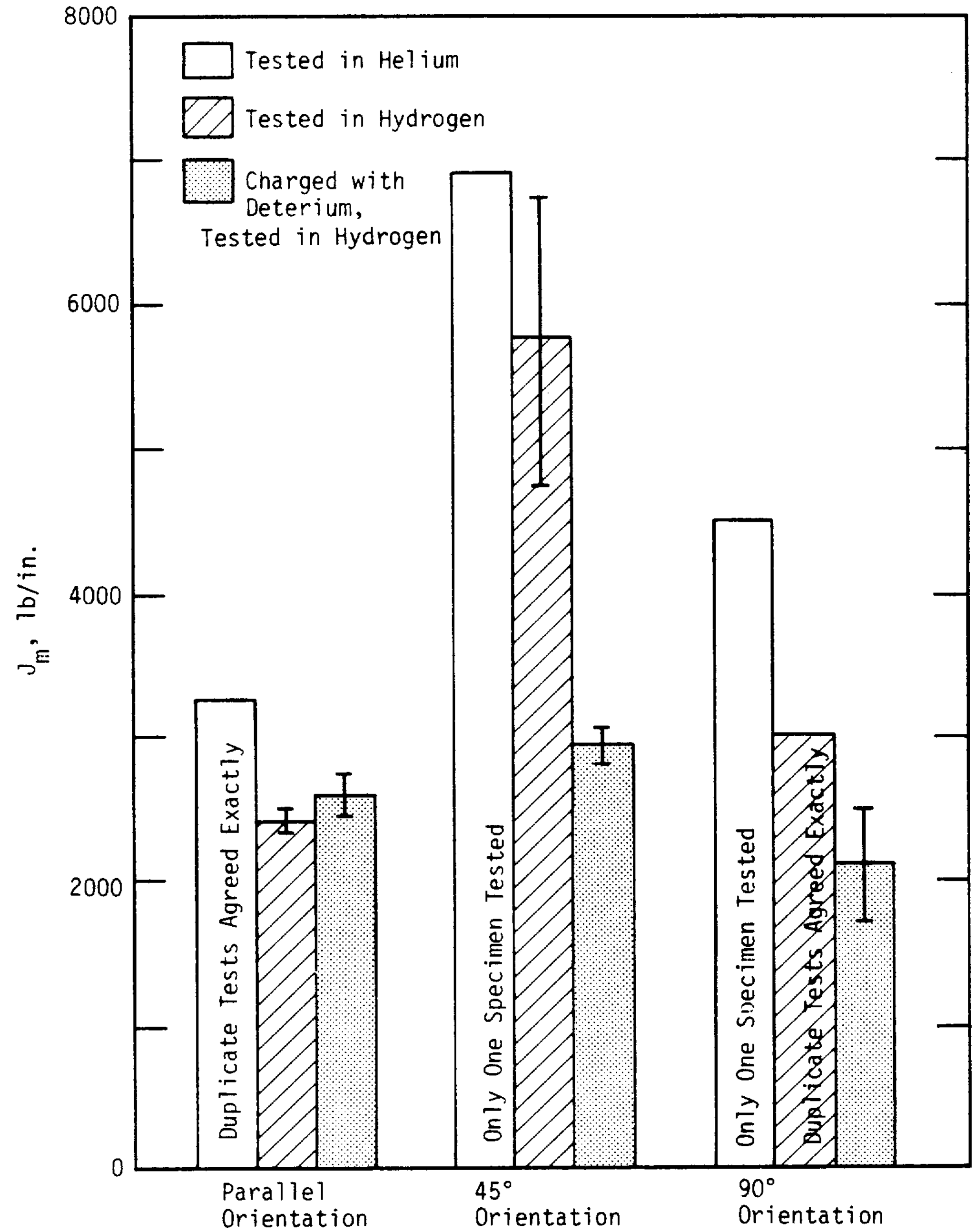


Fig. 3a. Fracture Parameters for Type 304L Stainless Steel

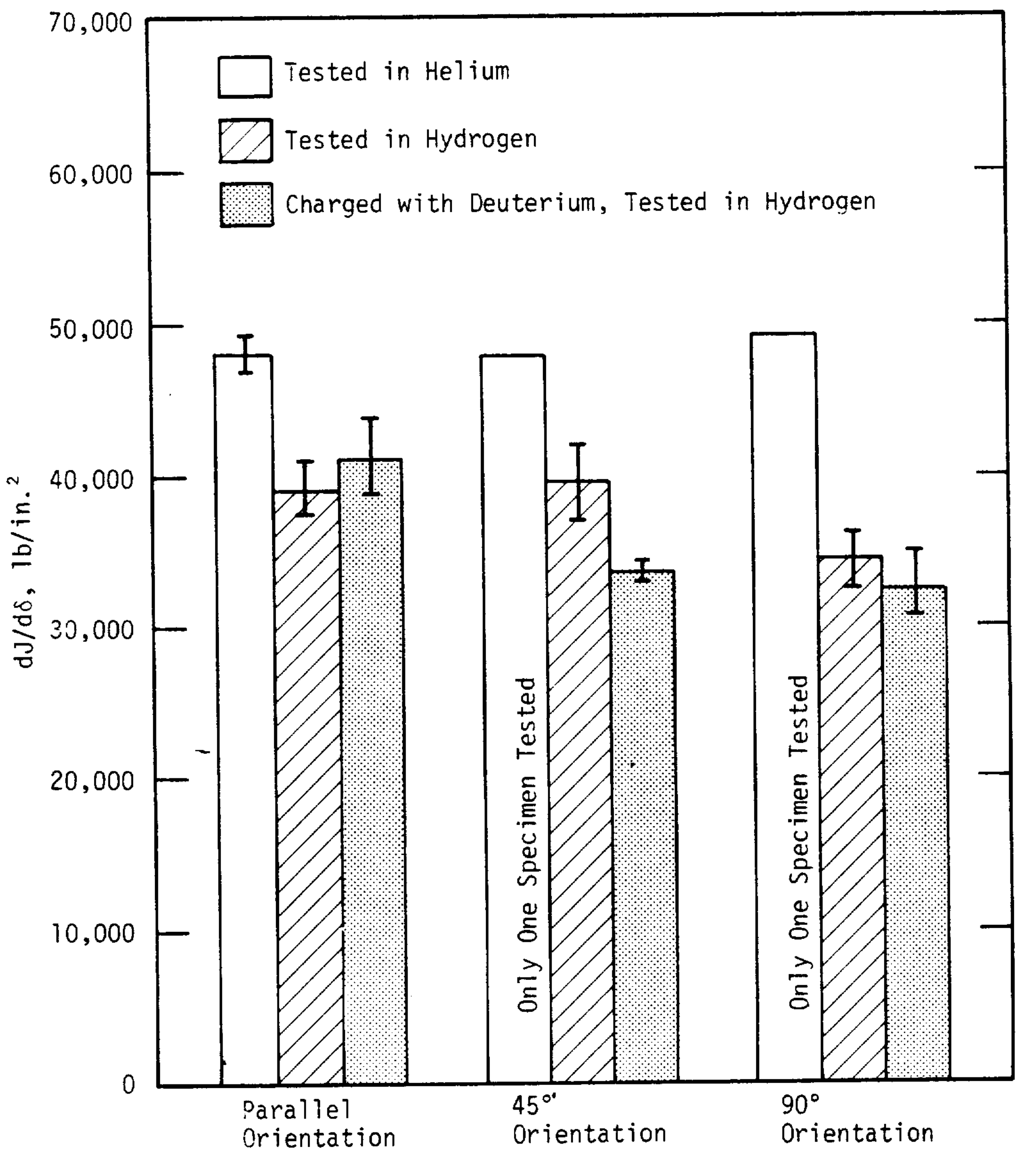


