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High Temperature Tension-Compression Fatigue Behavior of a Tungsten Copper Composite

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HIGH TEMPERATURE TENSION-COMPRESSION FATIGUE BEHAVIOR OF A TUNGSTEN COPPER COMPOSITE

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Summary

The high temperature fatigue of a $[0]_{12}$ tungsten fiber reinforced copper matrix composite was investigated. Specimens having fiber volume percentages of 10 and 36 were fatigued under fully-reversed, strain-controlled conditions at both 260 and 560 °C. The fatigue life was found to be independent of fiber volume fraction because fatigue damage preferentially occurred in the matrix. Also, the composite fatigue lives were shorter at 560 °C as compared to 260 °C due to changes in mode of matrix failure. On a total strain basis, the fatigue life of the composite at 560 °C was the same as the life of unreinforced copper, indicating that the presence of the fibers did not degrade the fatigue resistance of the copper matrix in this composite system. Comparison of strain-controlled fatigue data to previously-generated load-controlled data revealed that the strain-controlled fatigue lives were longer because of mean strain and mean stress effects.

Introduction

The projected use of metal matrix composites at elevated temperatures will subject these composites to thermal and thermomechanical cycles, thus requiring an understanding of composite behavior under these conditions. These types of loadings are expected to be severe because of the inherent difference of the coefficient of thermal expansion between the matrix and fiber. As part of a program to study the fatigue of metal matrix composites, the fatigue behavior of tungsten fiber-reinforced copper has been investigated.

Previous work on this composite system [1,2] focused on load-controlled fatigue under high temperature isothermal and thermomechanical fatigue (TMF) conditions. During the tension-tension load controlled tests performed, the cyclic mean strains of the $[0]_4$, 0.1 fiber volume fraction composite increased significantly during the fatigue cycling, resulting in hysteresis loops which never stabilized. To gain a better understanding of the fatigue failure processes the current effort concentrated on the fully-reversed strain-controlled fatigue behavior of this same composite system. Isothermal fatigue tests were performed as a first step in the characterization of overall fatigue behavior. This paper reports the results of these isothermal tests.

The specific objectives of this work were to compare the strain-controlled low cycle fatigue behavior of two fiber volume fractions of a tungsten-copper composite at two temperatures, and also to compare this data with previously-generated load controlled fatigue data.

Material and Specimens

The material studied, copper reinforced with tungsten fibers, is a candidate material for rocket nozzle liner applications. This composite was manufactured in the form of 12 ply panels using an arc spray technique [3]. The matrix was oxygen-free high conductivity (OFHC) copper and the fibers were G.E. 218 CS continuous tungsten wire of 200 μm diameter. The composite plates contained unidirectional tungsten fibers arranged in a square array, with the center of the fiber axes located at the corners of the square.

Specimens were machined from unidirectional composite plates having fiber volume percents (v/o) of 10 and 36. All specimens had the fibers oriented parallel to the loading axis. Figure 1 shows the two specimen geometries employed. The specimen shown in Fig. 1(a) was used for all experiments conducted at 260 °C and for the 10 v/o composite tested at 560 °C. The specimen geometry of Fig. 1(b), which has a shorter (17.78 mm) straight section and a bigger transition radius between the grip end and straight section, was used to test the 36 v/o composite at 560 °C. As the fiber spacing was smaller in the 36 v/o composite than in the 10 v/o composite, the 36 v/o plate was thinner than the 10 v/o plate. Thus, the second specimen geometry was necessary to minimize the possibility of buckling of the thinner 36 v/o composite at the higher temperature.

Test Procedures

Fatigue tests were conducted using a 90-kN servohydraulic test system fitted with an environmental chamber. Strain was utilized as the control variable in fatigue experiments using an R-ratio (R = minimum strain/maximum strain) of -1. A triangular strain waveform was employed for test control, using a strain rate of 0.002 in./in./sec. Strain was measured and controlled using a 12.7 mm gage length high temperature extensometer. Strain control was employed to enable life comparisons to be made on a constant strain basis and to eliminate strain ratchetting which occurred during the load-controlled experiments [1,2]. The failure criteria used was a 25 % decrease of the tensile stress from the maximum value attained during the test.

