Effect of Specimen Size on the Fracture Toughness of V-4Cr-4Ti - R. J. Kurtz (Pacific Northwest National Laboratory)*, Huaxin Li (Associated Western Universities-Northwest Division), and R. H. Jones (Pacific Northwest National Laboratory)*

OBJECTIVE

The purpose of this research is to characterize the effect of specimen dimensions on the fracture toughness of a low activation vanadium alloy.

SUMMARY

J-R curves were generated using the single specimen unload-compliance technique on four specimens of V-4Cr-4Ti to determine the effect of specimen dimensions on the fracture behavior. Ductile crack initiation and growth was observed in the 6.35 mm thick specimens but not in the 12.70 mm thick specimens. The J-R curves determined from these tests were not valid per ASTM validity criteria so quantitative measures of the resistance to ductile crack initiation and growth were not obtained. These data suggest that standard fracture toughness tests performed with small-scale DCT specimens may also not be valid.

PROGRESS AND STATUS

Introduction

Development of vanadium alloys for the first-wall and blanket structures of fusion power systems requires detailed information on the fracture properties in both the unirradiated and irradiated conditions. Irradiation volumes for typical neutron sources limit the in-plane dimensions of fracture toughness specimens to a few millimeters. Small-scale disk compact tension (DCT) specimens are being used [1,2] to determine the fracture toughness of irradiated V-4Cr-4Ti. A recent study [3] of the mixed-mode (I/III) fracture toughness behavior of V-5Cr-5Ti (Heat BL-63) annealed at 1125 °C for one hour and tested at room temperature (RT) and 100 °C indicated the mode I toughness was about 60 kJ/m^2 and 470 kJ/m^2, respectively. ASTM validity requirements were satisfied for the RT tests, but not for the 100 °C tests. Recent developments in vanadium alloy processing indicate the unirradiated fracture toughness will be high at RT and above. Tensile test data on unirradiated and irradiated V-4Cr-4Ti specimens [4-5] suggest that room temperature mechanical properties of unirradiated material are similar to irradiated material at about 600 °C. Thus, measurements of the fracture toughness of unirradiated V-4Cr-4Ti at room temperature will provide insight as to the validity of elevated temperature toughness measurements using small-scale DCT specimens of irradiated material. A study of the effect of in-plane and thickness dimensions on the mode I J-R curve behavior of unirradiated V-4Cr-4Ti was performed to aid the development and interpretation of results from small-scale specimens used in irradiation experiments.

Experimental Procedure

The material used in this study was V-4Cr-4Ti (Heat #832665) produced by Teledyne Wah Chang. Material fabrication details have been reported previously [6]. The material was annealed by the manufacturer for 2 hours at 1050 °C in a vacuum better than about 1.3 x 10^{-3} Pa. Compact tension test specimens in the T-L orientation were machined from 6.35 and 12.7 mm thick plates. All specimens were heat treated at 180 °C for 2 hours following machining to remove hydrogen. Table

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1 gives the pertinent specimen dimensions employed in this study.

Table 1. Compact Tension Specimen Dimensions for J-R Curve Testing

Specimen ID	Width, mm	Thickness, mm	Side Groove Depth, %	Net Thickness, mm
V95 T1-2	50.80	12.70	None	12.70
V95 T2-1	50.80	6.35	10	5.08
V95 S1-2	30.48	12.70	10	10.16
V95 S2-1	30.48	6.35	10	5.08

J-R curves were generated by the single specimen unload-compliance test procedure. All tests were performed in laboratory air at 25 °C. Specimens were fatigue cracked before and after J-testing to mark the extent of ductile crack growth.

Results

Plots of the J-R curves for the 6.35 mm thick specimens are shown in Figures 1 and 2. Figure 1 presents results for the 30.48 mm wide specimen and Figure 2 gives the results for the 50 80 mm specimen. The results for the two specimens are similar. Figures 1 and 2 show J-values approaching 1500 kJ/m^2 for both specimens. ASTM validity criteria for J_{max} and Δa_{max} were violated for these tests so critical J-values for crack extension were not computed from the data.