Fig. 3b. Fracture Parameters for Type 304L Stainless Steel

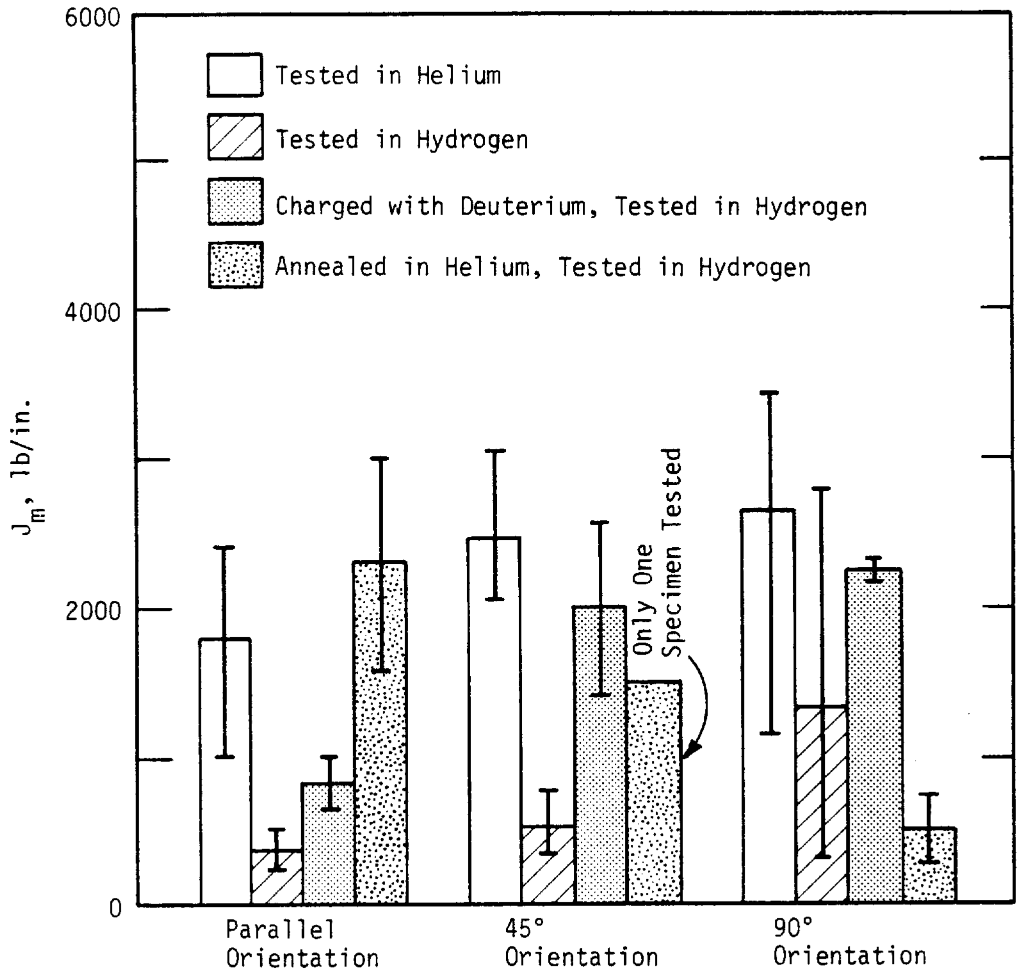


Fig. 4a. Fracture Parameters for Type 21-6-9 Stainless Steel

