The Effects of Hydrogen on the Fracture Toughness Properties of Upset Welded Stainless Steel (U)

by

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Materials Compatibility and Joining Technology

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THE EFFECTS OF HYDROGEN ON THE FRACTURE TOUGHNESS PROPERTIES OF UPSET WELDED STAINLESS STEEL (U)

By
Michael J. Morgan

SUMMARY

The effects of hydrogen on the fracture toughness properties of upset welded Type 304L stainless steel were measured and compared to those measured previously for as-received and as-welded steels. The results showed that the upset welded steels had good fracture toughness properties, but values were lower than the as-received material. The fracture toughness value of the base material was 6420 in-lbs / sq. in., while the welded steels averaged 3660 in-lbs /sq. in. Hydrogen exposure lowered the fracture toughness values of the as-received steel by 43 % to 3670 in-lbs /sq. in. and the welded steels by 21 % to 2890 in-lbs /sq. in. The fracture morphologies of the unexposed steels showed that ductile fracture occurred by the microvoid nucleation and growth process. The size of the microvoids on the fracture surfaces of the welded steels were much smaller and more closely spaced than those found on the base material fracture surfaces. The change in the size and spacing of the microvoids indicates that the fracture toughness properties of the welded steels were lower than the base steels because of the higher concentration of microscopic precipitates on the weld plane. The welds examined thus far have been "good" welds and the presence of these precipitates was not apparent in standard "low"-magnification metallographic sections of the weld planes. The results indicate that hydrogen did not weaken greatly the solid-state welds but that other inclusions or impurities present prior to welding did. Improvements in surface cleaning and preparation prior to welding should be explored as a way to improve the strength of solid-state welded joints. This report is the main deliverable toward the completion of the controlled milestone WRC02.

INTRODUCTION

Upset welding is a form of resistance welding that is applied in a variety of applications on the Savannah River Site. Resistance welds serve to seal tritium reservoirs, for attaching new fill stems to reservoirs for reclamation, and for closing the defense waste canisters (1-3). Upset resistance welds are also being proposed for fabrication of new reservoirs and for welding caps on reclaimed reservoirs (4).

Upset welds have many attractive features when compared to fusion welds (1). One of these is the nature of the bond—upset welds achieve a solid-state metallurgical bond with virtually no melting of the steel. Diffusion and grain growth across the interface are present in good welds and are used as evidence of a strong, high-quality weld. The properties of upset welds are assumed to be similar to those of a hot-worked steel and

therefore different than the properties associated with the solidification microstructures found in fusion welds.

The strength of upset welds has been demonstrated by pressure testing of containers, bend testing, tensile testing, and impact testing (4). Fracture toughness measurements can also be used for assessing the strength of welded joints. A sharp fatigue crack can be introduced into a test sample at or near the weld line and the resistance to cracking of the weld joint can be compared to that measured when the crack is in the base material. One of the advantages of the fracture toughness technique is that the samples can be forced to fracture on or near the weld plane and so that the effects on weld strength of the various weld parameters can be measured directly. Another advantage is that fracture toughness results can be used to predict loads at which a vessel would begin to crack or leak.

The chief purpose of this study was to measure the effects of hydrogen on the fracture toughness properties of upset welded stainless steel and to relate the fracture toughness properties to those measured in as-received and as-welded stainless steel. Although the results will be used chiefly to assess the properties of upset welded steels for the containment of hydrogen and its isotopes, they may also be useful for characterizing the properties of the large upset welds used to seal the defense waste canisters.

EXPERIMENTAL PROCEDURE

Three-point bend fracture toughness samples were cut from the walls of two 2.5" diameter hollow cylinders that were fabricated with a large upset girth weld. Both vessels were fabricated from hollowed Type 304L stainless steel bar stock. Figure 1 shows the orientation of the samples cut from the welded cylinders. Fracture toughness samples were prepared by cutting an electric-discharge-machined (EDM) notch on their weld line so that a fatigue crack could be introduced into the welded microstructure. The nominal sample dimensions are given in Figure 3. The weld center line was identified by first using an oxalic etch and then machining the EDM notch as close as possible to the weld center line. Control samples for the study were fabricated by cutting samples from the welded containers but machining the notch in the base material and away from the weld line. Typical notch locations with respect to the weld plane are shown in Figure 3 and the microstructure of the as-received and welded steels are shown in Figure 4.

