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Effect of Tritium and Decay Helium On Weldment Fracture Toughness

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Background

Welded stainless steel vessels are used for the containment of tritium gas. Weldments have not been well-characterized with respect to embrittlement by tritium and its radioactive decay product and fracture toughness properties are needed to assess the long-term effects of tritium on crack nucleation and growth in tritium reservoirs. The purpose of this work was to measure the fracture toughness properties of tritium-exposed-and-aged weldments and compare them to base metal toughness. This paper is a summary of a more comprehensive SRNL report issued in July of 2006 (1).

Experimental Procedure

Fracture toughness samples were fabricated from weldments of Type 304L Stainless Steel. The composition of the steels and weld filler materials used in the study are listed in Table I. The base metal was supplied by the Kansas City plant in the form of forward extruded cylindrical forgings.

Notched groves were cut along the length of the Type 304L forging and the grooves were filled using the Gas Tungsten Arc (GTA) process and the Type 308L filler wire. Figure 1 shows the Type 304L forging and the welds. 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 differences in ferrite content or microstructure. Arc-shaped fracture-mechanics specimens having the shape and dimensions shown in Figure 2 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.

Three sets of samples were prepared for the study. One set was tested in the as-forged or as-welded condition. The other two sets were exposed to tritium at 350°C and an over-pressure of 5000 psi and then aged in air at -50° before testing. The temperature of exposure was designed to saturate the samples with tritium without changing the steel microstructure while

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	-	-

*304L composition from SRS ICPES analysis; all other heats are manufacturers' supplied compositions.

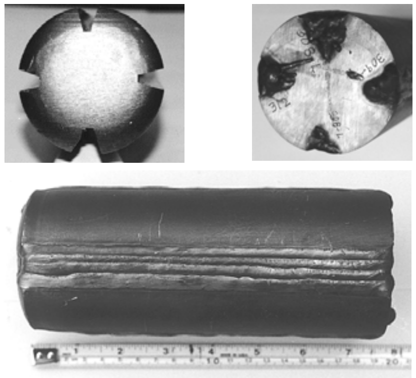

Figure 1. Type 304L Forging with Cut Grooves and Weldments Made Using Types 308L, 309L MOD, and 312 MOD Filler Materials.

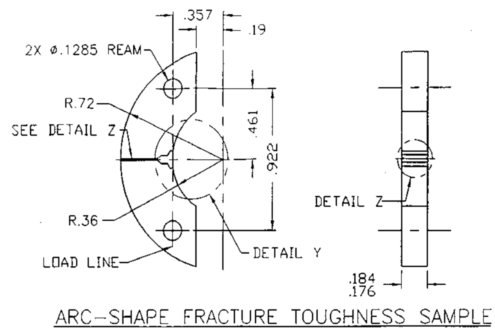

Figure 2. Shape and Dimensions of Fracture Toughness Sample.

the aging temperature was designed to minimize tritium off-gassing during aging. The effect of decay helium on fracture toughness was measured by testing after six months and 30 months of aging.

Tritium-charged samples were analyzed by vacuum extraction for helium concentration from tritium decay. The measured value of decay helium in the base metals agrees with the expected value calculated from tritium solubility, diffusivity, and decay and the results are shown in Table II. The helium content of each sample was calculated from the measured values and by accounting for the decay of tritium to the date of the fracture test. The results show that estimated values of decay helium on the date a weldment was tested was about 25 % lower than those in base metal for the same tritium exposure. Note in Table II, the base metals were estimated to have an initial concentration of 1600 appm tritium while the welds had just 1200 appm tritium. The difference is attributed to the fact that weldments contained about 8% ferrite by volume and tritium diffusivity values in ferrite are orders of magnitude higher than in austenite. Thus, tritium losses from weldments are higher during handling and storage.

Table II. Tritium and Helium Contents for Tritium-Exposed Base Metal and Weldments

Material Description	Measured Helium Content* (appm)	Calculated Initial Tritium Content (appm)	Aging Time 1st J-Integral Test (days)	Calculated Helium Content for 1st Test (appm)	Aging Time 2nd J-Integral Test (days)	Calculated Helium Content for 2nd Test (appm)
Type 304L Base Metal	129	1600	244	60	851	200
Type 304L/308L Weldment	216	1200	156	37	760	170

*The helium content from tritium decay was measured on different dates for base metals and welds. The helium content of each sample was calculated from the measured values and by accounting for the decay of tritium 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 0.005 in / min. 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. The J-Integral versus crack length increase (J vs. da) curves were constructed from the data using ASTM E1820-99. 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 and can be used to estimate the vessel stresses that would cause the growth of a crack from a pre-existing flaw from the vessel service history.

Results

Typical J-da plots for the steels are shown in Figure 3 for the unexposed weldments and base metals. The J_Q fracture toughness data from these data and the tensile properties are summarized in Table III. Note from Figure 3 that the unexposed weldments had fracture-toughness values two-to-three times higher than the base metal values. The presence of delta-ferrite in the microstructure, at least at these levels (8 volume %) has a beneficial effect on fracture toughness and cracking resistance. The resistance to crack propagation was improved as well and is indicated by the steep slope for the J-da Type 308L weld data of Figure 3.

The effect of tritium exposure and aging on the base metal J-da behavior is shown in Figure 4. Tritium and its decay product, helium had the effect of lowering 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. Tritium and decay helium had a similar effect on the weld toughness. Figure 5 shows that the weldment J-da curve was markedly lowered by tritium exposure and aging. The delta ferrite phase has a beneficial effect on cracking resistance for unexposed weldments but a detrimental effect on tritium-induced cracking resistance. The percent reduction by tritium and helium on toughness was greater for welds than base metals. Table III indicates that the tritium-charged weldments had fracture toughness values reduced from 4975 lbs / in to values ranging from 1500-1900 lbs / in while base metals had toughness reduced from about 1700 to 1100 lbs / in.

