

High Temperature Fatigue Behavior of Tungsten Copper Composites

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HIGH-TEMPERATURE FATIGUE BEHAVIOR OF TUNGSTEN-COPPER COMPOSITES

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SUMMARY

The high-temperature fatigue behavior of a 9 vol %, tungsten fiber-reinforced copper matrix composite was investigated. Load-controlled isothermal fatigue experiments at 260 and 560 °C and thermomechanical fatigue (TMF) experiments, both in phase and out of phase between 260 and 560 °C, were performed. The stress-strain response displayed considerable inelasticity under all conditions. Also, strain ratcheting was observed during all the fatigue experiments. For the isothermal fatigue and in-phase TMF tests, the ratcheting was always in a tensile direction, continuing until failure. The ratcheting during the out-of-phase TMF test shifted from a tensile direction to a compressive direction. This behavior was thought to be associated with the observed bulging and the extensive cracking of the out-of-phase specimen. For all cases, the fatigue lives were found to be controlled by damage to the copper matrix. Grain boundary cavitation was the dominant damage mechanism of the matrix. On a stress basis, TMF loading reduced lives substantially, relative to isothermal cycling. In-phase cycling resulted in the shortest lives, and isothermal fatigue at 260 °C, the longest.

INTRODUCTION

Tungsten fiber-reinforced copper matrix (W-Cu) composites have been studied for over 30 years as model metal matrix composites (MMC's). Interest in this material stems from its relatively easy manufacture, its strong fiber-to-matrix bond, and an apparent absence of interfacial products. Early investigations of mechanical behavior concentrated on such basic properties of W-Cu composites as tensile behavior (refs. 1 to 6) and creep behavior (ref. 6). Later research involved isothermal fatigue (refs. 7 to 9) and thermal fatigue (refs. 10 to 15).

A concern about the effect that the thermal coefficient of expansion (α) mismatch between the fibers and the matrix may have on high-temperature behavior led to an interest in thermal fatigue. During thermal cycling of a fiber-reinforced MMC, internal stresses are generated because of this difference. When W-Cu composites undergo thermal cycling, these internal stresses can result in such damage to the composite as inelastic deformation of the matrix via slip, grain boundary migration, void formation, grain boundary sliding (ref. 10), thermal ratcheting of the matrix relative to the fibers (ref. 15), and cavitation at the fiber-matrix interface (ref. 12).

As a structural material for a high-temperature application, a fiber-reinforced MMC such as W-Cu would experience both mechanical and thermal cyclic loadings, or thermomechanical fatigue (TMF). Many monolithic materials have shorter lives from TMF than from isothermal fatigue at the temperature extremes of the TMF cycle (ref. 16). In a recent investigation (ref. 17), nonisothermal

fatigue loading degraded the fatigue resistance of a silicon carbide fiber-reinforced titanium matrix composite substantially more than isothermal loading did. This suggests that characterization of TMF behavior of a MMC is important for elevated-temperature applications.

A W-Cu composite is being considered as a combustor liner material for the space shuttle main engine. In this application the composite would experience cyclic thermal and mechanical loading. The purpose of our work was two-fold. (1) to determine the effect of simultaneous thermal and mechanical cycling on the low-cycle fatigue life of this composite system, and (2) to understand the mechanisms of deformation and failure under high temperature isothermal fatigue and TMF. Tensile tests, isothermal fatigue tests, and thermomechanical fatigue tests were performed on tungsten fiber reinforced copper composites. This paper deals with the behavior of the composite, and it presents data that were generated to provide guidance for the development of MMC fatigue life prediction schemes.

MATERIAL AND EXPERIMENTAL PROCEDURE

Material and Specimens

We studied a tungsten fiber-reinforced copper matrix composite, which was manufactured by using an arc-spray process. The fibers employed were 200- μm -diam General Electric 218 tungsten wire. The four-ply composite plates contained 9 vol % of unidirectional tungsten fibers in a matrix of oxygen-free, high-conductivity copper.

Specimens were electro-discharge machined from composite plates into the geometry shown in figure 1. All fibers were aligned parallel to the load axis. The machined surfaces of the specimen gage length were hand polished prior to testing.

Mechanical Test Procedures

All the mechanical tests were performed by using a 90-kN servohydraulic test system fitted with an environmental chamber that allowed high-temperature mechanical testing in a vacuum ($<5 \times 10^{-6}$ torr), in flowing Ti-gettered argon, or in laboratory air. Strain was measured by a 12.7-mm gage-length axial extensometer. Waveforms were generated and data were acquired with a minicomputer. Load, strain, and temperature were recorded during the tests by the test control software. Specimens were heated by induction, and temperature was measured with either Chromel-Alumel thermocouples or an infrared pyrometer. Strain-controlled tensile tests were performed in vacuum at 260 and 560 °C with a strain rate of 2.0×10^{-4} in./in./sec.

Load-controlled isothermal fatigue tests were also performed in vacuum at 260 and 560 °C. Load was chosen as the control mode for all the fatigue experiments because the composite specimens were thin, and therefore, strain-controlled tests would result in significant compressive loads, which would cause specimen buckling. A triangular waveform was employed, with R-ratios of about 0.05 (R = minimum load/maximum load). A cycle frequency of 3 cpm was

chosen to approximate the strain rate employed in the tensile tests. The failure criterion for all fatigue tests was separation of the specimen into two pieces.