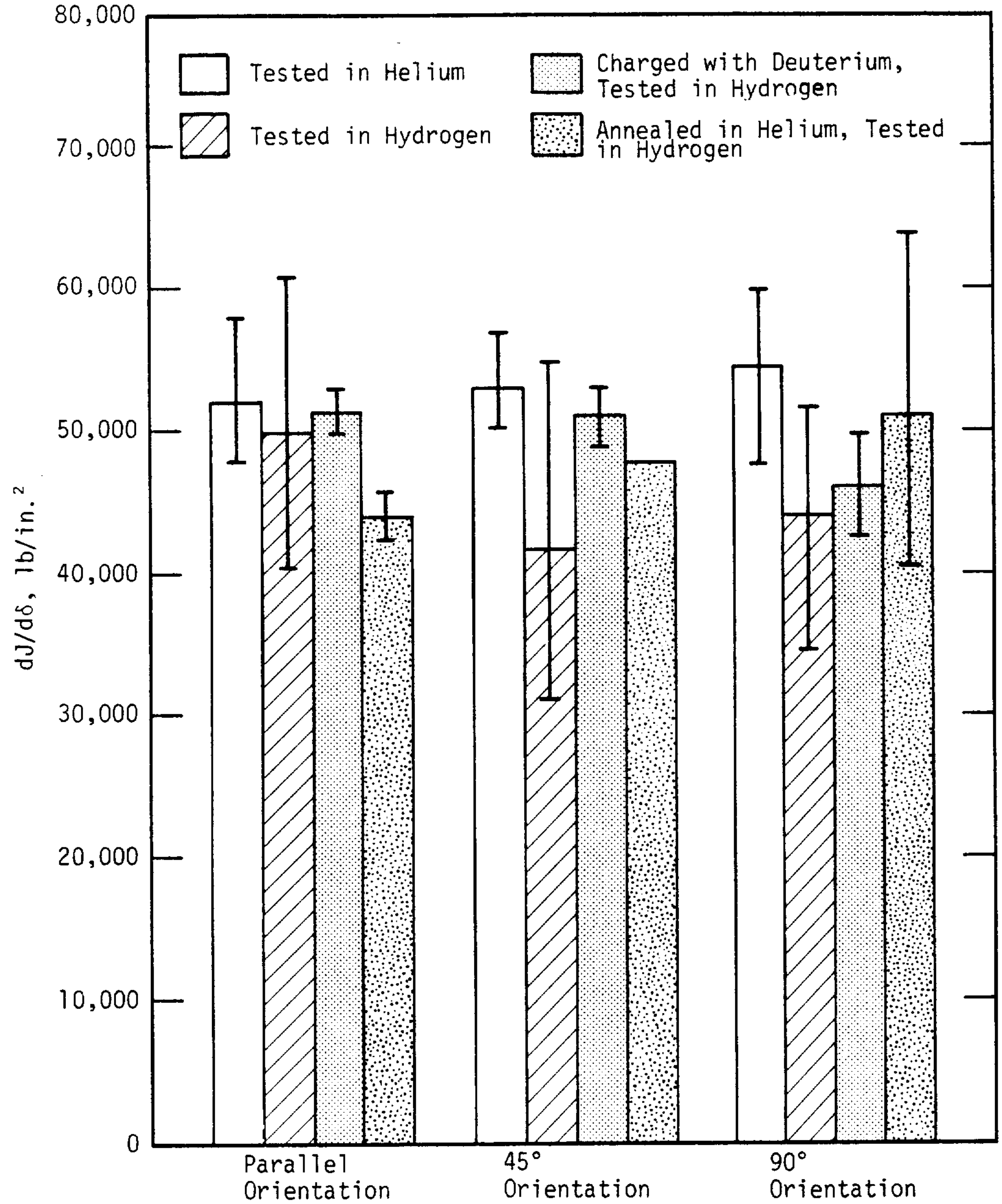


Fig. 4b. Fracture Parameters for Type 21-6-9 Stainless Steel

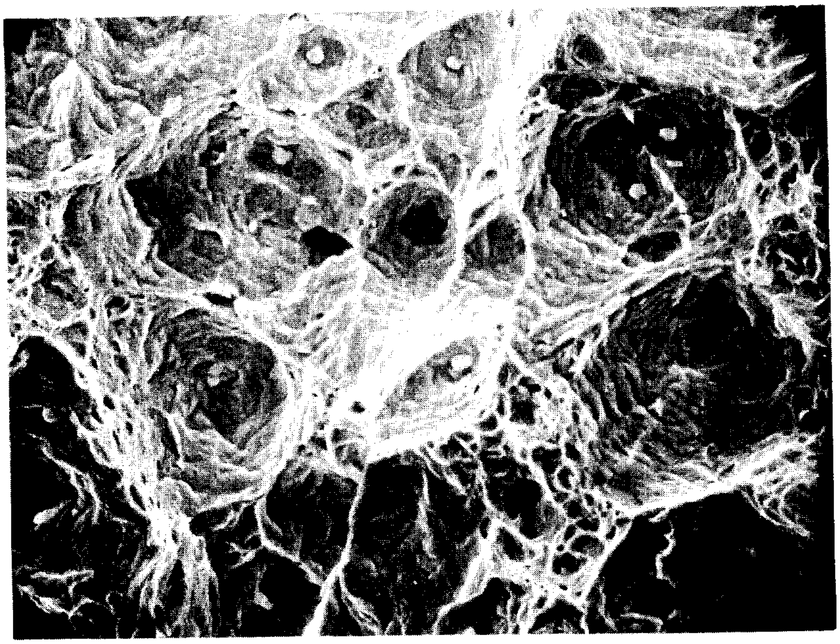


