FRACTURE TOUGHNESS AND FATIGUE CRACK GROWTH OF OXIDE-DISPERSION STRENGTHENED COPPER

D. J. Alexander and B. G. Gieseke, Oak Ridge National Laboratory

OBJECTIVE

The fracture toughness and fatigue crack growth behavior of oxide-dispersion strengthened copper alloys were examined. These alloys are candidate materials for first wall and divertor structural applications. The fracture behavior of these materials must be characterized to determine their suitability.

SUMMARY

The fracture toughness and fatigue crack growth behavior of copper dispersion strengthened with aluminum oxide (0.15 wt % Al) was examined. In the unirradiated condition, the fracture toughness was about 45 kJ/m^2 (73 MPa$\sqrt{m}$) at room temperature, but decreased significantly to only 3 kJ/m^2 (20 MPa$\sqrt{m}$) at 250°C. After irradiation at approximately 250°C to about 2.5 displacements per atom (dpa), the toughness at room temperature was about 19 kJ/m^2 (48 MPa$\sqrt{m}$), and at 250°C the toughness was very low, about 1 kJ/m^2 (12 MPa$\sqrt{m}$). The fatigue crack growth rate of the unirradiated material at room temperature is similar to other candidate structural alloys such as V-4Cr-4Ti and 316L stainless steel. The fracture properties of this material at higher temperatures and in controlled environments need further investigation, in both irradiated and unirradiated conditions.

PROGRESS AND STATUS

Introduction

High-strength copper alloys with high thermal conductivity are attractive candidates for some structural applications in ITER. One of these alloys is GLIDCOP AL-15, a commercially available dispersion-strengthened copper alloy with 0.15 wt % Al that has been internally oxidized to produce small Al_2O_3 particles in a copper matrix. However, there is very little information about the fracture behavior of these alloys, in particular the fracture toughness and fatigue crack growth resistance. A recent review of copper-based alloys [1] pointed out the need for additional data in these areas. Some preliminary testing was conducted to determine the fracture toughness before and after irradiation, and the fatigue crack growth rate in the unirradiated condition.

Experimental Procedure

Specimens were fabricated from an as-wrought plate measuring 165 mm wide by 12.7 mm thick by ~ 3 m long that was produced by SCM Metals for the ORNL Fusion Energy Division in 1987 [2]. This plate had been warm worked during the consolidation of the -20 mesh powder. The plate was then extruded at about 820°C with an extrusion ratio of 25:1. Both the fracture toughness and the fatigue crack growth specimens were oriented in the T-L orientation so that crack growth was in the extrusion direction.

Standard compact specimens 37.75 × 30.48 × 12.7 mm thick (1.25 × 1.20 × 0.50 in.) [designated 1/2 T C(T) specimens] were fabricated for the first set of fracture toughness tests. The second series of tests used small disk compact specimens 12.5 mm in diameter by 4.62 mm thick (0.491 by 0.182 in.) [designated 0.18 T DC(T) specimens]. The DC(T) specimen geometry was chosen to allow the specimens to fit into the High Flux Isotope Reactor target region. Specimens were irradiated as part of a larger experiment which included a variety of austenitic stainless steels [3,4]. The GLIDCOP specimens were irradiated at a nominal irradiation temperature of 250°C to a dose of approximately 2.5 dpa. The calculated fluences were 8.8 × 10^{17} n/m^2 (total), with a thermal fluence of 3.4 × 10^{17} n/m^2 (< 0.5 eV) and a fast fluence of 2.6 × 10^{17} n/m^2 (> 0.1 MeV) [5].

