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Considerations Concerning Fatigue Life of Metal Matrix Composites

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CONSIDERATIONS CONCERNING FATIGUE LIFE OF METAL MATRIX COMPOSITES

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SUMMARY

Since metal matrix composites (MMC) are composed from two very distinct materials each having their own physical and mechanical properties, it is feasible that the fatigue resistance depends on the strength of the weaker constituent. Based on this assumption, isothermal fatigue lives of several MMC's were analyzed utilizing Talreja's fatigue life diagram approach. For each MMC, the fatigue life diagram was quantified using the mechanical properties of its constituents. The fatigue life regions controlled by fiber fracture and matrix failure were also quantitatively defined.

INTRODUCTION

Due to their high stiffness and low densities, metal matrix composites (MMCs) are being considered for critical applications in aerospace components. A typical MMC system consists of a relatively stiff fiber in a somewhat more compliant matrix. The high strength fiber improves the tensile strength and stiffness of the matrix; but the fatigue strength of the composite also intimately depends on the fiber volume, fiber orientation, fiber/matrix bonding, and manufacturing defects (i.e., voids, inclusions, fiber fractures, etc.). Hence, MMC fatigue data might have a wider variability than metallic materials and hence more care has to be exercised in generating, analyzing, and interpreting the data.

Many of the components for which MMCs are candidate materials are subjected to fluctuating stress and strain conditions and hence prediction of fatigue life, with its inherent scatter, becomes very essential. Recent investigations have contributed to an extensive MMC fatigue data base (refs. 1 to 10). In these studies, both stress and strain controlled experiments have been conducted with the majority of these experiments having a stress ratio of approximately zero ($R_\sigma = 0$). These investigations have shown that the composite fatigue response depends on the stress and strain level in addition to other factors such as fiber volume, fiber orientation, number of plies, etc. Fatigue damage was found to be in the form of either complete breakage of the fiber, cracking of the matrix, debonding of the fiber from the matrix, nucleation and propagation of matrix voids, or a combination of these assisted by defects introduced in the manufacturing processes. It is thus difficult to characterize and predict fatigue damage and lives in a simple manner.

The objective of this study is to evaluate the fatigue life of several metal matrix composites based on the mechanical properties of their constituents. The intent here, is to be a catalyst that will spark the development of a useful engineering tool for fatigue life prediction of MMCs. For simplicity, isothermal fatigue cases with fiber orientation in the loading direction are considered in the present study.

THEORETICAL CONSIDERATIONS

The subject life analysis was based on the assumption that nucleation and propagation of composite fatigue damage is a local phenomenon and hence depends on the weakest link for a given loading condition. Thus, a composite may be strong at all locations showing no indication of damage nucleation or growth throughout a major portion of its life. Then failure of the material or its loss of load carrying capacity may occur suddenly when the damage accumulates beyond a critical amount.

Consider a simple composite model consisting of matrix surrounding a fiber with the loading direction parallel to the fiber orientation. As stated previously, the fiber, relative to the matrix, has a very high strength and an extremely low ductility. The fiber's mechanical behavior can be considered elastic up to fracture and in most cases having an associated fracture strain of approximately 1.0 percent (ref. 1). Such high strength elastic materials are very sensitive to the presence of any small defects. Even a scratch on the surface of a high strength elastic material can reduce its strength drastically. Typically, the fatigue strength of a defect free fiber is relatively high, and over a range of lives from 1 to 10^7 cycles, the fatigue stress levels are only reduced by approximately 80 percent of its fracture strength (refs. 1 and 4). Since the fiber is mainly elastic, one can say that the maximum strain levels in fatigue have the same 80 percent reduction from the fracture strain for fatigue lives ranging from 1 to 10^7 cycles. Figure 1 shows the relation between maximum strain and fatigue life of Tungsten and Boron fibers (refs. 1 and 4). Based on figure 1, the fatigue life relation for fibers can be given by

$$\varepsilon_{\text{max}} = A_{\text{fi}}(N_f)^{\alpha_{\text{fi}}} \tag{1}$$

where $A_{\text{fi}} = 0.01$ and $\alpha_{\text{fi}} = -0.015$ (the slope corresponding to an approximate 80 percent reduction of stress or strain over a life span of 10 million cycles). Note, strain instead of stress is chosen as an independent variable, because in a composite that is loaded along the fiber axis, both fibers and matrix would be subjected to the same strain while stresses in the two phases would differ depending on the fiber volume fraction and their elastic moduli.

