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A MODEL FOR PREDICTING HIGH-TEMPERATURE FATIGUE FAILURE OF A W/Cu COMPOSITE

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Fatigue failure of metal-matrix composites (MMC's) is a complex process. Matrix cracking, fiber/matrix interfacial failure, and fiber fracture can be major elements of the failure process. All these processes can work together to result in fatigue failure. However, depending on the failure process of the composite system of interest, a dominant failure mode can be identified. Modeling of dominant failure modes can serve as the basis of a fatigue life prediction scheme for MMC's.

The material studied in this research, a tungsten-fiber-reinforced, copper-matrix composite, is a candidate material for rocket nozzle liner applications. Previous research (ref. 1) on the fatigue behavior of a 10-vol % tungsten/copper composite at high temperatures has shown that the composite fails primarily from copper-matrix degradation. Fatigue cracks initiate and propagate inside the copper matrix through a process of initiation, growth, and coalescence of grain boundary cavities. The ductile tungsten fibers neck and rupture locally after the surrounding matrix fails. Complete failure of the composite then ensues.

This paper presents a simple fatigue life prediction model for the tungsten/copper composite system. The model is based on the failure mechanisms found through microscopic observations. Failure of the composite is assumed to occur when the matrix fails. The failure mechanisms of the fiber and its contribution to the overall composite fatigue life are neglected. It is assumed that no interfacial debonding or degradation occurs. The analysis in the present study is limited to isothermal fatigue of a unidirectional composite.

In the model the composite is assumed to fail when the average cavity in the matrix reaches a critical size. The cavity nucleation process in the copper matrix is neglected by assuming the preexistence of cavities in the as-received composite. This assumption was confirmed through metallographic examinations. In addition, it has been reported by others that at high temperatures the cavity nucleation process is very fast relative to the cavity growth process (ref. 2). All cavities are assumed to begin to grow at the moment of load application, all at the same rate. The average cavity growth size as a function of time is calculated by using a cavity growth law developed for creep conditions (ref. 3). In this model it is assumed that cavities grow with a quasi-equilibrium shape controlled by coupled diffusion and plasticity. Instantaneous stresses and strain rates as measured during the fatigue experiments are used in the calculation of cavity size. The average matrix stress is used to calculate cavity size. The calculation of

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the average matrix stress is based on the assumption of an isostrain condition between the fibers and the matrix.

The model-predicted fatigue lives were compared with the experimental results of a series of load-controlled, tension-tension fatigue tests conducted at 560 °C on 10-vol % tungsten/copper. The predicted lives were in good agreement with the experimental results. The variation of the numerically calculated cavity size as a function of cycle number was found to exhibit similar trends as the experimentally observed cyclic change of the composite maximum tensile strain. The model also predicted cavity shrinkage during the early stages of cavity growth, in agreement with the work of others (ref. 4).

References

1. Kim, Y.-S.; Verrilli, M.J.; and Gabb, T.P.: Characterization of Fatigue Failure Processes in Tungsten Copper Composites Under Fatigue Loading Conditions. NASA TM-102371, 1989.

2. Gittins, A.: The Mechanism of Cavity Growth in Copper During High Temperature Fatigue. Met. Sci. J., vol. 2, 1968, pp. 51-58.

3. Martinez, L.; and Nix, W.D.: Effects of Capillarity on Intergranular Cavity Growth Controlled by Diffusion and Plasticity. Scripta Met., vol. 15, 1981, pp. 757-761.

4. Tang, N.Y.; and Plumtree, A.: A Note on Grain Boundary Diffusion Controlled Cavity Growth During Elevated Temperature Fatigue. Met. Trans. A, vol. 16, 1985, pp. 300-302.