Load-controlled TMF tests were performed between 260 and 560 °C. A triangular waveform with a cycle frequency of 0.25 cpm was employed for both the load and temperature. The experiments were performed in flowing argon in order to increase the cooling rates of the thermal cycle. A load R-ratio of 0.065 was used. For in-phase TMF tests, the maximum load was attained at 560 °C, and the minimum load occurred at 260 °C. For the out-of-phase tests, the maximum load was reached at 260 °C, and the minimum load, at 560 °C. Prior to beginning each TMF experiment, the temperature of the specimen was cycled while maintaining zero load in order to measure the thermal expansion strain as a function of temperature. The thermal expansion strain of the composite was assumed to be constant throughout the test. After completion of the test, the thermal strain data were used to determine the applied mechanical strains from the recorded total (thermal plus mechanical) strains as follows: Temperature as a function of thermal expansion strain was fitted to a piecewise linear function; for each stress-total strain (ϵ_{total}) data point, the corresponding temperature was input into the piecewise linear function to calculate the thermal expansion strain, $\epsilon_{thermal}$ and then mechanical strain (ϵ_{mech}) was determined by using the relationship

$$\epsilon_{mech} = \epsilon_{total} - \epsilon_{thermal} \quad (1)$$

Metallography and Fractography

Fracture surfaces and polished sections of specimens from all experiments, both tested to failure and interrupted, were examined with optical and scanning electron microscopy. Results of the isothermal fatigue experiments, which reported elsewhere (ref. 18), will be summarized herein.

RESULTS

Tensile Behavior

Stress-strain behavior. - The tensile curves at 260 and 560 °C are plotted in figure 2, and tensile properties are summarized in table I. Note that the composite strain hardens until failure during tensile deformation at 260 °C, but at 560 °C the stress decreases after reaching its ultimate strength. The strain at which the composite failed was significantly higher at 260 °C than at 560 °C.

Fractography and metallography. - Examination of the fracture surfaces revealed that at both temperatures the tungsten fibers failed in a ductile manner, having a reduction in area of about 65 percent. Some longitudinal splitting of the fibers, which was much more prevalent at 260 °C than at 560 °C, was observed. Copper scales still adhered to the exterior of necked fibers, thus indicating good interfacial bonding. At 260 °C, the copper matrix failure was predominantly transgranular via microvoid coalescence, whereas at 560 °C, matrix failure was predominantly intergranular.

Fatigue Behavior

Stress-strain behavior. - The typical stress-strain response of the composite during the isothermal and thermomechanical fatigue cycling is shown in figures 3 to 6. Hysteresis loops that were measured throughout the fatigue tests are shown. For all hysteresis loops, both the loading and unloading responses have portions of nonlinearity, that is, inelastic flow of the composite. The amount of this tensile inelasticity in the hysteresis loops decreased as the test continued. The accumulation of tensile inelastic strain (ratcheting) continued until failure; consequently, the hysteresis loops never completely stabilized. At 260 °C the hysteresis loops eventually consisted almost entirely of elastic strain, with a small component of inelastic strain (0.03-percent inelastic strain at half life). Inelastic strain is represented by the maximum width of the hysteresis loop. At 560 °C the composite experienced significantly more inelasticity, as evidenced by the larger width of the loops (0.08-percent inelastic strain at half life). Also, no significant change of the elastic modulus was detected during the isothermal fatigue tests, except just prior to failure.

The stress-mechanical strain response of the composite during in-phase thermomechanical cycling (fig. 5) was similar to that at 260 °C (fig. 3). Just as in the 560-°C isothermal tests (fig. 4), significant cyclic inelasticity occurred during out-of-phase cycling (fig. 6); however, the shape of the hysteresis loop changed dramatically near composite failure. The inelastic-strain range decreased by 65 percent, and the composite stiffness decreased 32 percent (from 21.4 to 14.6 GPa), from half life (1000 cycles) to near failure (2000 cycles). Also, the loop that was measured at cycle 2000 was curved at the two extremes but linear in the middle.

The nature of the ratcheting behavior is more clearly shown in a plot of the maximum cyclic strain as a function of cycle number (fig. 7). The curves for specimens tested at 260 and 560 °C and for the in-phase specimen resemble typical secondary and tertiary creep response of a monolithic material. The ratcheting behavior for the out-of-phase specimen was markedly different. The maximum strain increased during the first 3 percent of fatigue life (0.03 Nf) but then steadily decreased until about 0.4 Nf (Nf = cycles to failure). Subsequently the maximum strain continually increased until failure.

Fatigue life. - Note that while the stress range is held constant, the strain range and maximum strain vary in complex ways among the different fatigue cycles. In a first attempt to understand what controls fatigue behavior, these variables will still be employed in comparing the fatigue lives.

Fatigue life was longest for specimens isothermally cycled at 260 °C (fig. 8). Although only two in-phase and one out-of-phase TMF tests were run to failure, the data show that the lives of thermomechanically fatigued composites are consistently shorter than the lives of those isothermally fatigued at either temperature extreme of the TMF cycle. As indicated by the very shallow slopes of the life lines, the fatigue lives were very sensitive to small changes in stress range in this life regime.

Life was decisively shorter for in-phase rather than out-of-phase TMF tested specimens. To illustrate the effect of phasing on composite life, an

In-phase TMF test was performed with a stress range of 108 MPa, and an out-of-phase TMF test was done with a stress range of 109 MPa. The in-phase specimen failed after 581 cycles whereas the out-of-phase test was stopped at 1788 cycles before failure.