The fatigue tests were conducted at temperatures of 260 and 560 °C. Specimens were heated by direct induction heating. The temperature variation along the specimen straight section was less than 5 °C. Temperature was measured and controlled using a type K thermocouple held tightly against the specimen gage section. A vacuum of less than $6x10^{-6}$ torr was used as the test environment to minimize specimen oxidation.

In order to determine the mechanisms of specimen failure, fracture surfaces and polished sections of specimens tested to failure were examined with optical and scanning electron microscopy.

Results

The results of fatigue tests on the 10 and 36 v/o composite specimens at both 260 and 560 °C are summarized in Table 1. The stresses shown are the stabilized values as measured at half life.

Cyclic Stress - Strain Behavior—Typical high temperature stress-strain behavior of a 10 and a 36 v/o specimen are shown in Fig. 2. Shown are the first fatigue cycle and a cycle near failure. As indicated by the open width of the hysteresis loops, the composite experienced inelastic strains. The change of the shape of the loops as the test progressed is due to cyclic deformation and damage accumulation. Near failure the hysteresis loops showed evidence of specimen cracking, as indicated by the cusp in the compressive portion of the stress-strain curve.

Fatigue Life—A comparison of the fatigue life as a function of fiber volume fraction and test temperature is given in Fig. 3. The lives are compared on a total strain basis. At a given temperature fatigue life does not vary between the two tested fiber volume fractions. However fatigue life is inversely temperature dependent. The fatigue lives at 260 °C on a total strain basis are about five times longer than those at 560 °C for the strain regime tested. Although not shown here, the correlation on an inelastic strain basis was even more divergent.

The 560 °C composite lives are compared with the lives of OFHC copper at 538 °C, as reported by Conway et al. [4], in Fig. 4. The copper tests were conducted under strain control at the same strain rate as the composite tests. Different test techniques were employed in the two studies, as will be discussed later. The data shown is for both fully annealed and fully hardened copper because one would expect the degree of work hardening of the as-received composite matrix to fall between these two bounds. Even though the copper data was generated at a slightly lower temperature, their fatigue lives are about the same as the 560 °C composite data. In contrast, a strain-based comparison of matrix and composite fatigue lives of a brittle/ductile metal matrix composite, SiC/Ti, at elevated temperatures [5] revealed that the life of the composite was less than that of the matrix.

The copper and composite life data are compared on a stress range basis in Fig. 5. The advantage of the composite in fatigue load carrying capability is shown. For a given fatigue life, the stress carrying capability of the 10 v/o W-Cu is about 4 times greater and the 36 v/o composite is about 10 times greater than that of the copper.

The 10 v/o composite lives are compared with fatigue lives of the same material tested in a tension-tension, load-control mode [2] in Fig. 6. Under the load-controlled test conditions, the composites continuously ratchetted, resulting in fatigue strains and hysteresis loops which never stabilized. Therefore the life comparison of the two test control modes was made on a stress range basis. The stress ranges shown for the strain-controlled tests were those measured at 1/2 fatigue life. For each temperature, lives of the strain-controlled tests are at least 2 orders of magnitude longer than those of the load-controlled tests. Although not shown here the lives were also compared on a stress range versus time to failure basis. Even though the cycle frequency employed during the load-controlled test program was slower by a factor of 10, the data showed the same trends as seen in Fig. 6.

Fractography and Metallography—Fatigue cracked regions of 10 and 36 v/o specimens tested in strain control at 260 and 560 °C are shown in Figs. 7(a) and (b). The fatigue cracking and failure modes did not significantly vary with volume fraction here and were similar to previous load-controlled results [1,2]. Fatigue damage was again not usually initiated at the strong fiber-matrix interfaces. The fatigue cracks initiated along the specimen surface in general, particularly at corners. The cracks initiated in the matrix along the specimen sides and corners, and also at machine-damaged fibers on the specimen edges.

In previous load-controlled tests, the cracks propagated only through the matrix, growing around and then past intervening tungsten fibers. These fibers, left bridging the crack and locally supporting the applied load, subsequently necked to 70 % reduction in area and failed by simple tensile overload.