In a typical MMC, the matrix is weaker and more ductile than the fiber. Thus during fatigue cycling, the matrix is likely to exhibit a greater amount of plastic deformation than the fiber and therefore is more susceptible to low cycle fatigue damage. Based on this rationale, the maximum strain versus fatigue life relation for the matrix should be applicable in defining the composite's fatigue response. The generalized form of the ε_{max} versus N_f relationship can be given by

$$\varepsilon_{\text{max}} = A_m \frac{\sigma_u}{E} (N_f)^{\alpha_m} + B_m(N_f)^{\beta_m} \tag{2}$$

where σ_u and E are respectively the ultimate tensile strength and the elastic modulus of the matrix, and constants A_m and B_m, are functions of temperature.

Figure 2(a) shows two idealized failure modes in the single fiber MMC model subjected to fatigue of varying maximum strain. If the applied strain condition is such that the maximum strain (ε_{max}) experienced by the material is greater than the fiber fracture strain (ε_{ofi}), then it can be expected that the fiber will fracture. Once the fiber breaks, a stress concentration region will be introduced and the remaining area of the matrix will not be able to take up the applied load and fracture of the composite will occur. If the maximum applied strain (ε_{max}) is less than the fiber fracture strain (ε_{ofi}), then the failure will start from the matrix as governed by the equation (2). The damage in the form of fatigue cracks will grow in the matrix and possibly along the interface of the matrix and the fiber and failure will occur. As the strain level is reduced, the damage will be only in the matrix. However, as the damage spreads along the cross section of the composite, it is likely to introduce a notch effect on the fiber, thereby increasing the local stresses in the fiber. This will eventually lead to the failure of the composite even though the fiber fracture strain is much higher than the applied maximum strain. Thus, in the present analysis it is assumed that the weaker of the two components, namely, the fiber or the matrix will govern the failure of the composite depending on the applied strain level.

Figure 2(b) shows schematically the fatigue life diagram of a typical composite as originally proposed by Talreja (ref. 7). The shaded area gives the possible scatterband inherent in any fatigue testing. Idealized fatigue lines representing equations (1) and (2) are shown for discussion purposes. Note that the fatigue limit of the composite in terms of maximum strain, is governed by the fatigue limit of the matrix. The diagram shows three distinct regions. In the first region, fiber fracture in the composite controls the fatigue life. The strain variation in this region, up to 10^3 cycles, is small, because the slope of the fatigue line of the fiber is only −0.015. In the second region, plasticity and low cycle fatigue strength of the matrix govern the relation, as given by equation (2). The second region spreads over a life of two decades, from around 10^3 to 10^5 cycles. The transition life, N_{fm}, which separates the fiber controlled fracture region (Region I) from the matrix controlled fracture region (Region II) in figure 2(b), can be obtained by equating equations (1) and (2). In the third region of the fatigue life diagram where the fatigue life is approximately 10^6 cycles and longer, the elastic strain of the matrix appears to determine the fatigue life.

DATA ANALYSIS

The experimental results of the following metal matrix composites are studied to understand and develop the fatigue life diagram.

(1) SiC/Ti-24Al-11Nb (ref. 6)
(2) SiC/Ti-15-3 (ref. 2)
(3) W/Cu (ref. 4)
(4) W/Waspaloy (ref. 11)
(5) W/Inconel 907 alloy (ref. 11)

In the first three cases the stress ratio was zero ($R_\sigma = 0$) and in the last two $R_\sigma = 0.2$. The fiber orientation is parallel to the loading axis. In all cases, the fiber fracture strengths were relatively high, in the range of 3500 to 4000 MPa, with fracture strains of approximately 1.0 percent. The stress-strain behavior of the fiber was assumed to be elastic. Taking the fiber fracture strain as the composite's fracture strain, with a corresponding cycle to failure as unity,* one can construct the composite's fatigue life relationship for Region I by using equation (1) and assuming a slope of −0.015. For the composite's fatigue life relationship in Regions II and III, equation (2) can be used with values of the constants based on the matrix properties as given in table I. Note that the values of α_m, A_m, β_m, and B_m were determined for each composite system by using each composites' fatigue data and its corresponding matrix tensile properties in a multiple regression analysis.