Fatigue life was also examined on a strain basis by plotting the mechanical strain range measured at half life with respect to cycles-to-failure (fig. 9). On this basis, the two isothermal data sets are close together. The out-of-phase TMF tests would appear to yield the longest lives and the in-phase TMF tests, the shortest. As will be discussed later, the strain measurements in out-of-phase TMF tests were deemed to be erroneous because of cracking and barreling of the gage section during cycling.

The strain at failure as a function of fatigue life was also plotted (fig. 10). For each fatigue condition, failure strains were highest for the shortest fatigue lives. Life was longest on this basis for the specimens tested at 260 °C. The high-temperature isothermal cycling yielded the shortest lives on this basis, and the TMF life appeared slightly longer than the 560 °C isothermal life.

Fractography and metallography. - We have reported elsewhere on the characterization of the isothermal fatigue failure modes through microscopy (ref. 18). We observed that the deformation of the copper matrix controls the failure of the composite. Cracks began in the copper matrix and propagated via cavity nucleation and coalescence processes. The failure of the matrix that was cycled at 260 °C was characterized as a combination of intergranular and transgranular failure, with intergranular failure predominating near the specimen surface (fig. 11(a)). At 560 °C the fracture was intergranular throughout (fig. 11(b)). The breakage of the tungsten fibers came after failure of the surrounding matrix (fig. 12). The fibers failed locally at matrix cracks by a ductile failure with necking to a large reduction in area (65 percent). A considerable amount of secondary cracking of the composite specimen was observed for 260-°C cycling, whereas one dominant crack appeared to nucleate and grow during fatigue at 560 °C.

Examination of the failed TMF specimens is still in progress; however, some characteristics of the fracture surfaces (fig. 13) and polished sections (figs. 12 to 14) have been observed. In specimens subjected to in-phase cycling (fig. 13(a)) the failure of the matrix was similar to that of the 560 °C isothermal experiments (fig. 11(b)). Intergranular cavitation of the copper matrix dominated, with clearly formed cavities evident on the grain surfaces. All of the tungsten fibers necked to about a 76-percent reduction of area at failure, nearly the same as observed in the isothermal fatigue and tensile failures. Unlike the isothermal specimens, the fracture surfaces and polished sections revealed localized matrix cracking near the fiber-matrix interfaces. These cracks were confirmed to be parallel to the fibers and could be found at a distance from the failed fiber ends in the longitudinal sections, as shown in figure 14. Work is in progress to determine the sequence of events leading to failure.

Three specimens were subjected to out-of-phase cycling, but only one was tested to failure. Dimensional instability of the specimens in the form of significant bulging of the gage length, and many secondary cracks both parallel and normal to the fibers were observed (fig. 15). The thickness of the gage

section of the specimen that was tested to failure increased by 40 percent. Intergranular cavitation of the copper matrix predominated, although the cavities on the grain surfaces (fig. 13(b)) were not as well formed as those of in-phase specimens (fig. 13(a)). The fiber failure mode was the same as observed in isothermal experiments. Most necked fibers were encased by a thicker layer of copper matrix, unlike those of isothermal specimens. These copper scales separated from the rest of the matrix because of intergranular cavitation. The fibers were often surrounded by deep circumferential matrix cracks very similar to those of the in-phase specimen. Examination of longitudinal sections again indicated localized matrix cracking near the fiber-matrix interfaces. More work is in progress to investigate this process.

DISCUSSION

Fatigue Stress-Strain Behavior

The isothermal hysteresis loops can be explained simply in terms of the four stages of deformation in a W-Cu composite as described by McDanel's (ref. 6) and Ham and Place (ref. 7). Initial loading of the composite gives an elastic response of both the fiber and the matrix (fig. 3) and, therefore, linear response of the composite (stage I). On further straining, the lower strength copper yields; but the tungsten continues to strain elastically, and the response of the composite is again linear but with a smaller slope (stage II). In stage III behavior both the fiber and the matrix are straining plastically, and the composite response is nonlinear. On cyclic reversal from the maximum stress, the fibers and the matrix initially contract elastically (stage I). The stress in the matrix surpasses its compressive yield strength before the composite reaches the minimum load. At this point the behavior again becomes stage II. At the end of the first cycle, the matrix is in compression, the fibers are in tension, and the composite is permanently elongated. Fatigue hardening of the matrix during subsequent cycles is responsible for the narrowing of the loops. The loops became narrower at 260 °C than at 560 °C because of the greater strain hardening of copper at 260 °C. Copper exhibits higher strain hardening rates at lower temperatures (ref. 19).

During fatigue of a W-Cu composite at room temperature, ratcheting was not observed (ref. 8). The similarity between plots of the maximum cyclic strain as a function of cycle number and the creep curves of a monolithic material suggests that the ratcheting observed during these high-temperature fatigue tests is the result of a creep-fatigue interaction. To examine this possibility, two creep tests were performed on the composite at 260 °C. For one test the creep stress was 241 MPa, and the time to specimen failure was 18.2 hr. The second specimen crept at a stress of 125 MPa for 1500 hr without failing. A fatigue test that was performed at 260 °C with a maximum cyclic stress of 241 MPa failed after 70 hr. Metallographic analyses indicated a significant difference in failure mode between these creep and fatigue specimens (ref. 18); this implies that a creep-fatigue interaction was present in the cyclic tests. More creep ratcheting was observed at 260 °C than at 560 °C because of the higher ductility of the composite at the lower temperature, as evidenced by the tensile response at these two temperatures.

