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Fatigue Life Prediction of an Intermetallic Matrix Composite at Elevated Temperatures

Paul A. Bartolotta
Lewis Research Center
Cleveland, Ohio

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Paul A. Bartolotta
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

A strain-based fatigue life prediction method is proposed for an intermetallic matrix composite (IMC) under tensile cyclic loadings at elevated temperatures. Styled after the "Universal Slopes" method, the model utilizes the composite's tensile properties to estimate fatigue life. Factors such as fiber volume ratio (V_f), number of plys and temperature dependence are implicitly incorporated into the model through these properties. The model constants are determined by using unidirectional fatigue data at temperatures of 425 and 815 °C. Fatigue lives from two independent sources are used to verify the model at temperatures of 650 and 760 °C. Cross-ply lives at 760 °C are also predicted. It is demonstrated that the correlation between experimental and predicted lives is within a factor of two.

INTRODUCTION

Fatigue life prediction of composite materials has been a topic of research for the past two decades. There are many prediction methods but most can be categorized into two classes, either modulus (stiffness) degradation theories (1-8) or residual strength degradation theories (9-14).

The residual strength degradation theories assume that due to cyclic damage accumulation, the composite's residual strength will continuously decrease as a function of applied cycles. Failure is assumed to occur when the residual strength of the composite is equal to the applied stress. These methods have proven quite successful in predicting fatigue lives (9-14). However, the difficulty in this type of approach is that in order to characterize the model, information about the relationship between residual strength with respect to cyclic loading is required. That is, one needs to know if the composite's residual strength degrades as a linear function or some other type of function with respect to cyclic loading. To obtain this information, several fatigue tests are conducted at the same condition. The tests are interrupted at various predetermined cycles and subsequently the specimens are tensile tested to obtain the residual strength of the composite. This process is time consuming and requires a large number of specimens. Also, it should be noted that this relationship between residual strength degradation and cycles is highly material dependent.

The modulus degradation theories are based on the fact that under cyclic loading, the stiffness of the composite decreases as a function of cycles. The method used to track the stiffness degradation is highly dependent on the model. In some cases, the unloading tangent modulus is used. In others, the secant modulus is used. A new concept, the fatigue modulus, which is the slope of the line from the point of origin to the maximum tensile peak of each cycle on a stress-strain plot has recently been proposed (3). Once again there are a multitude of material dependent functions to describe how the modulus degrades with respect to cyclic loads. Failure criterion is also dependent on the model. Some of the models use a percentage decrease in the modulus and some others use the point where the secant modulus degrades to the static modulus as the condition when failure occurs. The advantage of this approach over the residual strength degradation models is that the modulus degradation behavior can be experimentally observed in a nondestructive manner with a single specimen for a given load condition. In contrast, the strength degradation models requires testing of several specimens for the same load condition.

The models in the above two classes of composite life prediction have shown to provide good correlations between experimental and predicted fatigue lives in each of their respective studies (1-14). All of the models have well defined theories that are backed up by observed physical phenomena. Most of the models are statistical based, typically utilizing two- or three-parameter Weibull distributions. Like life prediction models for monolithic materials, all of them require extensive amount of testing and in most cases specialized tests and analytical procedures are required to characterize the model.

ESTIMATION OF FATIGUE LIVES FROM TENSILE PROPERTIES

From a practical view point, it can be extremely useful to be able to estimate fatigue lives of composites utilizing a few simple tests. For instance, the method of "Universal Slopes" (15) has been a standard practice in design of monolithic alloy components for the past twenty years. This method is viewed as a useful engineering tool for designers to approximate the fatigue life of a material without the need for a timely and expensive fatigue testing program. The Universal Slopes approach correlates fatigue lives with simple tensile data. The original form of the Universal Slopes equation is:

$$\Delta\epsilon=3.5(\frac{\sigma_{ult}}{E})N_f^{-0.12}+D^{0.6}N_f^{-0.6} \qquad (1)$$

where $\Delta\epsilon$ is the applied strain range, σ_{ult} is the material's ultimate tensile strength, E is the modulus of elasticity and D is the material's ductility. This method has estimated fatigue lives of several dozen monolithic materials to within a factor of 5 (15).

An attempt to extend the Universal slopes method to composites, in particular a metal matrix composite (MMC), has proven successful for a tungsten fiber reinforced superalloy composite system (16-17). In that study, the material constants for equation 1 were chosen to produce two bounds. The upper or high life bound was defined by equation 1 using the matrix (superalloy) ductility for D, the composite's stage II modulus (after matrix yield) for E, and the composite's σ_{ult}. The lower bound (low life) was defined using the tungsten fiber ductility, the composite's stage I modulus (before matrix yield) and the same σ_{ult}. In reference 17, a good correlation was observed between the lower predictions and experimental results from an independent source for several tungsten reinforced superalloys fatigued at 870 °C. This observation illustrates the possible applicability of this type of approach for composites. It by no means states that fatigue lives of all composite classes can be predicted by using the Universal Slopes method. However, it does suggest, that perhaps for tungsten reinforced superalloys this method can be used as a first approximation.