All specimens were fatigue precracked at room temperature and then side-grooved 10% of their thickness on each side prior to testing. Testing was conducted on an 89-kN (20-kip) capacity computer-controlled servohydraulic test machine operating in strain control in the laboratory. Tests in the hot cell used a 445-kN capacity (100-kip) servohydraulic machine with a 22-kN load cell, again operating in strain control. Testing was conducted in general accordance with ASTM E 813-89, Standard Test Method for J_{IC}, A Measure of Fracture Toughness, and ASTM E 1152-87, Standard Test Method for Determining J-R Curves using a computer-controlled data acquisition and analysis system [6]. The J-integral equations from E 1152-87 were used for the calculations. Tensile properties used in the analyses were taken from the literature [7]. Estimated values were used for the irradiated specimens [2].

Crack growth was monitored by the unloading compliance technique for all tests. Displacements were measured on the C(T) specimens with a clip gage seated on knife edges located on the specimen loading line in a notch cutout. For the DC(T) specimens an outboard clip gage was used that was seated in grooves machined on the outer diameter of the disk, above and below the loading holes. The experimental techniques developed for testing the small, irradiated DC(T) specimens have been described elsewhere [8].

After testing, the fracture toughness specimens were heat-tinted by placing them on a hot plate and heating them until a noticeable color change had occurred. The specimens were cooled to room temperature and then broken open to allow the initial and final crack lengths to be measured. Specimens tested in the laboratory were measured with a measuring microscope. The fracture surfaces of the irradiated specimens were photographed, and photographic enlargements were used with a digitizing tablet to measure the crack lengths.

The fatigue crack growth rate specimens had the same overall size as the 1/2 T C(T) specimens [37.75 by 30.48 mm (1.25 by 1.20 in.), but were only 4.95 mm thick (0.195 in.). These specimens were tested in laboratory air in a servohydraulic test machine operating at 20 Hz with a sinusoidal waveform with a minimum-to-maximum load ratio of 0.1. Crack growth was monitored by the direct current potential drop technique. A constant current of 20 A was introduced on the top of the specimen halfway between the loading line and the back face of the specimen (a/W = 0.5). The voltage drop across the specimen was monitored on the front face of the specimen. The crack length determined from the potential drop measurements was compared to the visually measured crack length at the beginning and end of the test as measured from the specimen fracture surface after the test was completed, and the crack lengths determined by the potential drop measurements were within 1.5% of the visual measurements.

Results and Discussion

The results of the fracture toughness testing are shown in Fig. 1 and are summarized in Table 1. At room temperature the unirradiated material had a J_Q value of about 45 kJ/m². Similar values were found for the C(T) and smaller DC(T) specimens. This indicates that the small DC(T) specimen can generate useful fracture toughness data in dispersion-strengthened copper alloys. The slope of the J-R curve for the small DC(T) specimens was higher than for the larger C(T) specimen, suggesting that constraint had been lost in the small specimen. These effects of specimen size are similar to those observed for previous tests with a low-toughness austenitic stainless steel [8].

The fracture toughness of the unirradiated material decreases markedly as the test temperature increases, as Fig. 1 shows. At 250°C the toughness is very low (3 kJ/m²) and the J-R curve has a very low slope. Tearing begins as soon as the specimen is loaded. Irradiation at 250°C to 3 dpa also causes a decrease in the fracture toughness (Fig. 1). At room temperature the toughness drops by about one-half as compared to the unirradiated material, and the slope of the J-R curve decreases also. At 250°C the toughness was so low that the specimen broke as it was being loaded for the first cycle of the test, so no J-R curve could be determined. Based on the peak load that the specimen reached, the fracture toughness value was estimated to be 1 kJ/m² (12 MPa√m).

The fracture toughness of this material in the unirradiated condition is usefully high. However, there is a significant decrease in the toughness as the test temperature increases. For the unirradiated material, the toughness drops from about 75 to 20 MPa√m with an increase in test temperature from 20 to 250°C. This is a surprising response, as there is no indication of a significant change in the tensile properties over this same range of temperatures [1,7]. These results are similar to data for the AL-25 alloy [9], which has 0.25 wt % Al. Interestingly, impact tests of notched specimens of AL-25 [9] do not show a decrease in toughness over this temperature range. This suggests that an environmental embrittlement may be responsible for the drop in toughness. The fracture toughness may not be so impaired in a vacuum environment. Further testing at intermediate and higher temperatures and in controlled atmospheres is necessary to confirm these preliminary results.