The stress-mechanical strain behavior during in-phase TMF tests was similar to that observed during the isothermal tests. For a given cyclic load

range, the matrix deformed more easily near the maximum applied composite load at the higher instantaneous temperatures encountered during the in-phase test than it did during a 260 °C isothermal test. Because of the lower temperature, more hardening occurred near the minimum applied composite load at the lower instantaneous temperatures encountered during the in-phase TMF cycle than occurred during a 560 °C cycle. Hence, for a given load range, the in-phase fatigue stress-mechanical strain response should be a hybrid of the isothermal response at the two temperature extremes.

The out-of-phase TMF response was vastly different from the other three cases. The deformation during the first 10 to 20 cycles was similar to that observed during the 560 °C isothermal tests. During the out-of-phase cycling, more compressive flow of the matrix occurred near the minimum applied composite loads where the instantaneous temperature approached 560 °C. Continued compressive loading of the matrix at the highest temperature of the cycle caused bulging, or "barrelling" of the specimen. This barrelling apparently caused the temporary decrease in the maximum tensile strain due to constancy of volume. Barrelling, which has been observed during high-temperature isothermal fatigue of copper alloys, (ref. 20) was found to be most prevalent during strain cycling at low strain rates; it was particularly severe when compressive hold periods were involved. Barrelling of the type observed here also occurred during out-of-phase TMF of tantalum base alloys (ref. 21).

Continued out-of-phase cycling caused numerous large edge cracks to be formed (fig. 14). These edge cracks were normal to the applied stress direction. The later increase in maximum tensile strain appeared to be associated with the initiation and growth of these edge cracks. Soon the crack opening displacement became large relative to the strain of the composite, and the measured strains were erroneously large. The time sequence and the mechanism of localized matrix cracking near the fibers in the out-of-phase and in-phase specimens is currently being investigated. Localized matrix cracks in longitudinal sections away from the fracture surface may indicate that these cracks occurred early in the TMF tests. Near the end of the fatigue life, the damaged matrix carried little of the applied loads, and the shape of the hysteresis loop reflects the response of the tungsten fibers.

Fatigue Life

Isothermal life at 260 °C versus 560 °C. - The observed reduction in fatigue life with increased temperature of the isothermal experiments can be explained by examining the effect of increased temperature on the copper matrix behavior. Through fractographic and metallographic examination, the fatigue damage was found to initiate in the matrix and propagate via cavity nucleation and growth during the isothermal tests. Breakage of the fibers, which occurred after failure of the surrounding matrix, appeared the same at both temperatures. At 260 °C the matrix failed by a combination of intergranular and transgranular cracking (ref. 18). The matrix of the specimens tested at 560 °C failed almost entirely intergranularly, thereby suggesting that void formation was the dominant damage mechanism (ref. 18). This implies that there was less cavitation at 260 °C than at 560 °C. Void nucleation (ref. 22) and growth rates (ref. 23) are known to be strongly temperature dependent, both rates increasing with increasing temperature. Therefore, the reduction in fatigue

life that occurs between 260 and 560 °C is due to the increase in cavitation rate that is associated with an increase in temperature.

In-phase versus out-of-phase TMF. - The difference between in-phase and out-of-phase TMF life is also related to the increase in cavitation rate in the matrix with increasing temperature. During the in-phase test, the maximum tensile stresses were applied at the highest temperatures. For a given temperature and stress range, the cavitation rate was higher when the maximum stress was applied at the highest temperature of the cycle than it was when the maximum stress was applied at the lowest temperature. Since composite failure during the TMF experiments is believed to be controlled by failure of the copper matrix, composite life should be shorter for the in-phase cycling. The existence of more cavity dimples in specimens cycled in phase than those cycled out-of-phase confirmed that the cavitation rate was higher for the in-phase tests.

Isothermal fatigue versus thermomechanical fatigue. - The differences between lifetimes of composites subjected to TMF versus isothermal fatigue are difficult to resolve. To explore the effect of the α -mismatch strains imposed during the TMF cycles, let us examine the mechanical strain range with respect to fatigue lives. Figure 9 shows the mechanical strain ranges measured at half life as a function of fatigue life. Note that the two isothermal data sets are close together. This suggests that axial matrix strain limits isothermal fatigue life, since the matrix failed before the fibers. For thermomechanically fatigued composites, those tested out of phase seem to have the longest lives, and those tested in phase, the shortest. However, the out-of-phase data are deceiving. As discussed earlier, the strains measured are a combination of specimen strain and crack opening displacement, so the actual strain values are lower.

Since axial matrix strain limits the life of an isothermally fatigue composite, it is useful to examine the axial matrix strains experienced during TMF. In the absence of cracking, the composite axial strain that was measured during the isothermal tests was the same as the average axial strain in the matrix. Thermal cycling between 260 and 560 °C at zero load produced an axial matrix strain $\Delta\alpha\Delta T$ (T = temperature) of about 0.34 percent, with the maximum tensile strain occurring at 260 °C and the minimum at 560 °C. Applying this thermal expansion mismatch correction to obtain the total axial matrix strain in the worst case, the in-phase TMF cycle, requires subtracting this component from the applied axial composite strain. However, this axial matrix strain correction increases the divergence between TMF and isothermal fatigue lives. Therefore, although axial matrix strains are important in isothermal fatigue life, this variable alone cannot reconcile TMF-isothermal fatigue life differences.

This simple analysis also suggests that the TMF life is not controlled solely by axial matrix strain. Fractography and metallography of the specimens subjected to TMF suggest that the matrix also cracks locally near the fibers in a direction parallel to the fibers, rather than cracking normal to the applied load only, as was observed for the isothermally cycled specimens. The cracks parallel to the fibers may be caused by multiaxial stresses near the fibers rather than the simple farfield axial stress due to the applied load, and they may be important in determining TMF life. A detailed micromechanical analysis of the local stresses in the composite during the TMF cycles could help answer these questions.