Objectives

- Present a fatigue life prediction methodology for an MMC
  - Model based on observed failure characteristics
- Compare predictions with experimental results

Figure 1

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Tungsten-Fiber-Reinforced Copper

- Matrix, OFHC copper
- Fiber, GE 218 tungsten wire
- Fabrication, arc-spraying technique

Figure 2

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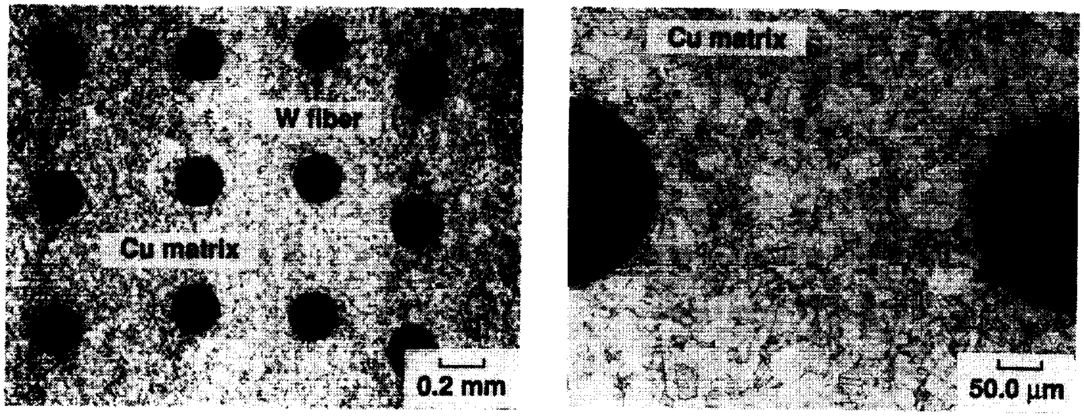
As-Received Composite Microstructure



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Test Conditions

- Temperature, 560 °C
- Control mode, load
- R-ratio, 0.05
- Waveform, triangular
- Cycle frequency, 3 cpm
- Environment, vacuum

Figure 4

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Stress-Strain Curves for W/Cu Fatigued at 560 °C