Fractographic evidence suggested the fibers fracture differently in the crack growth process in strain-controlled tests. Metallographic examinations of secondary cracks away from the fracture surfaces indicates cracking still preferentially occurred in the matrix as in load-controlled tests. These cracks still grew around the impeding fibers. The remaining crack-bridging fibers subsequently necked and fractured behind the crack tip as shown in Fig. 8. Unlike the case for the load-controlled specimens, the fibers fractured at about the same elevation as the matrix, but the fiber and matrix fracture surface topologies were not continuous. The fibers were necked only 1 to 14 % in fatigue cracked regions of the strain-controlled test specimens. The lower reduction in area is in some part due to the constant maximum strain amplitude imposed in these tests. The strain-controlled failure mode differed substantially from the earlier tensile overload failure of the load-controlled tests, as evidenced by the lower reduction in area.

The matrix failed in fatigue principally by formation of cavities at grain boundaries, as shown in Fig. 9, as in previous load-controlled tests. In tests at 260 °C the cavitation was mixed with minor secondary transgranular microvoid coalescence. The intergranular cavitation was more severe at 560 °C and clearly predominated. The fatigue-cracked regions sometimes had significant compressive damage as evidenced by surface flattening, especially near crack initiation points.

In summary, fractographic analyses indicated surface crack initiation and preferential matrix cracking occurred for specimens of each volume fraction tested at each temperature. The matrix failed in fatigue predominantly by cavitation at grain boundaries.

Discussion

The composite and copper fatigue lives are the same at the elevated temperature. This may be related to the preferential fatigue cracking in the copper matrix of the composite. The matrix failed principally by formation of grain boundary cavities, the same fatigue damage mechanism observed in stand alone copper [6]. This data suggests that fatigue cracking of the matrix played the major role in controlling the failure of the composite, and cracking of the tungsten fibers was less important. The coincident fatigue lives may indicate that an axial-strain driven failure process is operative here. For isostrain conditions employed in this study the axial strain in the matrix would be equivalent for both composite volume fractions as well as unreinforced copper.

The composite lives may actually be better than the copper lives under equivalent testing conditions. Different test techniques were employed in the testing of the copper [4] and the composite. The copper specimens had a cylindrical cross section, not a square cross section as the composite specimens did. Cracks in the composite initiated at corners and machine-damaged fibers, probably yielding lower lives than one would obtain testing a cylindrical specimen with no corners or machine-damaged fibers. Also, the failure criteria used for the composite tests was not separation into two pieces as used in the copper tests but a drop in tensile load. As most composite specimens did not break before the load drop occurred, the composites would be expected to have even longer lives if allowed to fatigue to separation. As an example, one 10 v/o composite specimen was tested using a strain range of 0.927 % at 260 °C. The life, as defined by the 25 % drop in tensile load failure criteria, was 1680 cycles, however, the specimen was allowed to accumulate 63 389 cycles before the test was stopped with the specimen still in one piece. Hence, the composite data given in Fig. 4 is probably a lower bound and the composite probably has better fatigue resistance than the stand alone copper, when compared on a strain basis.

Although no copper data was available for comparison to the composite data at the lower temperature, the fatigue life of copper would be expected to be similar to that of the composite, as the failure of the composite at 260 °C was also controlled by matrix cracking.

Preferential matrix cracking appears to dominate composite fatigue life. Because of the preferential matrix cracking in the composite, fatigue lives were independent of fiber volume fraction at each temperature. The microscopic examination suggested that the failure mechanism of the fibers was independent of temperature. Therefore, the shorter composite fatigue lives at 560 °C as compared to 260 °C can be largely attributed to changes in matrix failure between the temperatures. The observed temperature dependency on the degree of matrix damage indicate, as shown by others [7], that the cavitation rates at 560 °C were higher than at 260 °C.

Load-controlled fatigue lives were shorter than the strain-controlled lives probably due to the accumulation of much larger mean strains and the higher mean stress. The composite tested under the load-controlled conditions experienced large mean strains, up to 14 % at 260 °C [2]. The load-controlled tests were conducted using a load R-ratio of 0.05, whereas the strain-controlled tests were conducted under fully-reversed (R_ε= -1) conditions. This produced tensile mean stresses in the load controlled tests, which can degrade fatigue life [8], in the range of 110 to 137 MPa at 260 °C and around 70 to 76 MPa at 560 °C. In contrast, little or no mean stress was generated during the strain-controlled tests. Although this discussion is based on 10 v/o composite data, the same trends would be expected for the 36 v/o composite as well, since the life differences are due to tensile mean stresses and mean strains imposed by the test method.

