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# Tritium and Decay Helium Effects on the Fracture Toughness Properties of Stainless Steel Weldments


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**Effect of Tritium and Decay Helium on the Fracture Toughness Properties of Stainless Steel Weldments**

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*J-Integral fracture toughness tests were conducted on tritium-exposed-and-aged Types 304L and 21-6-9 stainless steel weldments in order to measure the combined effects of tritium and its decay product, helium-3 on the fracture toughness properties. Initially, weldments have fracture toughness values about three times higher than base-metal values. Delta-ferrite phase in the weld microstructure improved toughness provided no tritium was present in the microstructure. After a tritium-exposure-and-aging treatment that resulted in ~1400 atomic parts per million (appm) dissolved tritium, both weldments and base metals had their fracture toughness values reduced to about the same level. The tritium effect was greater in weldments (67 % reduction vs. 37% reduction) largely because the ductile discontinuous delta-ferrite interfaces were embrittled by tritium and decay helium. Fracture toughness values decreased for both base metals and weldments with increasing decay helium content in the range tested (50-200 appm).*

## I. INTRODUCTION

Fusion power plants will require large scale tritium processing facilities that will be constructed from stainless steels because of their good compatibility with tritium. Although these steels are highly resistant to the embrittling effects of hydrogen isotopes and helium from tritium decay, they are not immune (1-4). Ductility, elongation-to-failure, and fracture toughness are reduced by exposures to tritium and the reductions increase with time as helium-3 builds into the material from tritium diffusion and radioactive decay (3,4).

Fracture toughness properties and fracture mechanics analyses can be used to provide designs that minimize the potential for tritium-induced crack growth in plant process equipment. However, limited fracture toughness data is available for tritium-exposed steels, particularly weldments. The purpose of this work was to measure the effects of tritium and decay helium on the fracture toughness properties of Types 304L and 21-6-9 stainless steel weldments. Type 304L is commonly used in tritium applications and Type 21-6-9, a nitrogen-strengthened alloy, has been used for high-strength applications. A number of studies have been published on the effects of hydrogen and tritium on the properties of the base metals of these alloys ( ).

## II. EXPERIMENTAL PROCEDURE

Fracture toughness samples were fabricated from weldments of Types 304L and 21-6-9 Stainless Steel. The composition of the steels and weld filler material used in the study are listed in Table I. The base metal was supplied in the form of forward extruded cylindrical forgings. Notched groves were cut along the length of the forgings and the grooves were filled using the Gas Tungsten Arc (GTA) process and Type 308L filler wire.

After welding, the forgings were sectioned into round discs and radiographed to verify that there was no unusual porosity, cracks, or other macroscopic defects from the welding process. This was done to ensure the fracture-toughness samples were machined from high-quality welds and that any differences in properties could be attributed to the weldment microstructure. Arc-shaped fracture-mechanics specimens having the shape and dimensions shown in Fig. 1 were fabricated from the perimeter of each disc and oriented with their notches along the centerline of a weld. The samples were fatigue-cracked along the weld centerline so that the crack-length to sample-width ratio was between 0.4 and 0.6.

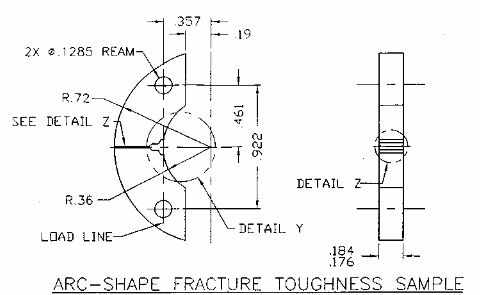


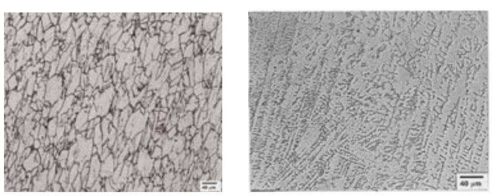

Fig. 1. Shape and Dimensions of Fracture-Toughness Sample. Dimensions shown are in Inches.