Irradiation also reduces the fracture toughness. Again, test temperature also has a significant effect. After irradiation at 250°C to 3 dpa, the room temperature fracture toughness is lower than for the unirradiated condition, but is still fairly high, at about 48 MPa√m. However, when the test temperature is increased to 250°C, the toughness is greatly reduced, to about 12 MPa√m. These low toughnesses at higher temperatures, both before and after irradiation, are certainly cause for concern, and need to be verified with further testing.

The results of the fatigue crack propagation (FCP) test are presented in Fig. 2. Typical FCP results for type 316 stainless steel [10] and recent results for V-4Cr-4Ti [11] have been included for comparison to other materials under consideration for ITER applications. The stainless steel offers better resistance to crack propagation than either of the other alloys in air. Both the vanadium alloy and the 316 stainless steel show improved resistance to crack growth in vacuum [11,12], an environment representative of the ITER applications. It is expected that the GLIDCOP AL-15 will also have better resistance to crack growth in vacuum as well.

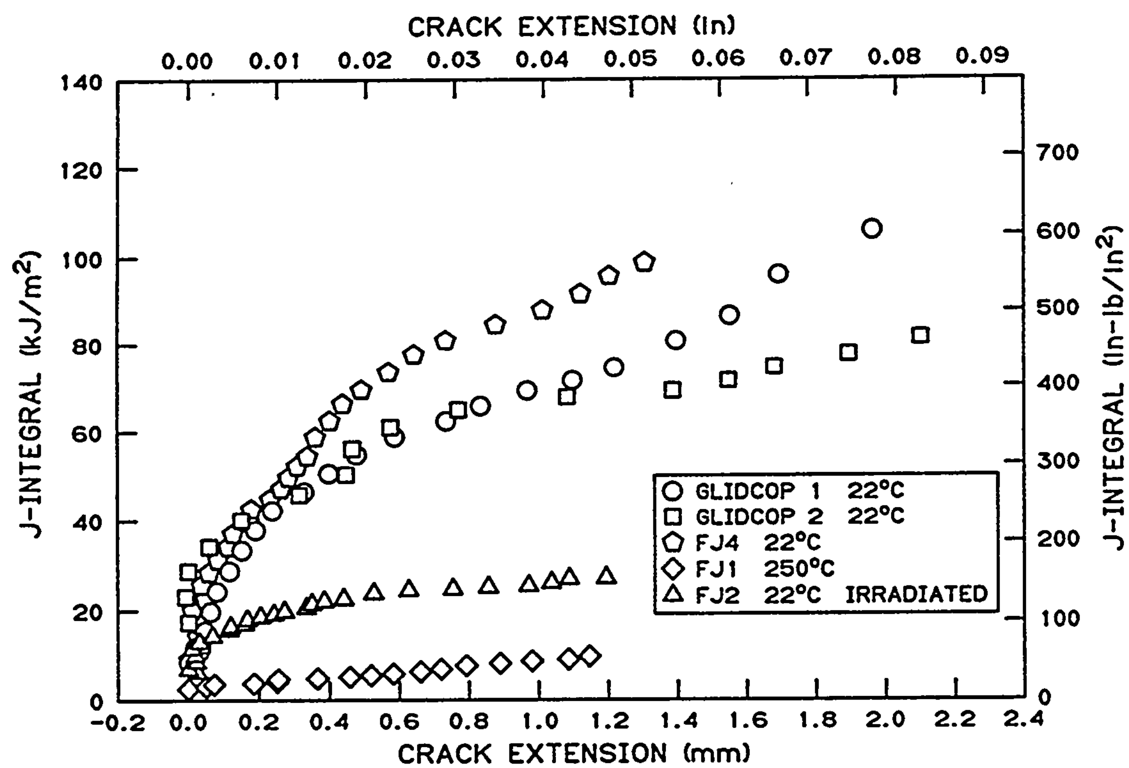

Fig. 1. J-integral-resistance curves for GlidCop AL-15 specimens.