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*This differs from conventional fatigue ideology where life would be considered 0.5 for a tension-tension fatigue test.

The fatigue life diagrams for SiC/Ti-24Al-11Nb, SiC/Ti-15-3, W-Cu, W/Waspaloy, and W/IN 907 are presented in figures 3(a) to (d). Note that in these figures, the strain-controlled test data are denoted by closed symbols and the open symbols represent load-controlled tests. Matrix fatigue lives were also plotted if available (figs. 3(b) and (c)). The fatigue life diagrams were obtained by the combination of the two fatigue life relations (eqs. (1) and (2)) and the values from table I.

In all cases, there were good correlations between theoretical approximations and experimental data (figs. 3(a) to (d)). Note some of these cases had fatigue data from tests with different control modes (figs. 3(a), (b), and (d)) and test specimens with different fiber volumes (fig. 3(c)), thus illustrating the viability of this approach for a number of situations. However, more work is needed to examine the feasibility of this approach as it pertains to different ply layups and types of loadings.

The transition life of the composite from fiber controlled to matrix controlled mechanism, N_{fm}, has been obtained by equating relations (1) and (2). Figure 4 shows the correlation between the calculated and the experimental values. The prediction appears to be within the experimental scatter.

DISCUSSION

Talreja (ref. 7) has discussed the fatigue behavior of glass/epoxy and graphite/epoxy composites and suggested that a strain based fatigue life relation can be represented by three regions. In the present analysis, it was found for metal matrix composites, a similar type of fatigue diagram is applicable and that the three regions can be quantified in terms of the basic fatigue properties of the fiber and the matrix. In the first region the fatigue strength is governed by the fracture strain of the fiber which is of the order of 0.01 with an attendant scatter. The slope of the fatigue life line in this region is taken as -0.015 assuming that the life reduction of the defect free fiber is by about 80 percent over a life span of 10^7 cycles. The second region starts from the point where the fatigue life line of the matrix intersects the fatigue life line of the fiber. Beyond this point the fatigue properties of the matrix controls the life of the composite. The second region extends up to around 10^5 cycles where both the elastic and plastic deformation of the matrix will play a role in the initiation and propagation of fatigue cracks. In the third region, where elastic strain of the matrix controls the fatigue life, the slope of the fatigue line was approximately -0.12, interestingly this is identical to the Universal Slopes Equation proposed by Manson (ref. 13). Due to the small magnitude of this slope, it appears that a fatigue limit of the composite is reached at strain levels corresponding to a life of 10^7 cycles.

The analysis in the present investigation has been verified only for cases where the fiber orientation is parallel to the loading axis. If the fibers are oriented at an off-angle relative to the loading direction (i.e., ±30°, ±45°), then the shear strain along that direction and the shear fracture strain corresponding to debonding between the fiber and the matrix should be considered for a fatigue life analysis.

CONCLUSIONS

From the present study, the following conclusions can be drawn for the prediction of fatigue of metal matrix composites with the loading axis parallel to the fiber orientation:

1. For a composite, the maximum strain level in fatigue loading corresponds to the fracture strain of the fiber.

2. The maximum strain—fatigue life of the fiber can be described by the equation

$$\epsilon_{\max} = A_{fi}(N_f)^{\alpha_{fi}}$$

where the exponent α_{fi} is of the order of −0.015.

3. The maximum strain-fatigue life relation of the matrix can be expressed by a simple equation of the form

$$\epsilon_{\max} = A_m \frac{\sigma_u}{E} (N_f)^{\alpha_m} + B_m (N_f)^{\beta_m}$$

where the constants and the exponents are dependent on the material and temperature.