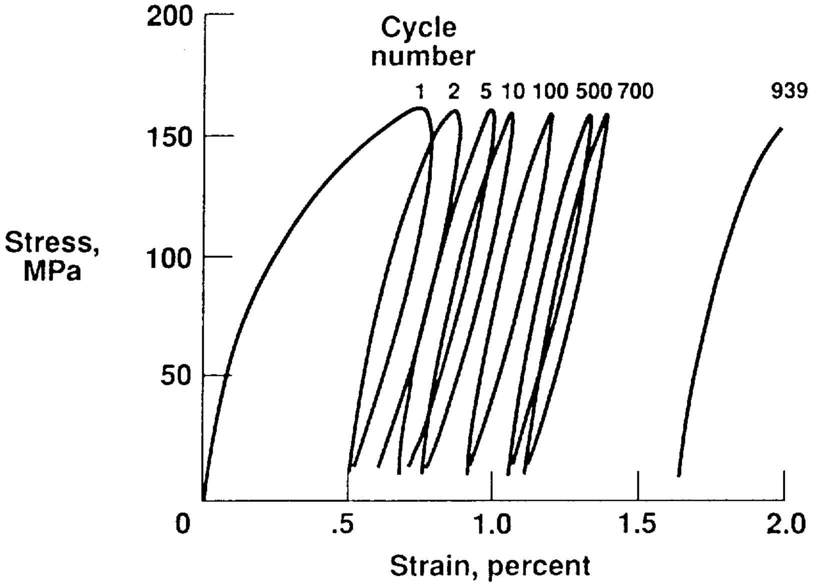

Figure 5

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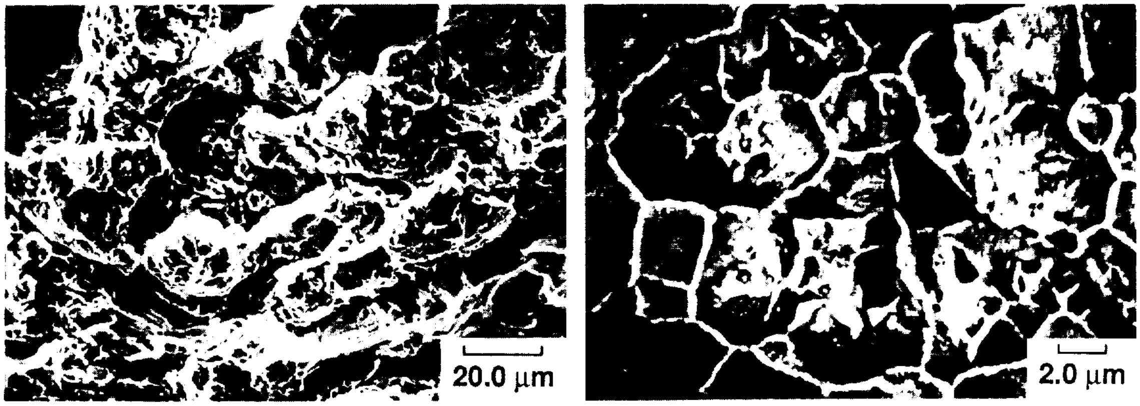
Fractographs of Specimens Fatigued at 560 °C



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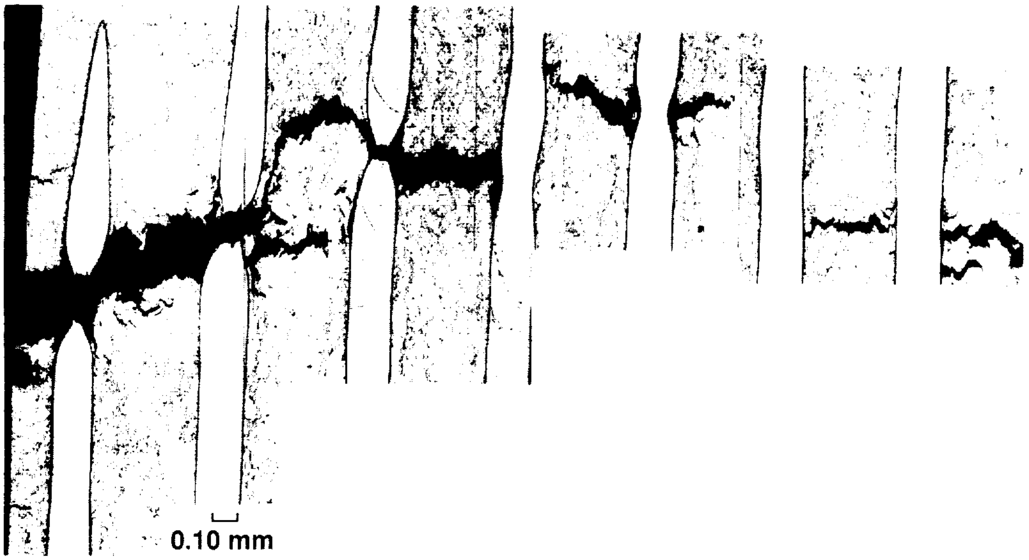
Overall Fatigue Crack Appearance in W/Cu Composite



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Features of Numerical Model of Isothermal Fatigue Failure in W/Cu Composite

- Composite failure is assumed to occur when matrix fails (experimentally observed).
- Failure mechanism of composite is cavitation of matrix (experimentally observed).
- Creep cavity growth model can describe fatigue failure.
- Contribution of cavity nucleation to fatigue life is neglected (preexisting cavities experimentally observed).
- Failure characteristics of fibers are not considered.

Figure 8

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Features of Numerical Model of Isothermal Fatigue Failure in W/Cu Composite

(Concluded)

- ϵ_{11} is the same (isostrain) in fibers and matrix.
- Interfacial debonding is not considered.
- Model applies only to isothermal cycling.
- Inelastic strain in matrix is described by simple power-law relations.
- Failure criterion: Area fraction of cavities = $a^2/c^2 = 0.8$ (based on observed fracture surfaces).