It is important to note that the difference in composite life due to isothermal fatigue as opposed to TMF may be affected by the difference in the cycle frequencies used for each type of test. However, in light of the dissimilar failure modes observed, the relative positions of the isothermal fatigue and TMF data on a life curve would probably not change.

CONCLUDING REMARKS

The work reported herein can be summarized as follows:

1. Copper reinforced with 9 vol % tungsten fibers was tested isothermally at 260 °C and at 560 °C in tension-tension load-controlled fatigue experiments. Out-of-phase and in-phase thermomechanical fatigue tests were performed between these two temperatures.

2. Lives of isothermally fatigued composites were much longer than the lives of thermomechanically fatigued composites. In-phase TMF tests resulted in the shortest lives, on a stress basis, and 260-°C isothermal fatigue tests produced the longest lives.

3. For all cases the stress-strain response of the composite showed considerable inelasticity. Both the fibers and the matrix failed in a ductile manner. The matrix failed through grain boundary cavitation, and the fibers failed via tensile overload.

4. Ratcheting was observed during all of the fatigue experiments. For the isothermal fatigue and in-phase TMF tests, the ratcheting was always in a tensile direction, continuing to failure. The ratcheting observed that was during the out-of-phase TMF tests reversed from a tensile direction to a compressive direction. This anomaly was thought to be associated with the bulging and extensive cracking of the specimen.

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TABLE I. - TENSILE PROPERTIES OF 9 vol % W-Cu COMPOSITE

Temperature, °C	Tensile strength, MPa	0.05-percent offset yield strength, MPa	Elastic modulus, GPa	Strain at failure, percent
260	290	143	120	9.68
560	168	84	80	4.84

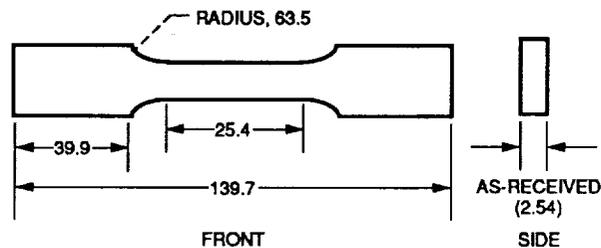


Figure 1. - Composite specimen; all dimensions are in millimeters.

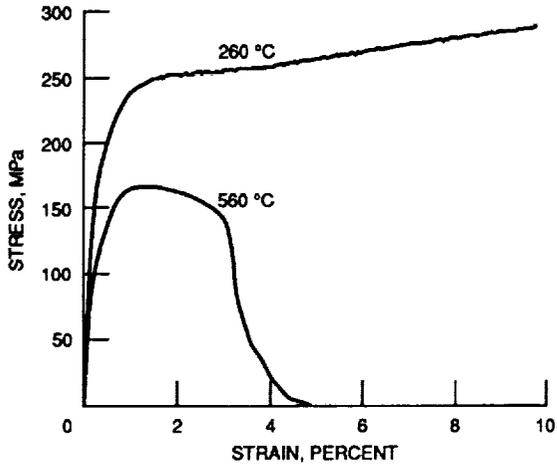


Figure 2. - Tensile curves for W-Cu composite at 260 and 560 °C.

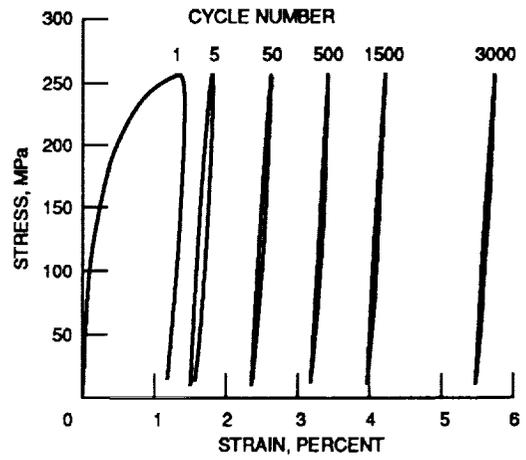


Figure 3. - Fatigue stress-strain response of W-Cu composite at 260 °C ($\Delta\sigma = 246$ MPa, $N_f = 3117$).

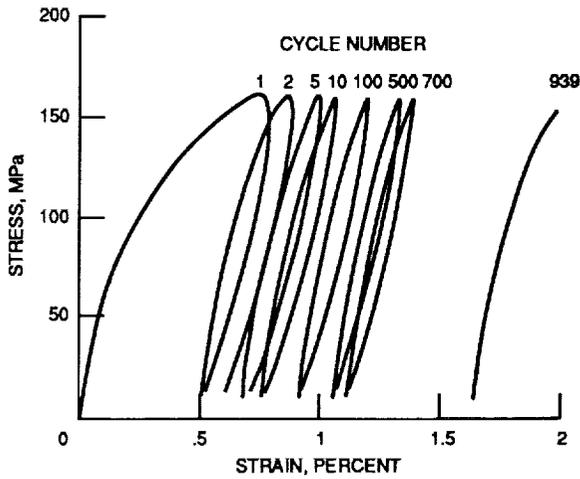


Figure 4. - Fatigue stress-strain response of W-Cu composite at 560 °C ($\Delta\sigma = 152$ MPa, $N_f = 939$).