4. The fatigue life relation of the composite can be given by a combination of the above two relations. This results in three regions of the life diagram; (a) Up to around 10^3 cycles the maximum strain variation is almost negligible and the fatigue life is governed by the fiber fracture. (b) A region from 10^3 to 10^5 cycles where the maximum strain decreases with a resultant increase in the fatigue life. In this region the fatigue life is controlled by the plasticity and the low cycle fatigue strength of the matrix. (c) In the third region at around 10^7 cycles, the decrease in strain is very small and this could be considered as the shakedown value with the corresponding life to be infinity for all practical purposes.

5. For the five MMCs analyzed, the above approach of predicting the fatigue life based on the properties of the constituents appears to give a very good correlation with the experimental data. The fatigue life diagram suggested by Talreja is also applicable to MMC and is quantified in terms of the fatigue properties of the fiber and the matrix.

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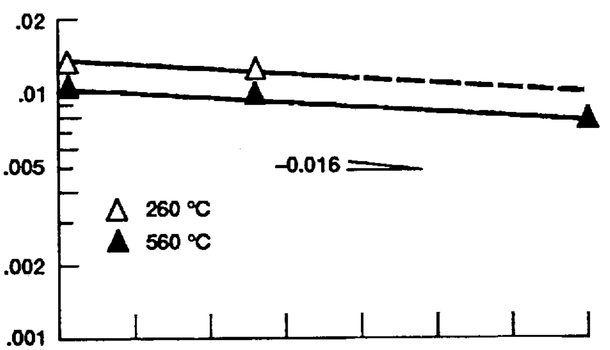
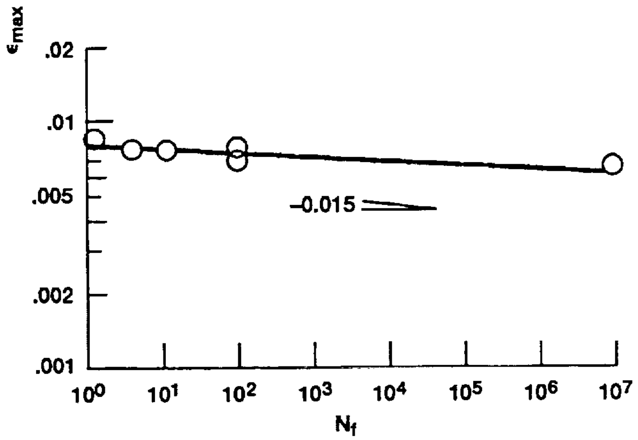
TABLE I.—MATRIX PROPERTIES AND CONSTANT VALUES USED IN THE FATIGUE LIFE DIAGRAM CONSTRUCTION

Material	Temperature, °C	A_m	α_m	B_m	β_m	σ_u, MPa	E, GPa
SiC/Ti-24Al-11Nb	425	3.5	-0.175	0.065	-0.4	550	76
	815	2.0	-0.12	0.01	-0.6	300	43
SiC/Ti-15-3	300	2.0	-0.12	0.04	-0.6	937	97
	550	1.5	-0.12	0.04	-0.6	670	76
W/Cu	260	6.2	-0.12	0.20	-0.6	275	101
	560	6.8	-0.12	0.20	-0.55	90	58
W/Waspaloy	860	1.7	-0.12	0.04	-0.6	800	85
W/IN 907 alloy	860	1.7	-0.12	0.04	-0.6	800	85

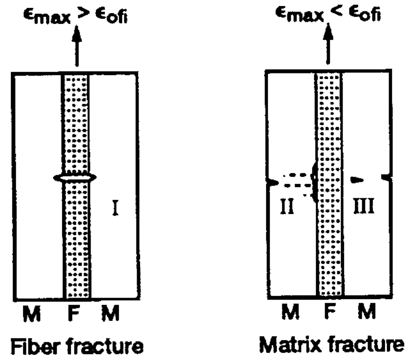


(a) W fiber.