**Table I. Compositions of Stainless Steel Forgings, Plates and Weld Filler Wires (Weight %)**

| | Cr | Ni | Mn | Mo | C | Si | Cu | P | S | N | Co | O | Al |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **304L Forging Base Metals*** | 18 | 11.3 | 1.7 | 0.039 | 0.024 | 0.42 | - | 0.007 | 0.003 | 0.036 | 0.027 | - | -- |
| **304L Forging Weldments** | 19.9 | 10.4 | 1.7 | 0.04 | 0.029 | 0.63 | - | 0.015 | 0.002 | 0.039 | 0.03 | - | - |
| **308L** Filler Wire** | 20.5 | 10.3 | 1.56 | <0.01 | 0.028 | 0.5 | 0.015 | 0.006 | 0.012 | 0.055 | 0.068 | - | - |
| **21-6-9 HERF Forging** | 19.4 | 6.4 | 8.5 | .- | .04 | .33 | - | .021 | <.001 | .28 | - | .0022 | <.001 |
| **21-6-9 Conventional Forging** | 19.1 | 6.7 | 9.9 | - | .03 | .41 | - | .01 | .004 | .28 | - | .001 | .005 |
| **21-6-9 CF Heat 2** | 19.3 | 6.7 | 9.9 | - | .03 | .38 | - | .01 | .001 | .28 | - | .002 | .004 |

*304L composition from ICPES analysis; all other heats are manufacturers' supplied compositions.
**Filler wire used for Types 304L and 21-6-9 weldments

Typical microstructures of the base metal and weldments are shown in Fig. 2. The base metal microstructures of both steels consisted of austenite with grains elongated in the direction of forging while the weldment microstructures consisted of discontinuous skeletal ferrite phase in a predominant austenite matrix.



(a) (b)

Fig. 2. Microstructures of Type 21-6-9 Stainless Steel: (a) Forged Base Metal and (b) Weld Metal

Samples of both steels were tested in air at ambient temperature in the as-forged and as-welded conditions. Companion samples were exposed to either hydrogen or tritium gas at 623 K and an over-pressure of 34.5 MPa or 69 MPa and then stored in air at 223 K. The temperature of exposure was designed to saturate the samples with hydrogen or tritium while minimizing any change in the steel microstructure; the storage temperature was designed to limit any tritium off-gassing and allow for the build-in of helium from tritium decay until testing was performed. Testing of the tritium-charged samples was conducted over a period of years to measure the combined effect of tritium and decay helium on the fracture toughness properties. After testing, tritium-charged samples were analyzed by vacuum extraction for helium concentration from tritium decay. The helium content of each sample was calculated from the measured values and by accounting for the decay of tritium back to the date of the fracture test.

J-integral tests were conducted at room temperature in air using a screw-driven testing machine and a crosshead speed of 0.002 mm/s while recording load, load-line displacement with a gage clipped to the crack mouth, and crack length. Crack length was monitored using an alternating DC potential drop system and guidelines described in ASTM E647-95 (5). The J-Integral versus crack length increase (J vs. da) curves were constructed from the data using ASTM E1820-99 (6). The $J_Q$ value is defined as the material fracture toughness value and was obtained from the intercept of an offset from the crack tip blunting line with the J-da curve.

## III. RESULTS

Typical J-da curves for the unexposed base metals and weldments of both steels are shown in Fig. 3. The unexposed weldments had average $J_Q$ fracture-toughness values two-to-three times higher than the base metal values. The presence of delta-ferrite phase in the microstructure, at least at these levels (5-8% by volume) has a beneficial effect on fracture toughness and cracking resistance for the unexposed weldments. The resistance to continued crack propagation was also improved in weldments over base metals and is indicated by the steep slope of the J-da curves of the weldments in Fig. 3.