Table 1. Results of fracture toughness testing

Specimen number	Specimen type	Test temperature (°C)	Irradiation temperature (°C)	Irradiation dose (dpa)	J_Q (kJm^2)	K_J[a] (MPa√m)	T	σ_y (MPa)	σ_u (MPa)	E (GPa)
1	0.5T C(T)	22	b	b	43	71	29	330	380	117
2	0.5T C(T)	22	b	b	47	74	18	330	380	117
FJ4	0.18T DC(T)	22	b	b	51	78	42	330	360	117
FJ1	0.18T DC(T)	250	b	b	3	20	9	262	283	112
FJ2	0.18T DC(T)	22	250	2.5	19	48	7	338	372	117
FJ3	0.18T DC(T)	250	250	2.5	1[c]	12[c]	--	290	317	112

[a] $K^2 = JE$.
[b] Unirradiated
[c] Specimen failed during first cycle; value estimated from peak load.

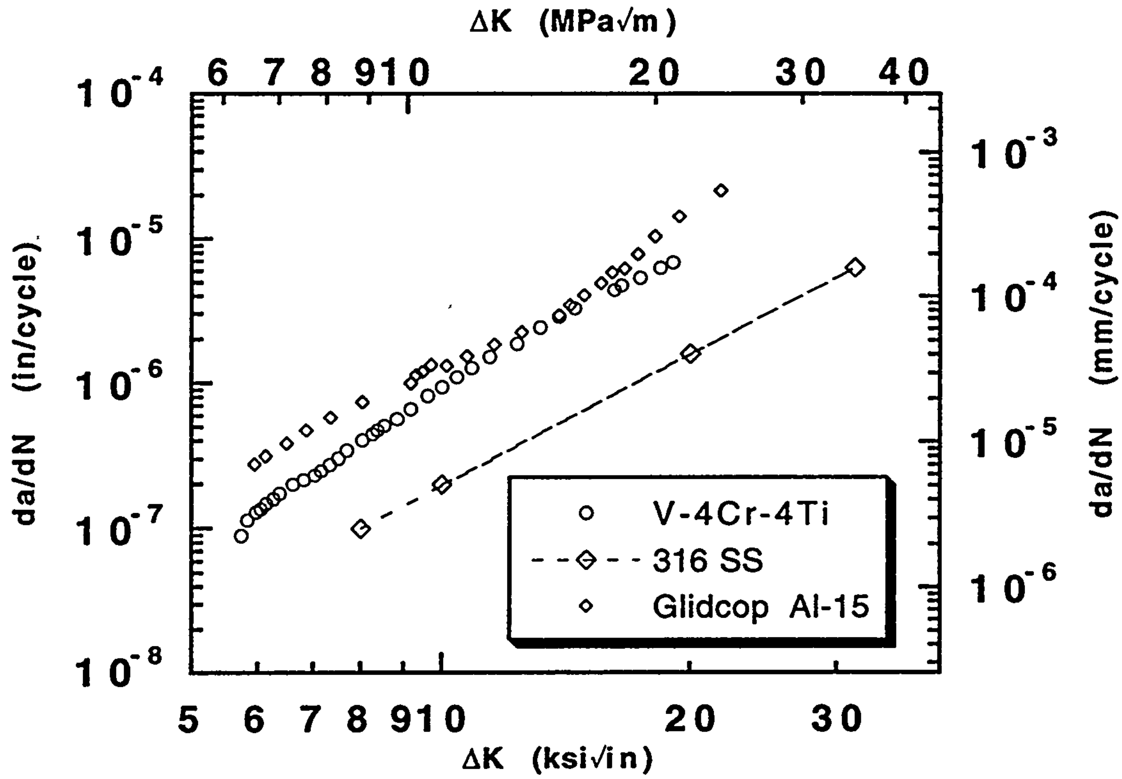

Fig. 2. Fatigue crack growth rate versus applied stress intensity for GlidCop AL-15. Data for V-4Cr-4Ti and type 316 stainless steel are included for comparison.