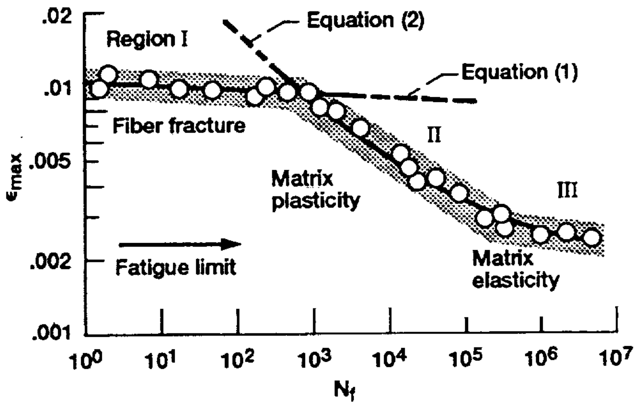


(b) Boron fiber.

Figure 1.—Relation between maximum strain and the fatigue life for tungsten and boron defect free fibers.

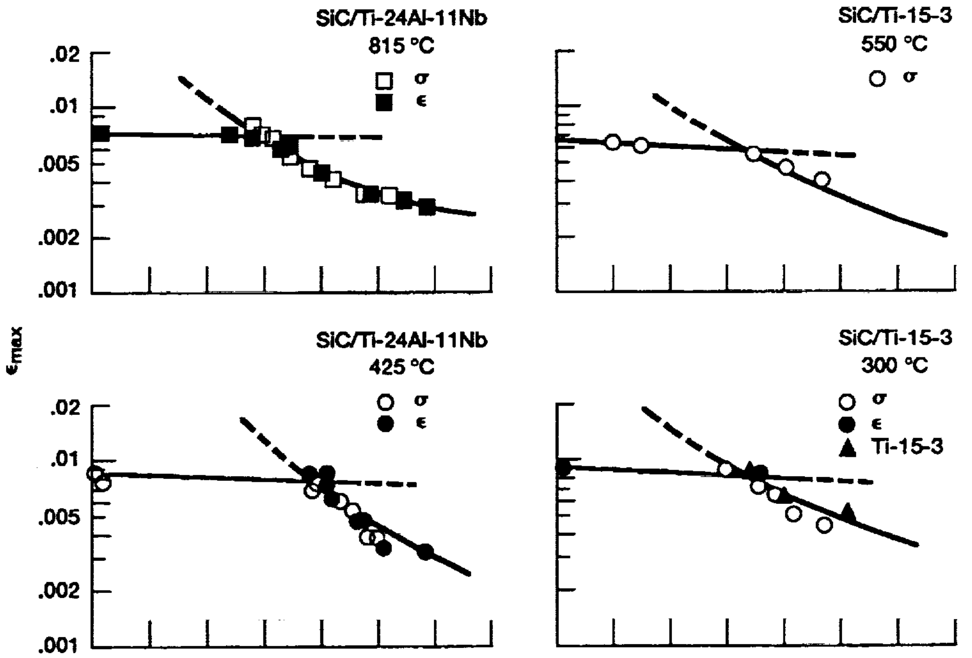


(a) Schematic diagram of fiber controlled and matrix controlled fracture in composite.