Fatigue cracks were introduced into the samples by cyclically loading them in three-point bending in displacement control according to the recommended practices of ASTM E399 (5). The fatigue cracks were introduced in displacement control and grown under decreasing loads in order to minimize residual stresses at the crack tip.

Some of the pre-cracked samples were then exposed to hydrogen gas at 350 C and 10,000 psi. This exposure saturated the samples with approximately 9500 atomic parts per million and is typically used to test the susceptibility of a steel to hydrogen embrittlement (6).

The samples were then tested in three-point bending at room temperature in air using an Instron Model 1125 Tension-Compression machine. The crosshead speed was 0.005 in./min. Load, load-line displacement, and crack length were monitored during the test. Crack lengths were monitored using a reversing DC potential drop technique by applying a 2 A current to the sample and monitoring the change in resistance of the sample across the notch tip as the crack grew. Resistance measurements were normalized with respect to resistance measurements made in a location on the sample that was not affected by crack growth. In this way, small temperature fluctuations during the test did not affect the resistance and crack length measurements. The method of Johnson (7) was used to calculate crack length from the resistance change. Fracture toughness data were obtained using the J-integral procedures of ASTM E813-89 by calculating the energy input to the samples from the area under the load-displacement records up to and beyond crack initiation (5).

RESULTS

Typical load-displacement records for the as-received and as-welded samples are shown in Figure 5. Although the data are typical for high-toughness austenitic stainless steel, the welded samples exhibited a sharper drop-off in load with increasing displacement after maximum load than the as-received samples. This indicated that crack propagation was somewhat easier in the welded steels. Hydrogen-charged samples had similar load-displacement behavior, Figure 6. In this case, both the base material samples and the welded samples exhibited the sharp drop in load after maximum load.

The J-integral fracture toughness data were calculated from the load-displacement records and the crack length measurements. Typical J-da plots for the steels are shown in Figures 7-10 and the fracture toughness results are summarized in Table I. The results show that although the upset welded steels had good fracture toughness properties, values were lower than the as-received material. The fracture toughness value of the base material was measured to be 6420 in-lbs/sq. in. on average, while the welded steels averaged 3660 in-lbs/sq. in.

The hydrogen-exposed steels had lower fracture toughness values than the unexposed steels. However, the base material fracture toughness value was affected more by hydrogen than the welded steels were. Hydrogen exposure lowered the fracture toughness values of the as-received steel by 43 % and the welded steels by just 21 %.

Fracture of the unexposed steels occurred by ductile rupture. For the welded steels, some of the fatigue starter cracks were not quite on the weld interface. As some of these samples were deformed, the cracks tended to run onto the weld interface; in others the cracks tended to stay away from the interface. Thus, these measurements are really an indication of the toughness of the material at or near the weld interface. Figures 11 and 12 show the typical fracture appearances for the as-received and the welded steels. The size of the microvoids on the fracture surfaces of the welded steels were smaller and more closely spaced than those found on the base material fracture surfaces. This was

particularly true when the cracks were right on the weld line. Figure 13 shows that many of the microvoids on the fracture surfaces of the welded steels were less than 0.5 μm in diameter.

DISCUSSION

The results of this study show that the upset welded steels had good fracture toughness properties but the values were lower than the as-received material. Although the fracture toughness values of the welded steels were just 57 % of the base material values, they both were within literature values for the fracture toughness properties of Type 304L (8, 9).

Table I Fracture Toughness Properties

Sample	Crack Location	Charging Condition	Fracture Toughness , in-lbs / sq. in
8	base mat'l	none	6126
08*	base mat'l	none	6716
1	on weld	none	3665
01*	on weld	none	4256
03*	on weld	none	3415
4	on weld	none	3301
9	base mat'l	H2-charged	3781
09*	base mat'l	H2-charged	3549
7	on weld	H2-charged	2517
5	on weld	H2-charged	3057
07*	on weld	H2-charged	3082

All samples were fabricated from Type 304L stainless steel.