Figure 9

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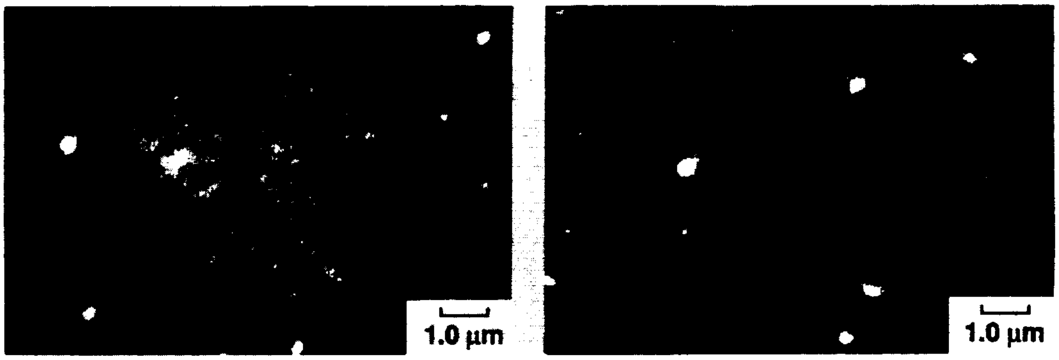
Preexisting Cavities in Cu Matrix



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Cavity Growth Controlled by Coupled Diffusion and Plasticity

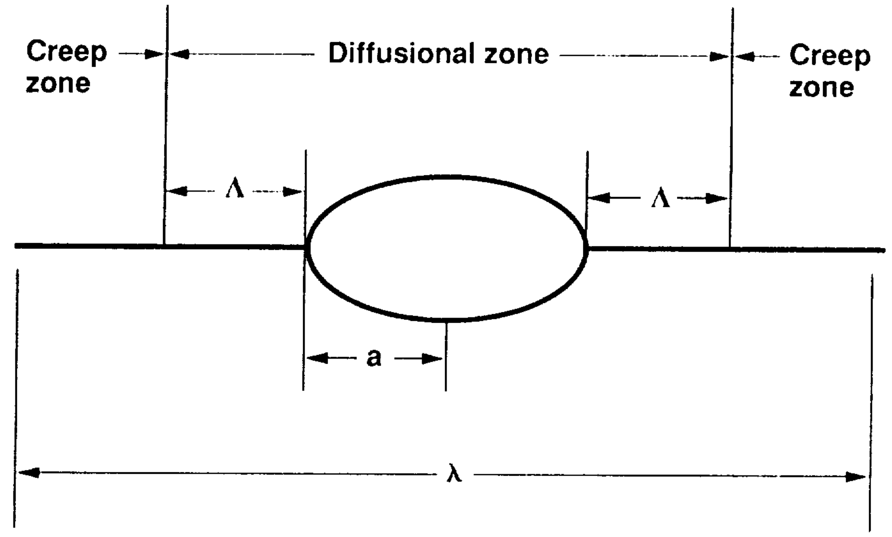

Figure 11

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Cavity Growth Mechanism

Cavity Growth by Coupling of Diffusion and Power-Law Creep

- Characteristic diffusion length

$$\Lambda = \left(\frac{D_B \delta_B \Omega \sigma}{KT\dot{\epsilon}}\right)^{1/3}$$

- Cavity growth rate

$$\frac{da}{dt} = \frac{a\dot{\epsilon}}{2h(\psi)}\left(\frac{\Lambda}{a}\right)^3 Q\left(\frac{a}{a+\Lambda}\right)$$

$$\times \left\{1 - \frac{2a}{(a+\Lambda)^2}\,\frac{\gamma_s}{\sigma} - 2\sin(\psi)\frac{\gamma_s}{\sigma a}\left[1 - \left(\frac{a}{a+\Lambda}\right)^2\right]\right\}$$