Table III. Mechanical Properties and Fracture Toughness Values for Base Metals and Weldments

Material Description	Ferrite %	Yield Strength	Ultimate Strength	J_Q As-Received	J_Q Tritium-Charged & Aged 6 Mos.	J_Q Tritium-Charged & Aged 30 Mos.
		ksi	ksi	lbs / in.	lbs / in.	lbs / in.
Type 304L	0	67	105	1690	1024	1117
Weldment Type 304L/308L	8	62	88	4975	1890	1494

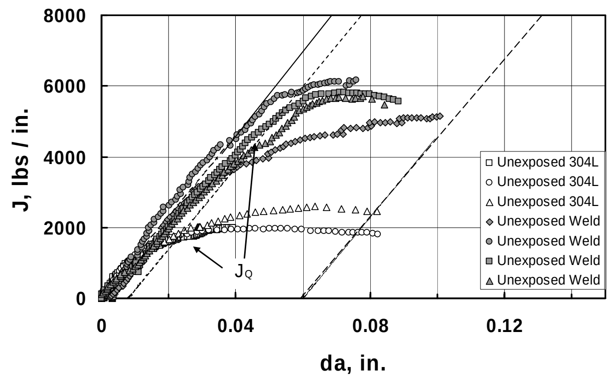

Figure 3. J-Integral vs. Change in Crack Length (J-da) Behavior for Unexposed Base Metals and Welds. Note that the weldments had higher fracture toughness values than base metals. J_Q fracture toughness values were determined from the intercept of the offset line (See arrows).

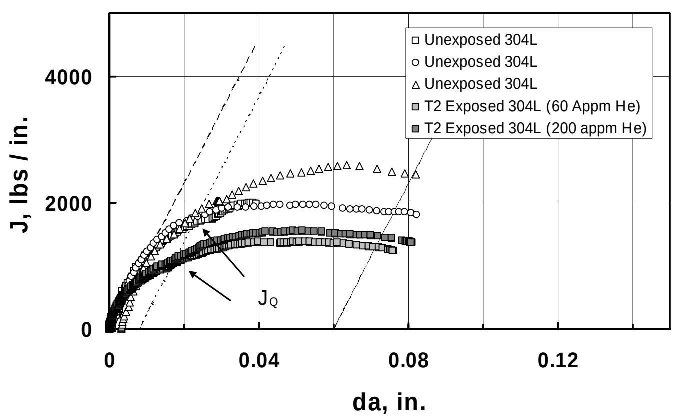

Figure 4. J-da Behavior for Unexposed and Tritium-Exposed Type 304L Base Metal.

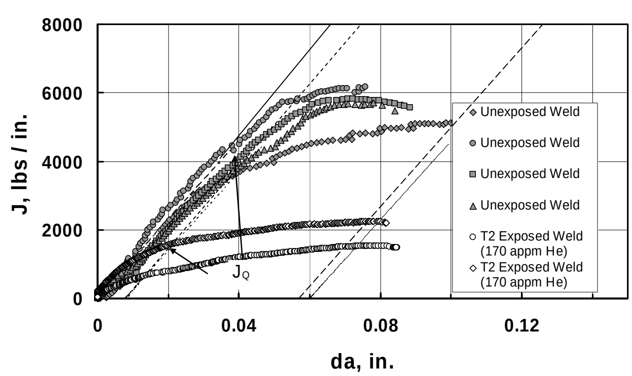

Figure 5. J-da Behavior for Unexposed and Tritium-Exposed Weldments. Only data for higher helium levels are shown.

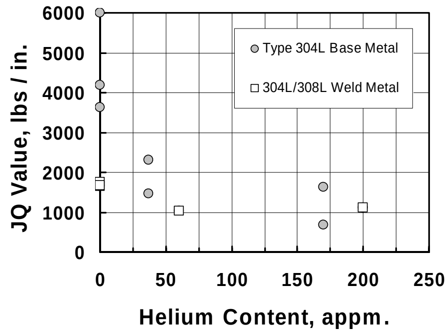

Figure 6. Fracture Toughness Reduction with Increasing Helium Content. The fracture toughness values of Type 304L base metals and weldments are reduced to similar values for these helium contents.

Decay helium effects on toughness were measured by using two sets of tritium-exposed samples, one tested after six months of aging and the other after 24 months of aging. There was little change in toughness for both base metals and weldments with increased helium contents after the initial loss in toughness (Figure 6). This indicates that Type 304L stainless steel and its weldments are resistant to the embrittling effects of tritium and its radioactive decay product for helium contents at least up to 200 appm.

Summary and Conclusions

The fracture toughness data collected in this study are needed to assess the long-term effects of tritium and its decay product on tritium reservoirs. The results show that tritium and decay helium have negative effects on the fracture toughness properties of stainless steel and its weldments. The data and report from this study has been included in a material property database for use in tritium reservoir modeling efforts like the Technology Investment Program "Lifecycle Engineering for Tritium Reservoirs". A number of conclusions can be drawn from the data:

1. For unexposed Type 304L stainless steel, the fracture toughness of weldments was two to three times higher than the base metal toughness.

2. Tritium exposure lowered the fracture toughness properties of both base metals and weldments. This was characterized by lower J_Q values and lower J-da curves.

3. Tritium-exposed-and-aged base metals and weldments had lower fracture toughness values than unexposed ones but still retained good toughness properties.

Acknowledgement

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References

1. M. J. Morgan, S. L. West, and M. H. Tosten, "Tritium Effects on Weldment Fracture Toughness", WSRC-STI-2006-00056, July, 2006.