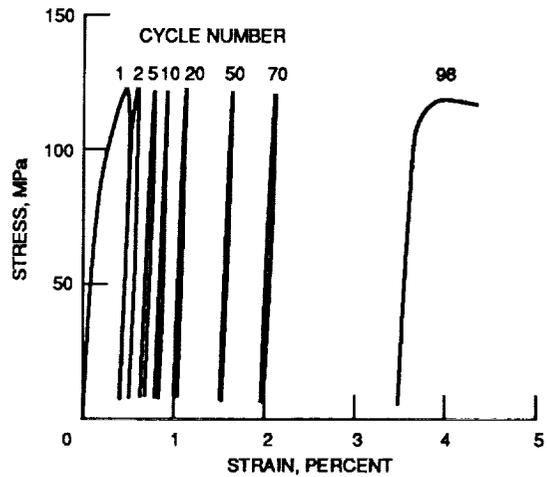


Figure 5. - Stress-mechanical strain response of W-Cu composite during in-phase TMF test ($\Delta\sigma = 116$ MPa, $N_f = 100$).

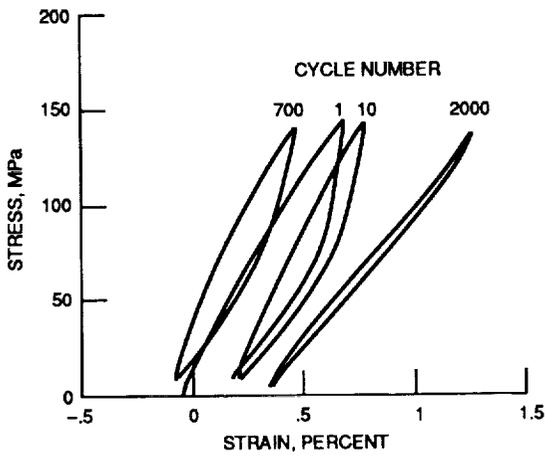


Figure 6. - Stress-mechanical strain response of W-Cu during out-of-phase TMF test ($\Delta\sigma = 133$ MPa, $N_f = 2135$).

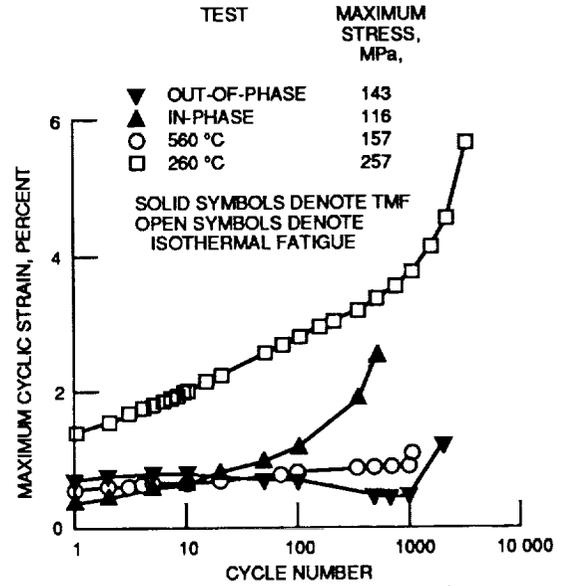


Figure 7. - Maximum cyclic strain as a function of cycle number.

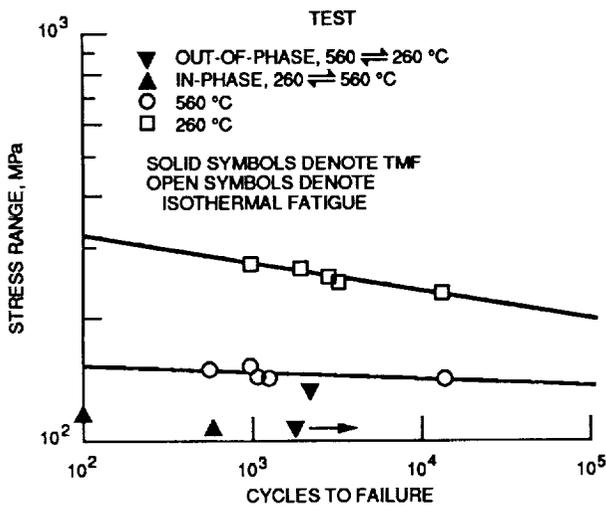


Figure 8. - Applied stress range as a function of fatigue life. Arrow indicates interrupted test.

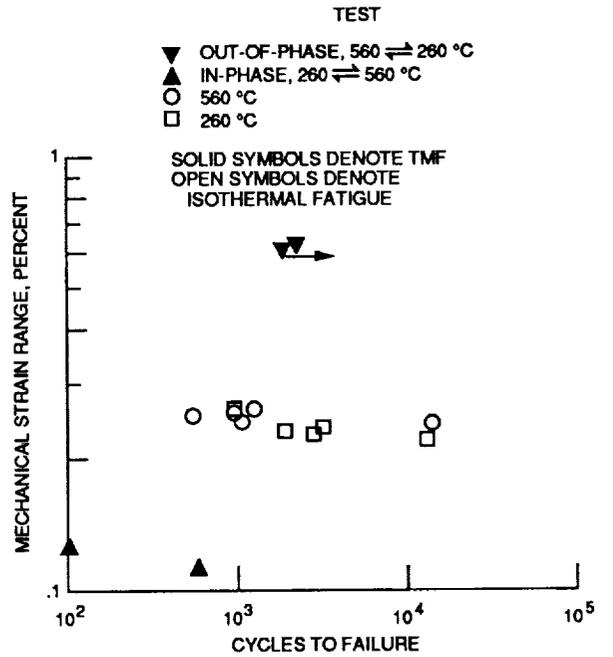


Figure 9. - Mechanical strain range measured at half life as a function of fatigue life. Arrow indicates interrupted test.