Fatigue tests of metal matrix composites are typically conducted using a zero-tension, load-controlled waveform. The data shown in this report implies that one should take great care in using this data for design purposes. For example, if the composite experiences compression in service, then the use of tension-tension, load-controlled data for design analysis may be overly conservative.

The tungsten fiber/copper matrix composite system presents unique opportunities to support the development of fatigue damage accumulation and life prediction models. Both the fibers and the matrix have good ductility and fatigue resistance over the temperature range of 260 to 560 °C. The fiber-matrix interface bond is very strong and does not fail prematurely in isothermal fatigue. In isothermal fatigue over the temperature range of 260 to 560 °C, this composite failed by a single general fatigue failure mechanism. This mechanism involved preferential matrix cracking through the formation of cavities at grain boundaries, a process which is very well understood and documented in monolithic materials including copper [7]. A model based on this matrix failure mechanism was very successful in predicting fatigue life of 10 v/o load-controlled tests at 560 °C in previous work [9]. The present results suggest such an approach would also be useful for isothermal strain-controlled fatigue of this composite in these test conditions.

Conclusions

1. For this composite tested at these temperatures, fatigue life is independent of fiber volume fraction because fatigue damage preferentially occurs in the matrix.

2. When compared on a total strain basis, fatigue lives of unreinforced copper and the composite were the same at 560 °C. Thus, the presence of fibers does not degrade the fatigue resistance of the copper matrix in this composite system.

3. Strain-controlled fatigue lives are longer than those generated using a load-controlled test method, presumably due to mean strain and mean stress effects.

4. This composite system is very well suited to support development of fatigue life prediction models.

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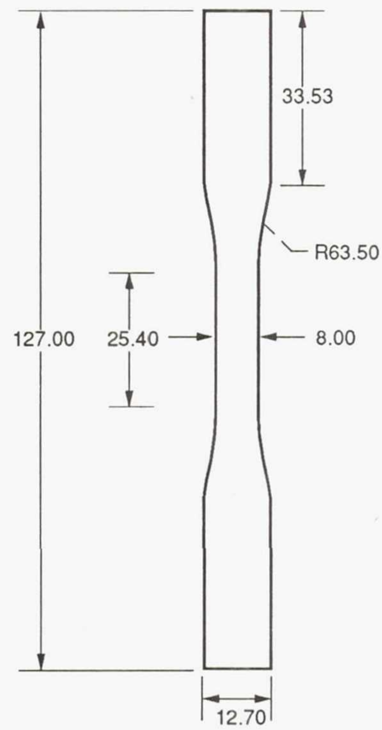
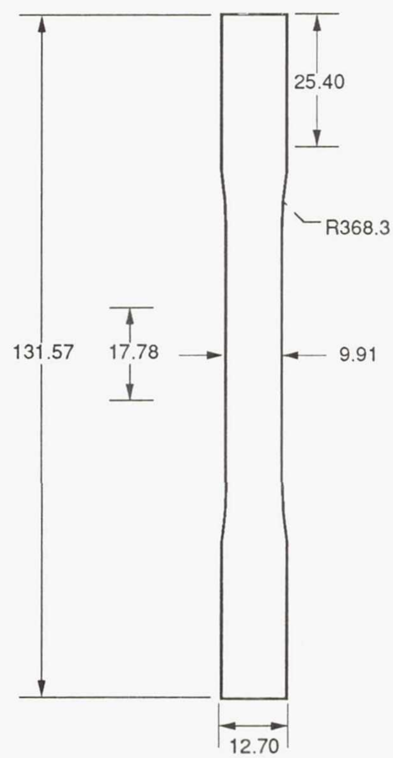
Table I—FATIGUE TEST RESULTS OF THE W/Cu COMPOSITE

Specimen number	Fiber volume fraction	Test temperature, °C	Strain range, mm/mm	Cycles to failure	Stress range, MPa
10-04	0.1	260	0.0123	625	599
10-03	.1	260	.0102	1710	559
10-05	.1	260	.0093	3317	555
10-06	.1	260	.0085	4726	522
10-07	.1	260	.0085	4309	523
10-13	.1	560	.0099	334	347
10-08	.1	560	.0085	733	330
10-09	.1	560	.0077	1370	313
10-10	.1	560	.0067	3770	283
10-14	.1	560	.0055	8050	247
40-08	.36	260	.0142	327	1087
40-07	.36	260	.0112	1200	1032
40-05	.36	260	.0093	1680	941
40-13	.36	260	.0085	6800	846
40-14	.36	260	.0077	7820	864
40-18	.36	560	.0077	1470	739
40-15	.36	560	.0057	8900	632



(a) Geometry used for all 10 vol. % material and 36 vol. % material tested at 260 °C.