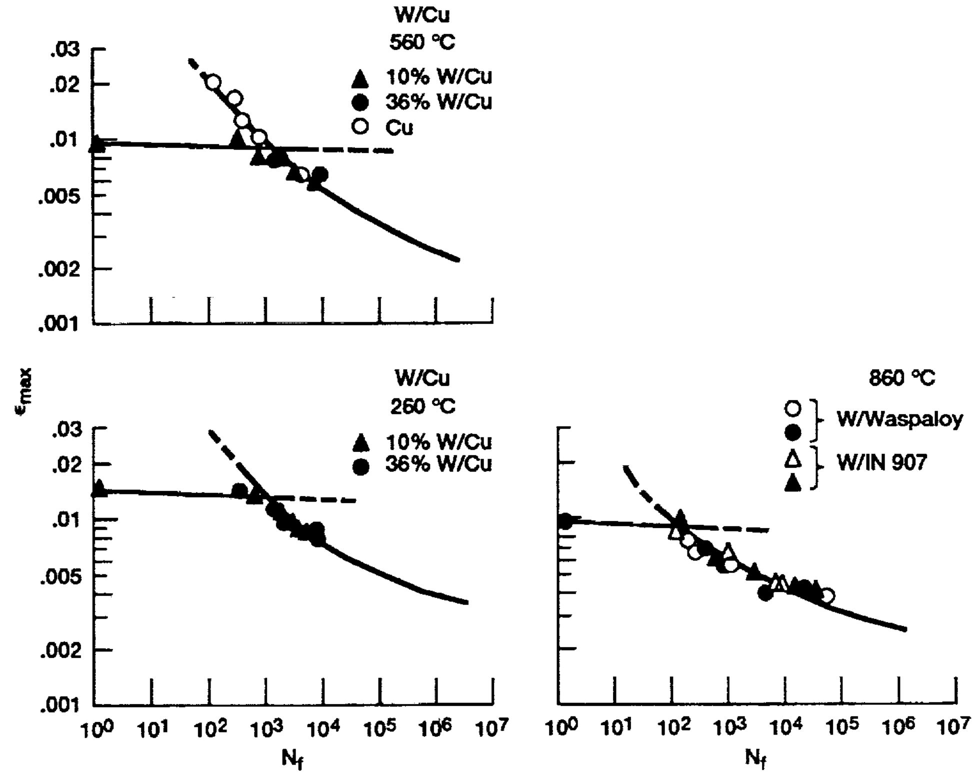
(b) Schematic diagram of Metal Matrix Composite showing the three regions controlled by fiber fracture, matrix plasticity and matrix elasticity.

Figure 2.—Basic approach.



(a) SiC/Ti-24Al-11Nb composite at 815 °C and 425 °C. Data of both load controlled and strain controlled test are shown.

(b) SiC/Ti-15-3 at 550 and 300 °C.



(c) W-Cu with 10 and 36% fiber volume at 560 °C and 260 °C.

(d) W/Waspaloy and W/907 alloy at 860 °C.

Figure 3.—Theory correlated to experimental data.

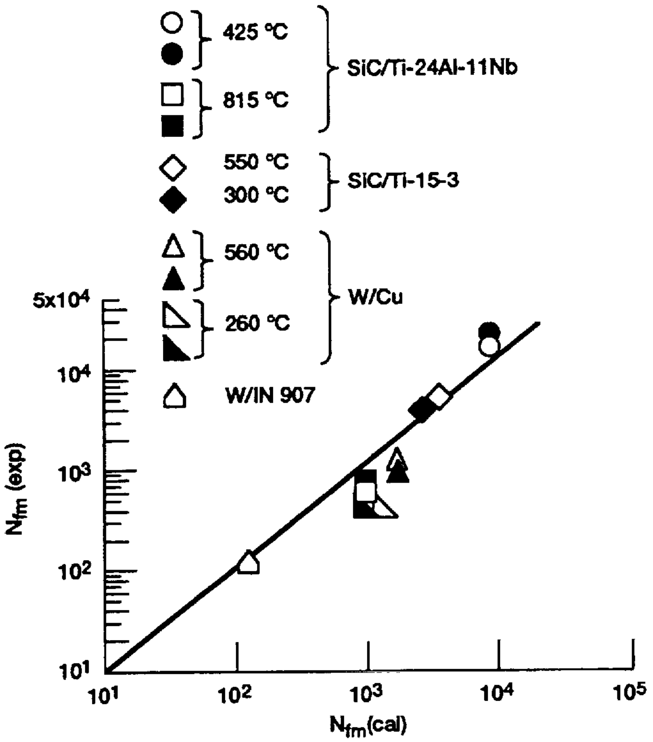


Figure 4.—Relation between the calculated and experimental values of the transition fatigue life giving the boundary between the fiber controlled and matrix controlled fatigue regions.

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13. ABSTRACT ***(Maximum 200 words)***

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