Figure 12

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Deformation Mode of Cu Matrix During Fatigue

$$\epsilon = \epsilon_{elastic} + \epsilon_{plastic} + \epsilon_{creep}$$

$$\epsilon_{elastic} = \frac{\sigma}{E}$$

$$\epsilon_{plastic} = K\sigma^{\frac{1}{N}}$$

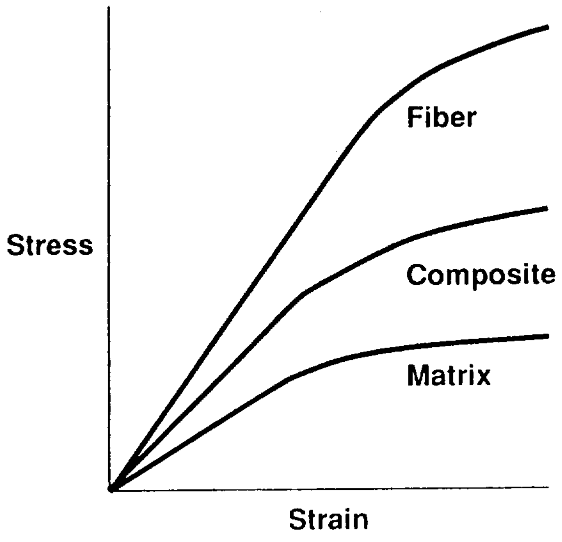
$$\dot{\epsilon}_{creep} = B\sigma^{n}$$

$$\dot{\epsilon} = \left(\frac{1}{E} + K\frac{1}{N}\sigma^{\frac{1}{N}-1}\right)\dot{\sigma} + B\sigma^{n}$$

$$\dot{\epsilon}_{inelastic} = K\frac{1}{N}\sigma^{\frac{1}{N}-1}\dot{\sigma} + B\sigma^{n}$$

Figure 13 CD-91-52041

Determination of Stress in Cu Matrix



- Isostrain condition
- Stress-strain curve of pure Cu at 833 K

Figure 14 CD-91-52042

Cavity Size Calculation

$$a = a_0 + \int_{t_1}^{t_2} \dot{a}\, dt$$

$$a_0 = \frac{2\lambda_s}{\sigma}$$

Figure 15

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Calculated Cavity Size in Cu Matrix as Function of Time

Model-Predicted Cavity Growth; W/Cu Composite; Temperature, 560 °C; Specimen Number, 0–15; Initial Cavity Radius, 0.4 μm

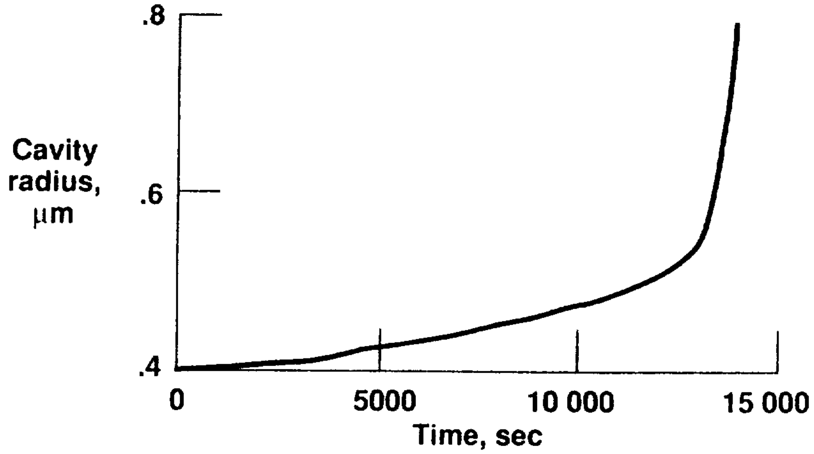

Figure 16

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Maximum Cyclic Strain Versus Cycle Number for Fatigue of W/Cu at 560 °C