(b) Geometry used for 36 vol. % material tested at 560 °C.

Figure 1.—Composite specimens. The 10 vol. % specimens were 6.99 mm thick and the 36 vol. % specimens were 3.91 mm thick. All dimensions are in millimeters.

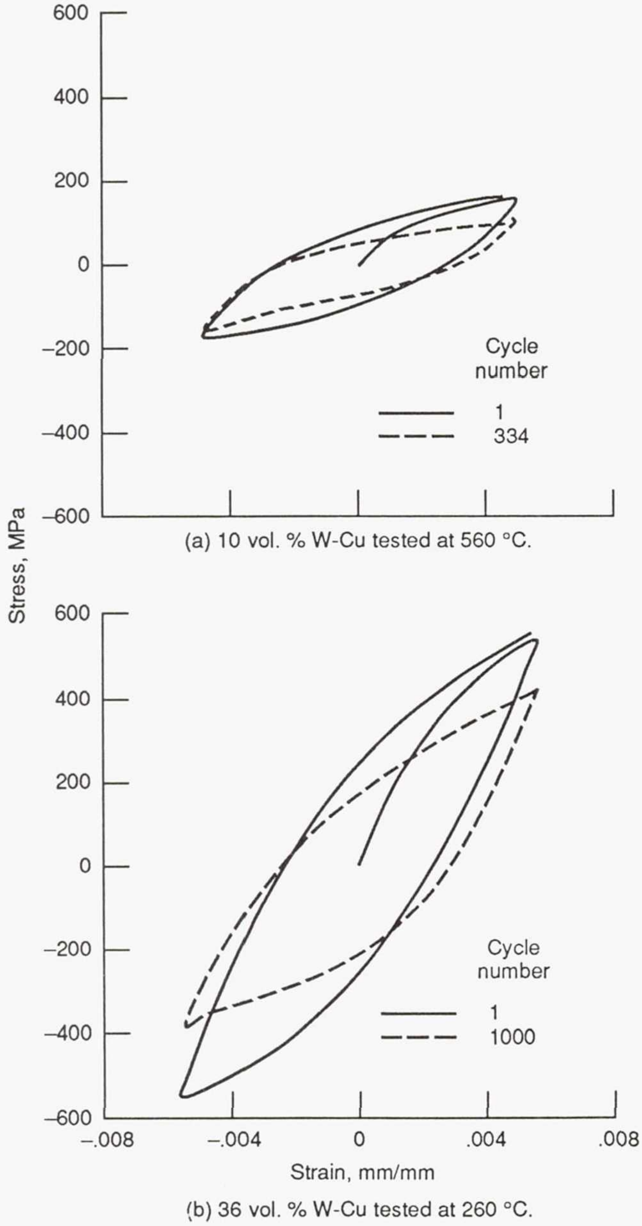


Figure 2.—Stress-strain behavior of W-Cu, showing the first hysteresis loop and one near failure.