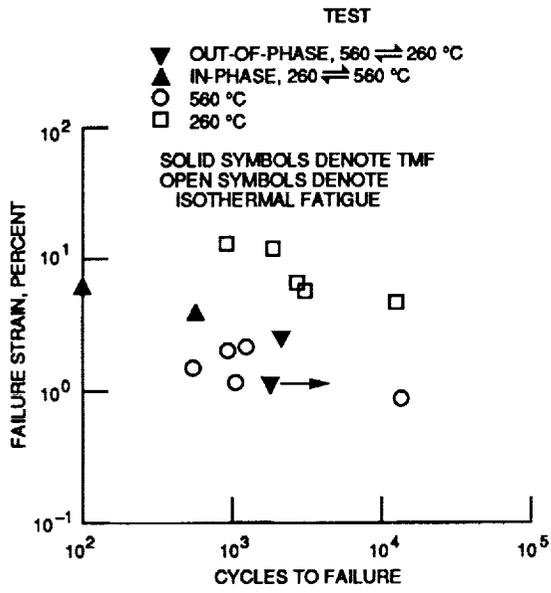
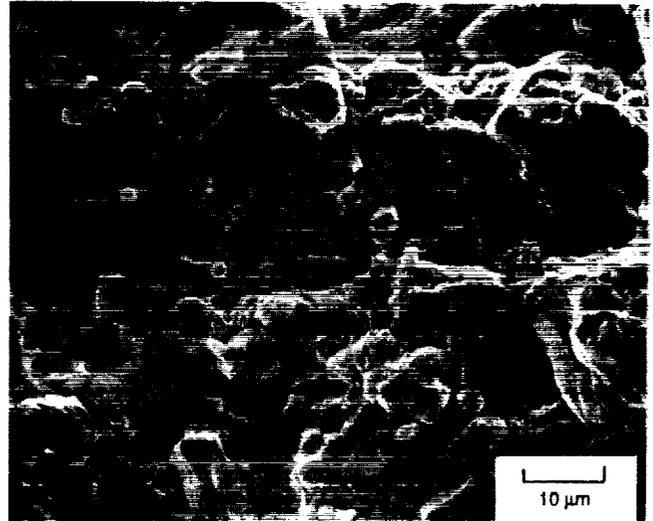
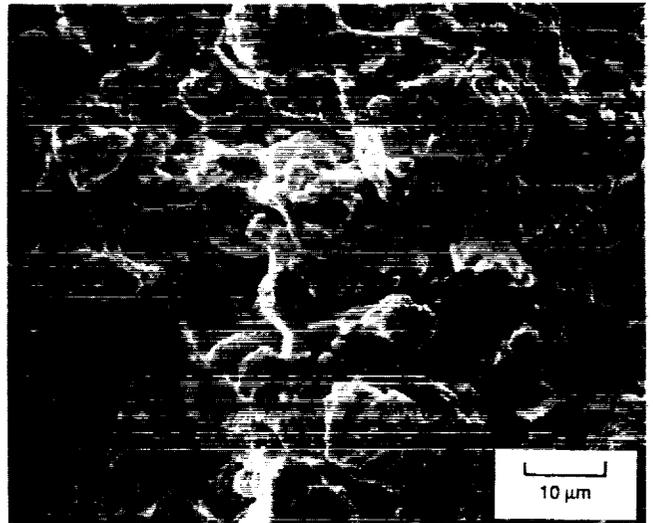


Figure 10. - Failure strain with respect to fatigue life.
Arrow indicates interrupted test.



(a) Isothermal fatigue at 260 °C.



(b) Isothermal fatigue at 560 °C.

Figure 11. - Matrix failure surface due to isothermal fatigue.