REFERENCES

1. S. J. Zinkle and S. A. Fabritsiev, "Copper Alloys for High Heat Flux Structure Applications," in *Fusion Materials Semiannual Progress Report for Period Ending March 31, 1994*, DOE/ER-0313/16, 1994, pp. 314-41.

2. S. J. Zinkle, Oak Ridge National Laboratory, personal communication, 1995.

3. J. E. Pawel, D. J. Alexander, M. L. Grossbeck, A. W. Longest, A. F. Rowcliffe, G. E. Lucas, S. Jitsukawa, A. Hishinuma, and K. Shiba, "Fracture Toughness of Candidate Materials for ITER First Wall, Blanket, and Shield Structures," *J. Nucl. Mat.*, 1994, Vol. 212-215, pp. 442-47.

4. D. J. Alexander, J. E. Pawel, M. L. Grossbeck, A. F. Rowcliffe, and K. Shiba, "Fracture Toughness of Irradiated Candidate Materials for ITER First Wall/Blanket Structures," *Effects of Radiation on Materials: 17th International Symposium, ASTM STP 1270*, D. S. Gelles, R. K. Nanstad, A. S. Kumar, and E. A. Little, Editors, American Society for Testing and Materials, Philadelphia, 1995; also published in *Fusion Reactor Materials Semiannual Progress Report for Period Ending March 31, 1994*, DOE/ER-0313/16, pp. 173-93.

5. L. R. Greenwood and C. A. Baldwin, *Fusion Reactor Materials Semiannual Progress Report for Period Ending September 30, 1995*, DOE/ER-0313/19, to be published.

6. R. K. Nanstad, D. J. Alexander, R. L. Swain, J. T. Hutton, and D. L. Thomas, "A Computer-Controlled Automated Test System for Fatigue and Fracture Testing," in *Applications of Automation Technology to Fatigue and Fracture Testing, ASTM STP 1092,* A. A. Braun, N. E. Ashbaugh, and F. M. Smith, Editors, American Society for Testing and Materials, Philadelphia, 1990, pp. 7-20.

7. T. J. Miller, S. J. Zinkle, and B. A. Chin, "Strength and Fatigue of Dispersion-Strengthened Copper," *J. Nucl. Mat.*, 1991, Vol. 179-181, pp. 263-66.

8. D. J. Alexander, "Fracture Toughness Measurements with Subsize Disk Compact Specimens," in *Small Specimen Test Techniques Applied to Nuclear Vessel Thermal Annealing and Plant Life Extension, ASTM STP 1204*, W. R. Corwin, F. M. Haggag, and W. L. Server, Editors, American Society for Testing and Materials, Philadelphia, 1993, pp. 130-42; also published in *Fusion Reactor Materials Semiannual Progress Report for Period Ending March 31, 1992*, DOE/ER-0313/12, pp. 35-45.

9. R. R. Solomon, A. V. Nadkarni, and J. D. Troxell, SCM Metal Products, Inc., unpublished information presented at ITER Workshop, Gatlinburg, Tenn., November 7, 1995

10. *Materials for Fusion Energy Systems*, DOE/TIC-10122, Book 1, Vol. 1, File Code AB02-2431, pp. 1.2-1.3, 1980.

11. B. G. Gieseke, et al., "Fatigue and Crack Growth of V-Cr-Ti Alloys," *J. Nucl. Mater.*, to be published.

12. J. E. Campbell, "Fracture Properties of Wrought Stainless Steels," in *Applications of Fracture Mechanics for Selection of Metallic Structural Materials*, J. E. Campbell, W. W. Gerberich, and J. E. Underwood, Editors, American Society for Metals, Metals Park, Ohio, 1982, p. 135.