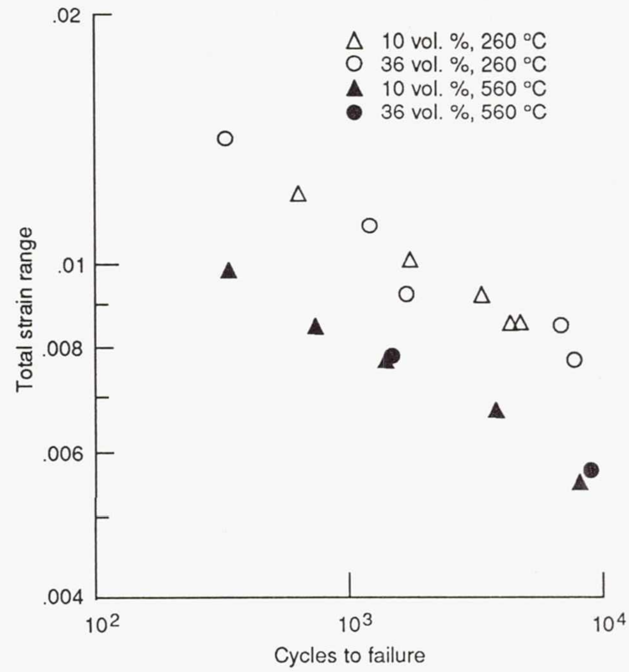


Figure 3.—Total strain range as a function of fatigue life for W-Cu at 260 and 560 °C.

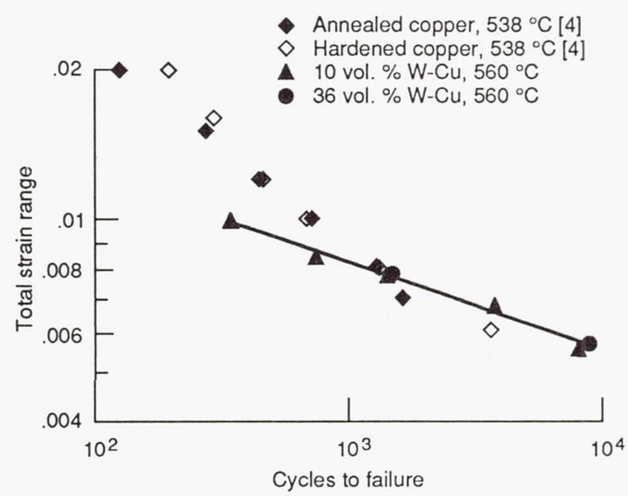


Figure 4.—Total strain range as a function of fatigue life for W-Cu tested at 560 °C and OFHC copper tested at 538 °C [4].

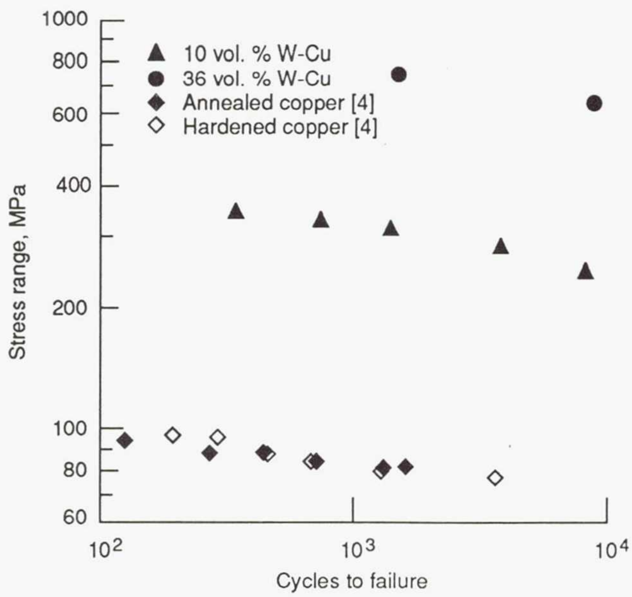


Figure 5.—Stress range as a function of fatigue life for W-Cu tested at 560 °C and OFHC copper tested at 538 °C [4].