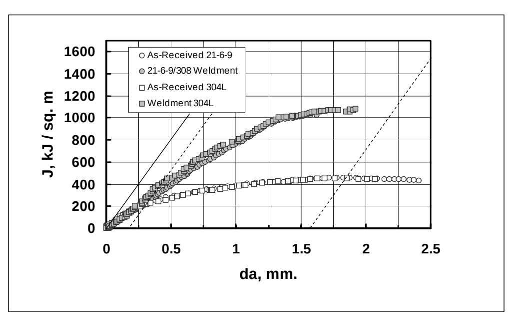



Fig. 3. J-da Curves for Base Metals and Weldments of Types 304L and 21-6-9 Stainless Steels

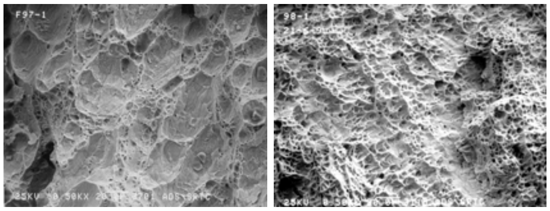


Fig. 4. Fracture Appearance in Unexposed Type 21-6-9 Stainless Steel: (a) Base Metal and (b) Weldment. Crack propagation was from left to right.

The fracture modes of as-forged and as-welded Type 21-6-9 samples are shown in Fig 4. The base metal fails by the dimpled rupture process: Microvoids nucleate at nonmetallic inclusions in the steels (sulfides, oxides, etc) and grow under strain until their coalescence causes fracture. Weldments have a dispersion of fine inclusions that are produced during the welding process. Their size and distribution can affect fracture toughness. In this case, the inclusions serve as microvoid nucleation sites during the dimpled rupture fracture process but don't significantly reduce fracture toughness from the base metal because of the presence of the discontinuous and ductile skeletal ferrite phase. Type 304L steels and weldments had similar fracture modes.

Hydrogen charging lowered the resistance of the steel to crack initiation and growth as indicated by the lower $J_Q$ values and the less-steep J-da curves in Fig 5. The effect was even greater as the charging pressure was increased from 34.5 MPa to 69 MPa. The effect of tritium exposure on Type 21-6-9 stainless steel J-da behavior is shown in Fig. 6. Tritium charged samples had lower fracture toughness than samples similarly charged with hydrogen because of the presence of helium from tritium decay. After exposure, hydrogen- and tritium-charged base metal fracture surfaces had a much smaller microvoid size and finer spacing (Fig. 7) than what was seen in the unexposed samples (Fig. 4).

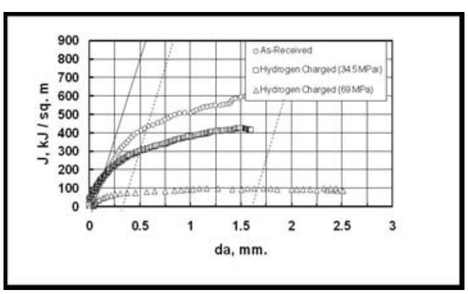



Fig. 5. Effect of Hydrogen on J-da Behavior of Type 21-6-9 Stainless Steel.

Tritium and decay helium had a remarkable effect on weldment toughness, as shown in Fig. 8 which shows the reduction in the J-da curves for tritium-charged weldments. Cracking along ferrite/austenite interfaces or through the ferrite is observed on the weldment fracture surfaces after tritium exposure (Fig. 9). Furthermore, the $J_Q$ fracture toughness values decreased further with increasing decay helium content (Figs. 10-11). After helium builds in from tritium decay the initially high weldment fracture toughness of both steels is reduced to values similar to those of the reduced base metal values.

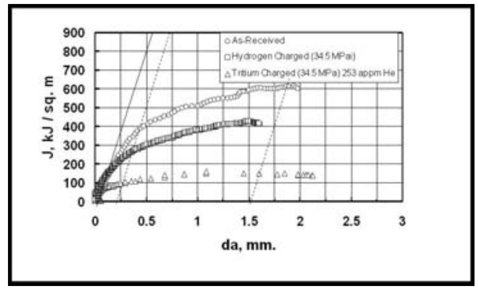



Fig. 6. Comparison of J-da Behavior of Uncharged, Hydrogen-Charged and Tritium-Charged-and-Aged Type 21-6-9 Stainless Steel.