Fig. 5a. HERF 21-6-9 Orientation 1 Dimple Fracture in Helium

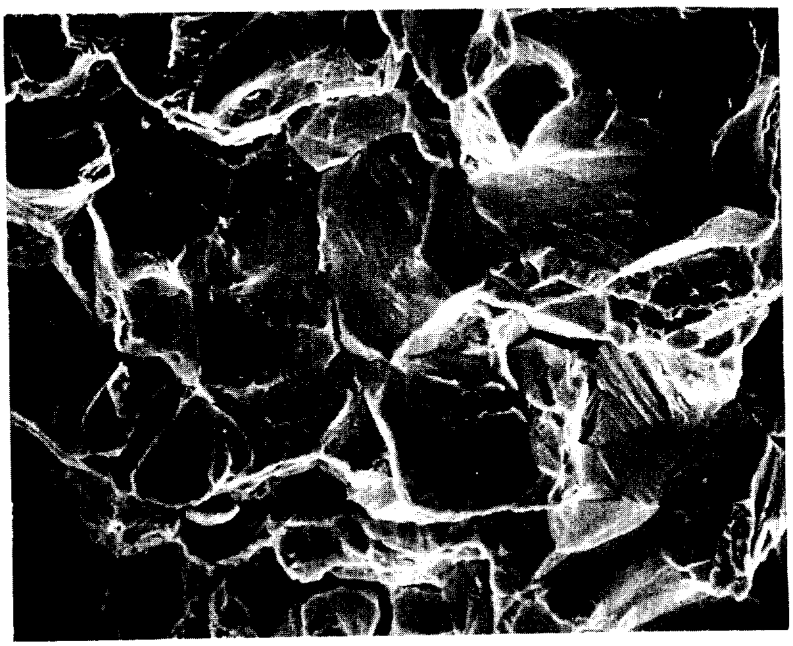


Fig. 5b. HERF 21-6-9 Orientation 