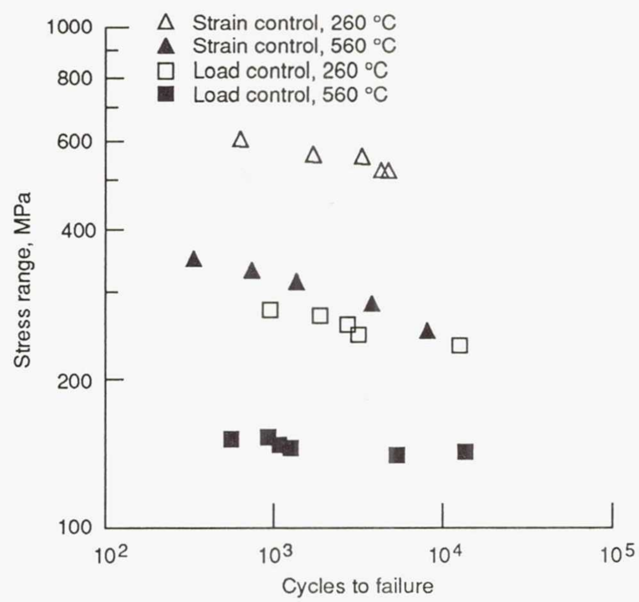
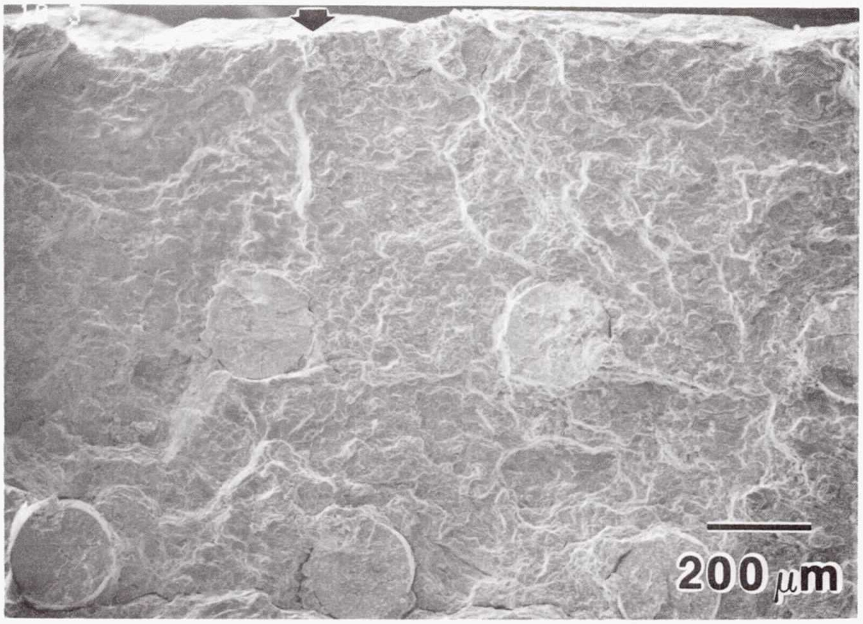
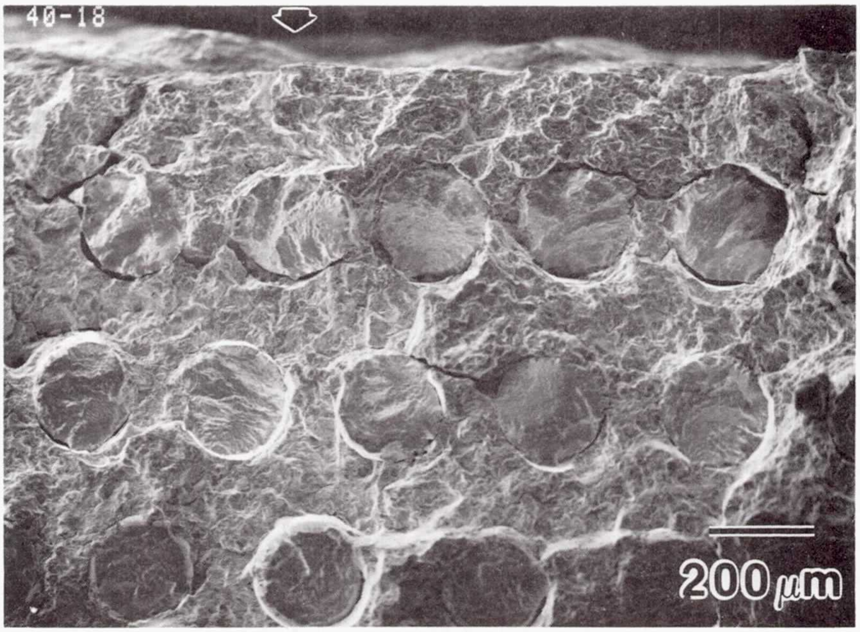


Figure 6.—Stress range as a function of fatigue life for 10 vol. % W-Cu fatigue tested under load and strain control.



(a) 10 vol. % specimen tested at 260 °C.



(b) 36 vol. % specimen tested at 560 °C.