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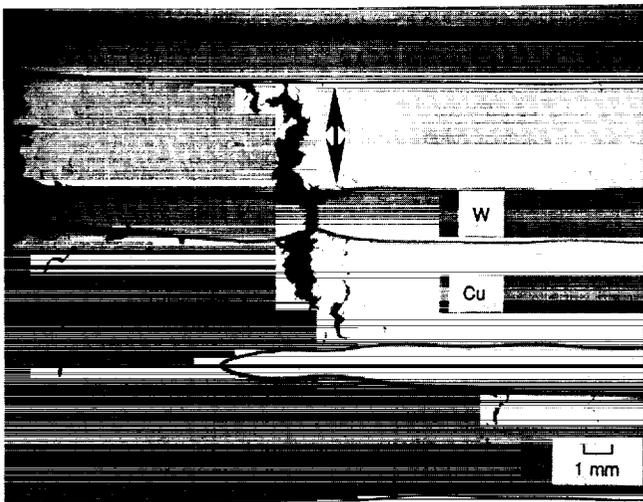
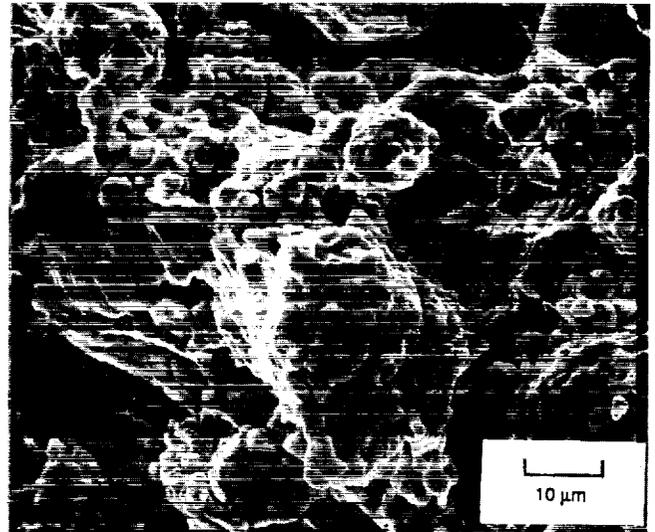
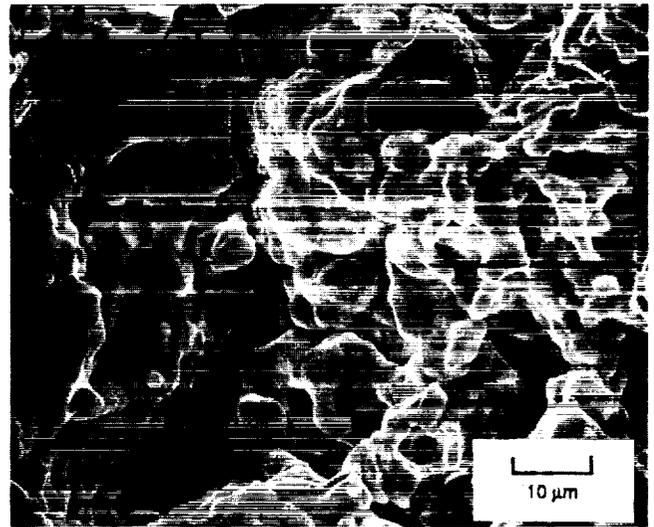


Figure 12. - Polished longitudinal section of a specimen fatigued isothermally at 260 °C ($\Delta\sigma = 246$ MPa, $N_f = 3117$). Arrow indicates direction of matrix cracking.



(a) In-phase TMF.



(b) Out-of-phase TMF.

Figure 13. - Matrix failure surface due to TMF.

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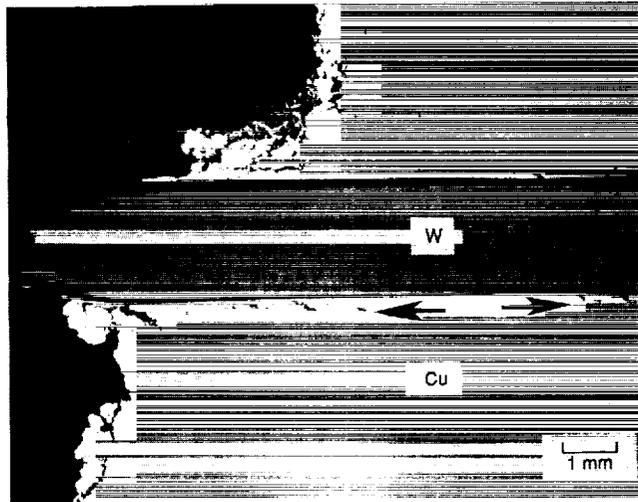


Figure 14. - Polished longitudinal section of a specimen fatigued under in-phase thermomechanical fatigue ($\Delta\sigma = 116$ MPa, $N_f = 100$). Arrow indicates direction of matrix cracking.

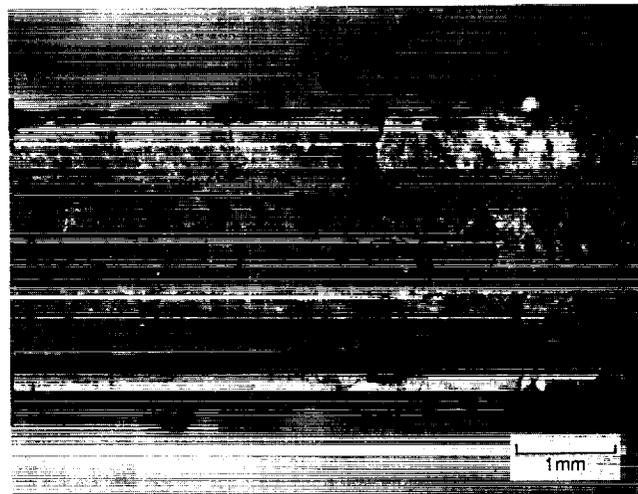


Figure 15. - Optical micrograph of an out-of-phase TMF specimen ($\Delta\sigma = 109$ MPa); test interrupted at 1788 cycles.

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16. Abstract The high-temperature fatigue behavior of a 9 vol %, tungsten fiber-reinforced copper matrix composite was investigated. Load-controlled isothermal fatigue experiments at 260 and 560 °C and thermomechanical fatigue (TMF) experiments, both in phase and out of phase between 260 and 560 °C, were performed. The stress-strain response displayed considerable inelasticity under all conditions. Also, strain ratcheting was observed during all the fatigue experiments. For the isothermal fatigue and in-phase TMF tests, the ratcheting was always in a tensile direction, continuing until failure. The ratcheting during the out-of-phase TMF test shifted from a tensile direction to a compressive direction. This behavior was thought to be associated with the observed bulging and the extensive cracking of the out-of-phase specimen. For all cases, the fatigue lives were found to be controlled by damage to the copper matrix. Grain boundary cavitation was the dominant damage mechanism of the matrix. On a stress basis, TMF loading reduced lives substantially, relative to isothermal cycling. In-phase cycling resulted in the shortest lives, and isothermal fatigue at 260 °C, the longest.					
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