1 Intergranular Fracture in Hydrogen

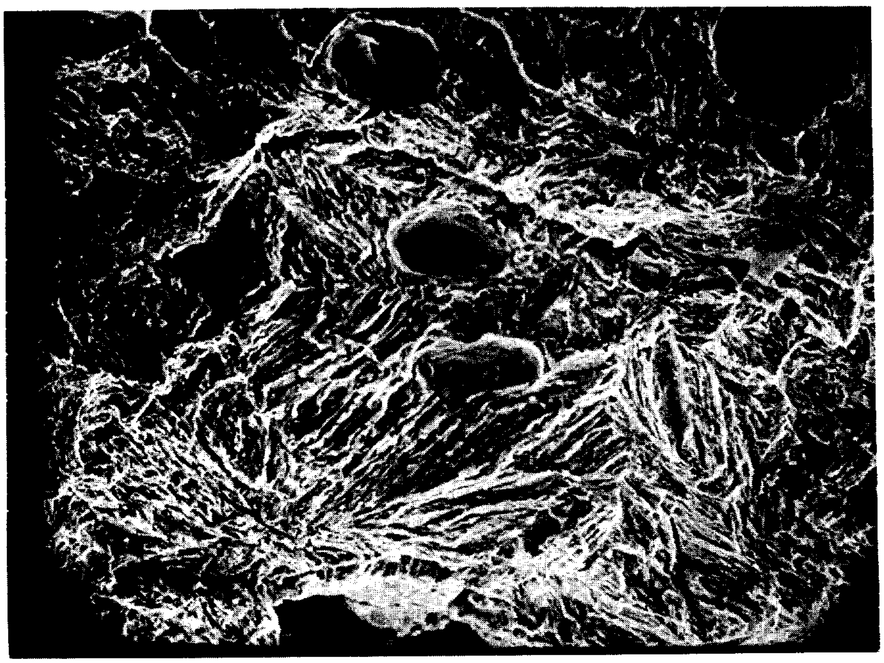


Fig. 5c. HERF 304L Orientation 1 Brittle Fracture in Hydrogen