The test results for the 12.70 mm thick specimens showed no ductile crack initiation and growth occurred. Inspection of the fracture surfaces after the test confirmed this finding. Normally the fracture toughness should decrease with increasing thickness until plane-strain conditions are reached. Under plane-strain conditions the fracture toughness will not depend on specimen thickness and therefore, constitutes a fundamental material property. The present tests were not conducted under plane-strain conditions. Thus, the fracture toughness would be expected to decrease with increasing thickness. The lack of ductile crack extension for the 12.70 mm thick samples suggests the toughness of these specimens is higher than for the thinner samples. This result is contrary to expectation.

Discussion

Elastic-plastic fracture mechanics using the J-integral is based on the concept of J dominance, where the stress and strain states near the crack tip are established by the J-level. The applicability of the J-integral is limited to high constraint crack geometries. For J to be the relevant fracture mechanics parameter controlling ductile crack initiation in the region of intense plastic deformation near the crack tip must be small relative to certain specimen dimensions such as the thickness and uncracked ligament. ASTM test procedure E 1152-87 [7] describes a standard method for determining valid J-R curves for metallic materials. This standard puts limits on the J-level and amount of ductile crack extension permitted for a measured J-R curve to be considered valid. The maximum J-integral capacity for a particular specimen is given by the smaller of:

$$J_{max} = b\sigma_Y/20, \text{ or}$$

$$J_{max} = B\sigma_Y/20$$

where σ_Y is the material flow stress (i.e., the average of the 0.2% offset tensile yield strength and the ultimate tensile strength), and B is the specimen thickness. The maximum crack extension, Δa_{max}, capacity for a specimen is given by:

$$\Delta a_{max} = 0.1 b_o$$

where b_o is the size of the initial uncracked ligament. Table 2 gives the maximum J-integral and crack extension capacities for the specimens used in this study compared to the standard DCT specimens used in irradiation experiments. The RT value of σ_Y used to generate Table 2 was 420 MPa [4]. Note the J-integral capacity of the DCT specimens is limited by their small in-plane dimensions, but the specimens used in this study are limited by their thickness dimensions. Clearly the results presented in Figures 1 and 2 are not valid J-R curves per ASTM criteria.

Thus, a critical J-value (J_{Ic}) for ductile crack initiation can not be determined from these curves. Larger test specimens or alternative analysis techniques such as those recently advanced by Edsinger, et. al. [8] may be needed to obtain valid estimates of the fracture toughness of V-4Cr-4Ti over the temperature range of interest in a fusion power system.

Table 2. Maximum J-Integral Measurement Capacities for Various Specimen Geometries

Specimen ID	J_{max}, kJ/m^2*	J_{max}, kJ/m^2**	Δa_{max}, mm
V95 T1-2	267	533	2.54
V95 T2-1	133	533	2.54
V95 S1-2	267	320	1.53
V95 S2-1	133	320	1.53
DCT-A***	75	50	0.24
DCT-B***	123	83	0.39

*Based on thickness dimension.
**Based on uncracked ligament dimension.
***Standard Fusion Materials Program DCT specimens.

CONCLUSIONS

The RT fracture toughness of V-4Cr-4Ti (Heat 832665) is very high. ASTM validity criteria for J-R curve determination were not satisfied for any of the specimens tested. These results suggest that standard fracture toughness tests performed with small-scale DCT specimens may also not meet ASTM criteria. No ductile crack extension was observed for the 12.70 mm thick specimens. This suggests the toughness of the 12.70 mm thick specimens is greater than the 6.35 mm specimens which is contrary to expectation since thicker specimens should exhibit higher constraint.

FUTURE WORK

Alternative fracture toughness measurement techniques will be investigated to determine applicability to fusion power system materials, components and structures.