*The samples marked with an 0 in front of their ID # were fabricated from a cylinder that was 2.63 " long; the others were taken from a cylinder 2.25 " long.

Hydrogen charged samples were exposed at 10000 psig and 350 C for three weeks and were saturated with 9500 appm hydrogen.

The toughness difference could partly be a yield strength effect. Fracture toughness tends to decrease within increasing yield strength and the yield strength in the vicinity of the welds in these steels may be slightly higher than that of the base material. However, the high concentration of microscopic precipitates on the fracture surfaces of the welded steels seems to be the main reason for the reduced fracture toughness properties.

Both as-received and welded steels fractured by the ductile rupture process, i.e., microvoid nucleation and growth. The size of the microvoids on the fracture surfaces of the welded steels were much smaller and more closely spaced than those found on the base material fracture surfaces. This indicates that the fracture toughness properties of the welded steels were lower than the base steels because of the higher concentration of microscopic precipitates served as many nucleation sites for microvoids. The microvoids did not have to grow very much under strain before they grew into a neighboring microvoid. The coalescence of the microvoids occurs at a lower strain and so a lower fracture toughness results.

The welds examined thus far have been "good" welds and the presence of these precipitates was not apparent from metallographic sections of the weld planes. The results also indicate that hydrogen did not weaken greatly the solid-state welds but that other inclusions or impurities present prior to welding did. These inclusions were not observable in standard low magnification metallographic sections. Improvements in surface cleaning and preparation prior to welding should be explored as potential ways to improve the strength of solid-state welded joints.

CONCLUSIONS

1. The measured fracture toughness values of upset welded Type 304L stainless steel were about 60 % those of as-received steels but with the range expected for this steel.
2. Hydrogen-exposure lowered the fracture toughness values but the welded steels were less affected than the base material.
3. Surface preparation and cleanliness appear to be the major factors in the reduced fracture toughness properties of upset welded steels.

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FIGURE 1. ORIENTATION OF 3-POINT BEND FRACTURE TOUGHNESS SAMPLES CUT FROM 2.5 INCH DIAMETER UPSET WELDED CYLINDERS.

FIGURE 2. NOMINAL ASTM E813 SINGLE EDGE NOTCH BEND (SENB) SPECIMEN (DIMENSIONS SHOWN ARE IN INCHES).

(a)

(b)

FIGURE 3. LOCATION OF NOTCH WITH RESPECT TO WELD PLANE (A) NOTCH ON WELD PLANE; (B) NOTCH IN BASE MATERIAL (10X).

(a)

(b)

FIGURE 4. TYPICAL MICROSTRUCTURE OF TYPE 304L STEELS NEAR EDM NOTCH IN: (A) AS-RECEIVED STEEL AND (B) UPSET WELDED STEEL (200X).

FIGURE 5. LOAD-DISPLACEMENT RECORDS FOR UNEXPOSED SAMPLES.

FIGURE 6. LOAD-DISPLACEMENT RECORDS FOR HYDROGEN-EXPOSED SAMPLES.

(a)

(b)

FIGURE 7. J-DA CURVES FOR UNEXPOSED SAMPLES (A) AS-RECEIVED STEEL; (B) UPSET-WELDED STEEL.

(a)

(b)

FIGURE 8. J-DA CURVES FOR HYDROGEN-EXPOSED SAMPLES TESTED IN AIR (A) AS-RECEIVED STEEL; (B) UPSET-WELDED STEEL.

(a)

(b)

FIGURE 9. TYPICAL FRACTURE APPEARANCE FOR: (A) AS-RECEIVED STEEL; (B) UPSET WELDED STEEL (8X).

(a)

(b)

FIGURE 10. DIMPLED RUPTURE FRACTURE FEATURES: (A) IN BASE METAL; (B) NEAR WELD INTERFACE (250X).

(a)

(b)

FIGURE 11. TYPICAL DIMPLED RUPTURE FEATURES SEEN ON FRACTURES ON WELD INTERFACE (A) 250 X; (B) 1000 X.

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