Figure 7.—Fatigue cracked regions. Cracks initiated at specimen sides at indicated locations.

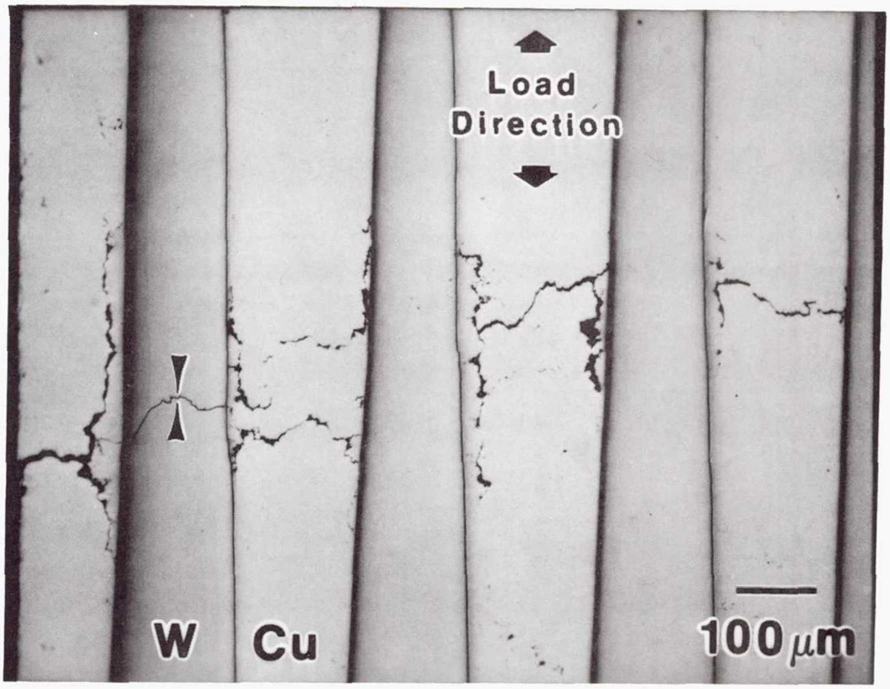


Figure 8.—Metallographic longitudinal section showing copper (Cu) matrix crack initiated at the specimen corner which grew around the tungsten (W) fiber. The outermost tungsten fiber subsequently necked and fractured at the indicated location. 36 vol. % specimen tested at 260 °C.

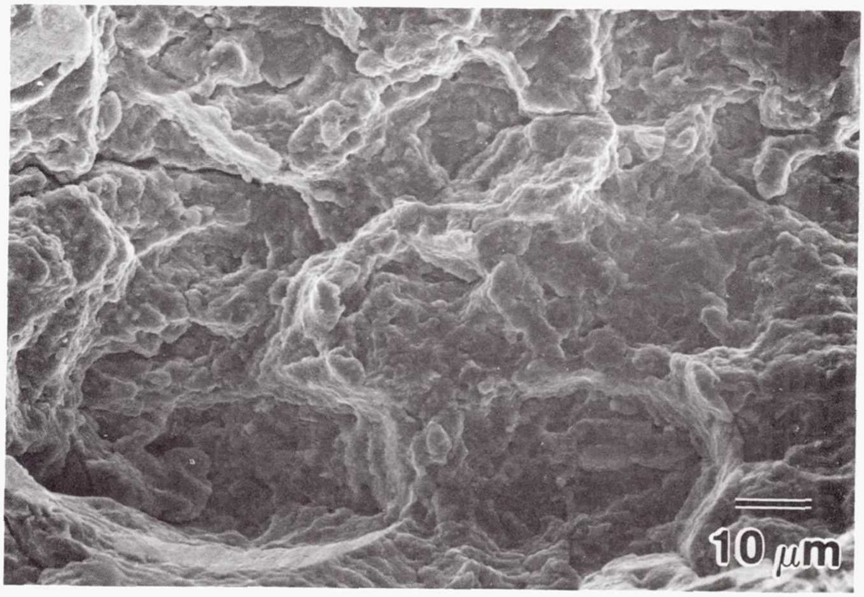


Figure 9.—Predominant intergranular cavitation fatigue failure in the Cu matrix. 36 vol. % specimen tested at 560 °C.

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16. Abstract

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