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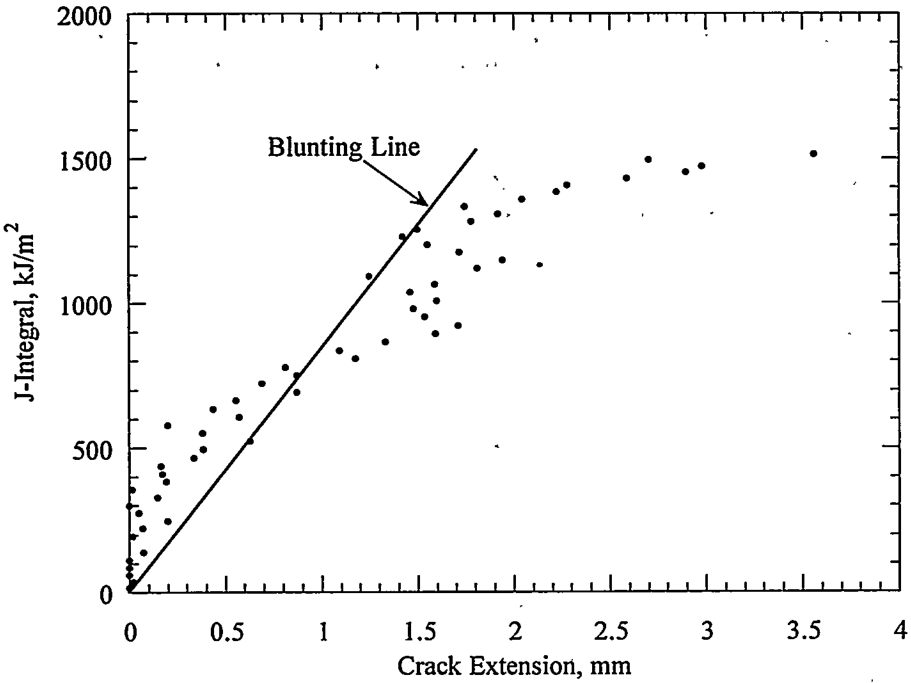

Figure 1. J-R Curve for Specimen V95 S2-1

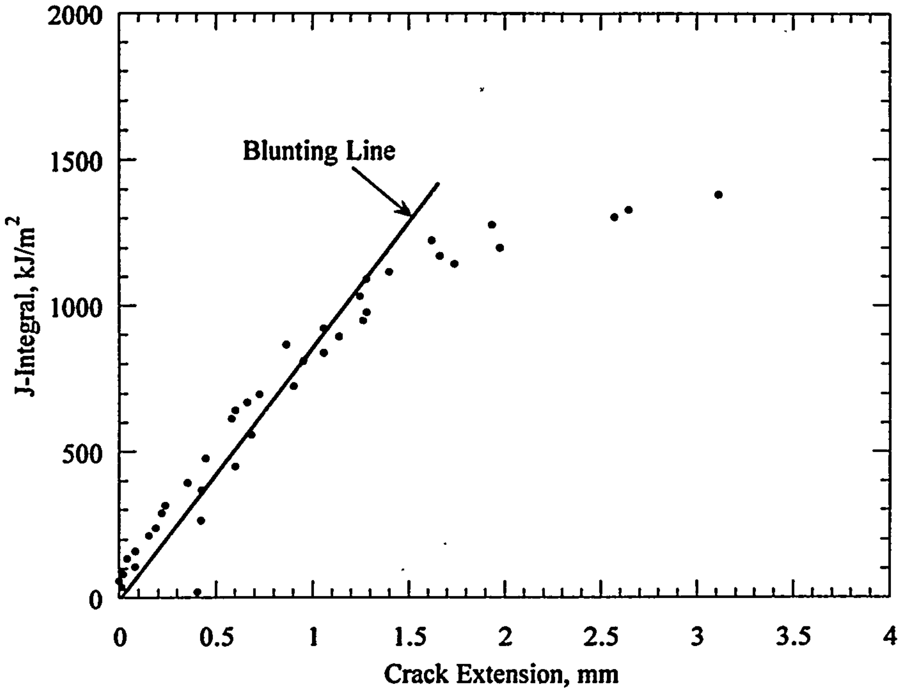

Figure 2 J-R Curve for Specimen V95 T2-1