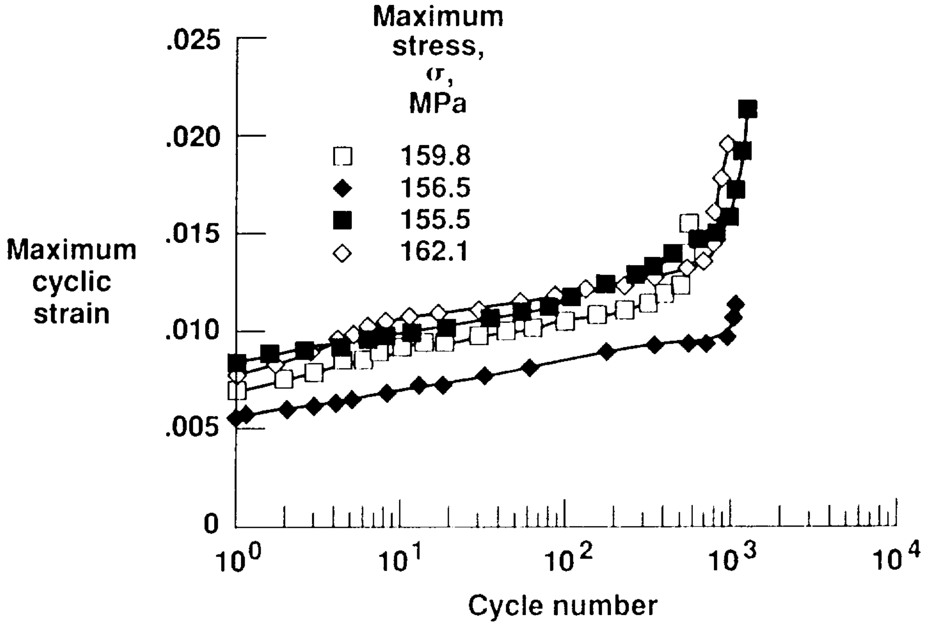

Figure 17

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Comparison of Model-Predicted Results With Experimental Results

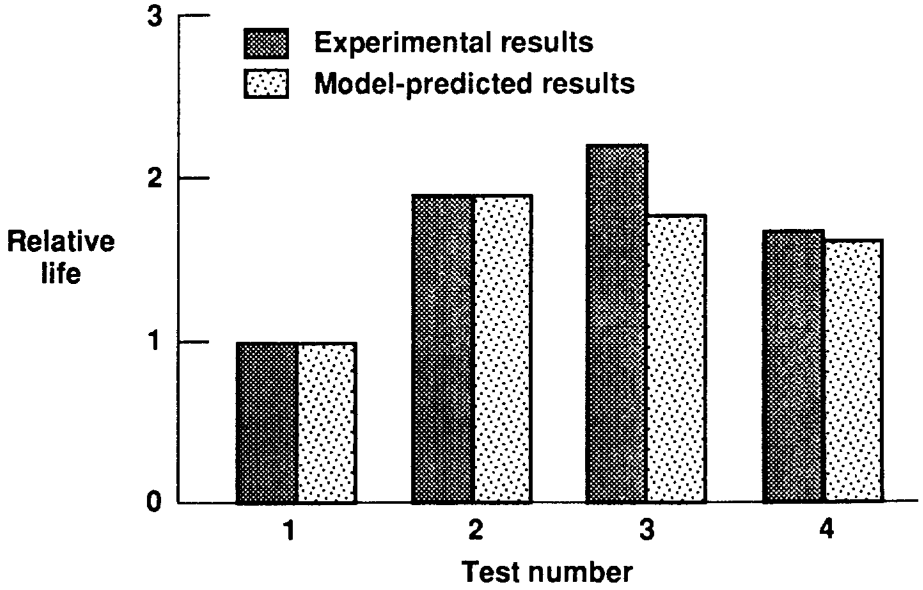

Figure 18

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Conclusions

- A fatigue life prediction model was developed based on the failure characteristics found through microscopic observations.
- The model uses a quasi-equilibrium cavity growth mechanism controlled by coupled diffusion and plasticity. Instantaneous values of stress and strain rate during a fatigue cycle were used for the calculation.
- The predicted fatigue lives are in good agreement with the experimental results.
- The model can be more generalized by incorporating other mechanisms, such as grain boundary sliding and strain hardening of the Cu matrix, that can influence the fatigue life of the composite.

Figure 19

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