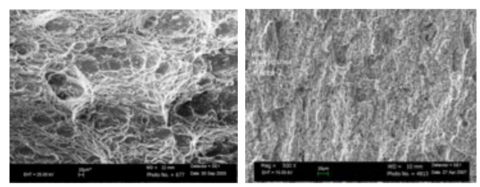


Fig. 7. Fracture Appearance of Type 21-6-9 Stainless Steel: (a) Hydrogen charged at 34.5 MPa and (b) Tritium-Charged at 34.5 MPa and Aged (253 appm Helium).

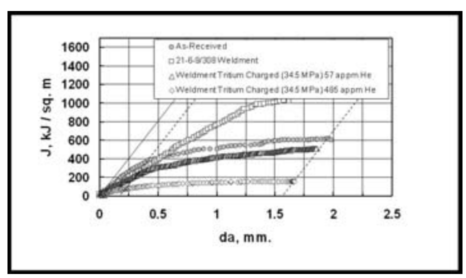



Fig. 8. Effect of Tritium and Decay Helium on the J-da Behavior of Type 21-6-9 Stainless Steel Weldments

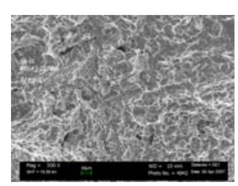


Fig. 9. Fracture Appearance of Tritium-Exposed-and-Aged Type 21-6-9 Weldment (485 appm Helium)

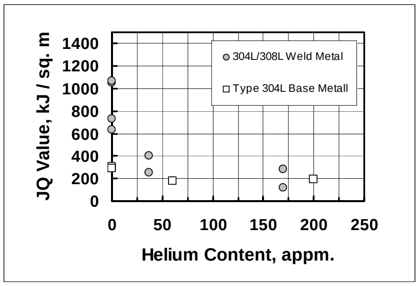



Fig. 10. Effect of Decay Helium Content on the JQ Value of Type 304L Stainless Steel and its Weldment.

The effect of ferrite weldment toughness is in agreement with that described in other studies (7-9). Brooks (7) points out that the ductile ferrite phase tends to blunt propagating cracks and provides a tortuous path through the microstructure of weldment while Mills (8) indicates that ferrite phases in stainless steel weldments are brittle at low temperature and welds exhibit a ductile-brittle transition temperature phenomenon. At ambient and elevated temperatures, Mills shows that the ferrite phase behaves in a ductile manner, and welds are more resistant to fracture. The weldments toughness behavior seen in this study is consistent with the fracture process that Mills describes if the ferrite phase is embrittled by tritium and helium. The fracture modes of weldments are consistent with Brooks (9) in that hydrogen-induced fracture occurs along or near the austenite-ferrite boundary in welds.

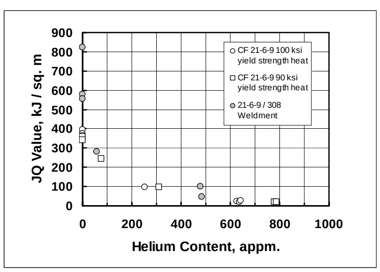



Fig. 11. Effect of Decay Helium Content on the JQ Value of Type 21-6-9 Stainless Steel and its Weldment.

## IV. CONCLUSIONS

[1]. For Types 304L and 21-6-9 stainless steels, the fracture toughness of weldments is two to three times higher than the base metal toughness. The toughness improvement is attributed to the the ductile ferrite phase in the microstructure.

[2]. Hydrogen and tritium exposure lowered the fracture toughness properties of both base metals and weldments to similar values. Toughness decreased with increasing helium content from tritium decay.

[3]. Fracture occurred by microvoid nucleation, growth and coalescence. Hydrogen and tritium fracture surfaces have a finer void size and spacing than unexposed fracture surfaces. Weld fracture surfaces showed evidence for tritium-induced cracking through ferrite or along ferrite-austenite interfaces.

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