In this paper, a model using a "Universal Slopes-type" approach for isothermal fatigue life prediction of a SiC/Ti-24Al-11Nb (atomic %) composite is proposed. Comparisons between experimental results (425 and 815 °C) and correlated fatigue lives are presented. Predictions for $[0]_8$ SiC/Ti-24Al-11Nb at 650 and 760 °C data from two independent sources are made. An attempt to predict fatigue lives of cross-ply composites at 760 °C is also presented.

MATERIAL

SiC/Ti-24Al-11Nb (atomic %) has been identified as a promising composite system for advanced aerospace applications that require light weight materials that can maintain their strength at relatively high temperatures. This composite system is relatively mature and is well characterized for temperatures up to 800 °C (18-24). Typically, this composite system is fabricated either by a powder cloth method (18-21), foil/fiber/foil method (22-23) or a low pressure plasma spray technique (24). A forth method, which is a arc-spray technique is presently being perfected (25). The microstructure of this composite system is quite complex and along with its mechanical properties is independent of fabrication technique. The SiC/Ti-24Al-11Nb microstructure is typically comprised of a 140 μm diameter, double carbon coated, SCS-6 SiC fiber manufactured by Textron that is surrounded by a fiber-matrix reaction zone (19). The matrix consists of equiaxed α_2 (Ti_3Al) surrounded by a disordered β phase. A β-depleted zone in the matrix is found adjacent to the reaction zone.

The tensile and fatigue data used in this study were generated on composites that were fabricated using the powder cloth and foil/fiber/foil techniques. The SiC/Ti-24Al-11Nb composite specimens had a fiber volume ratio (V_f) ranging from 27 to 33 percent. The powder cloth composites were fabricated at NASA/LeRC (25) and the foil/fiber/foil material was produced at Textron (23). The tests were conducted by three independent laboratories, all using similar specimen geometries.

TENSILE PROPERTIES

The mean tensile properties used in this study for both powder cloth and foil/fiber/foil SiC/Ti-24Al-11Nb composites are presented in Table 1. All tests were conducted in an air environment at temperatures ranging from 425 to 815 °C. As observed in this table, the composite shows a degradation in stiffness and ultimate tensile strength with respect to temperature. However, the composite fracture strains are close to 0.8% throughout the temperature range with the exception of 760 °C where it is 0.7%. The foil/fiber/foil data also follows, within experimental error, the linear regression equations of tensile properties for powder cloth SiC/Ti-24Al-11Nb of reference 18. This suggests that, at least for the foil/fiber/foil and powder cloth SiC/Ti-24Al-11Nb system, fabrication technique and number of plys has a minimum effect on tensile properties.

ISOTHERMAL FATIGUE DATA

The isothermal tensile fatigue lives for 0° unidirectional SiC/Ti-24Al-11Nb at 425, 650, 760 and 815 °C are presented on a maximum strain basis in figure 1 (21-23). This concept of presenting composite tensile fatigue data on a maximum strain basis (fatigue life diagram) was first used to explain room temperature fatigue mechanisms of polymer matrix composites (26). Later, the concept was successfully extended to SiC/Ti-24Al-11Nb at elevated temperatures (21).

Failure was defined as complete fracture with the exception of the 425 and 815 °C strain-controlled tests where failure was defined by a different criterion (21). In reference 21, it was shown that this alternative failure criterion defined fatigue lives that were in close agreement with lives from load-controlled lives which were determined by complete fracture. Thus, no distinction is made between fatigue lives of load-controlled or strain controlled tests in figure 1. Note, that the filled symbols in figure 1 denote the data that was generated with 3 ply SiC/Ti-24Al-11Nb.

The two horizontal lines in the fatigue life diagram define the scatter band of tensile fracture strains of SiC/Ti-24Al-11Nb throughout the temperature range. In this area, the fatigue lives are influenced by the statistical nature of the fiber (i.e., number of defects and their relative location to one and other). The lives in this region, were shown to vary between initial load-up (tensile test) to thousands of cycles for the same loading condition. For this reason, component design strains should be kept below the lower bound of this region.

In the region below the scatter band, lives behave more in a deterministic manner. As the maximum applied strains decrease, the fatigue lives increase. Likewise, the fatigue lives have a temperature dependence where the lives are longer at the lower temperatures compared to the higher temperatures. It is in this low cycle fatigue (LCF) regime, that the proposed life approximation scheme will aid in design applications.

Figure 2 illustrates the usefulness of the fatigue life diagram for representing LCF data of cross-plys at elevated temperatures. In this figure 760 °C fatigue data of 8 ply $[0/90]_{2s}$, $[0/\pm45/90]_s$, and $[0]_8$ SiC/Ti-24Al-11Nb are presented (23). Note that on a maximum strain basis, the cross-ply data collapses onto the $[0]_8$ data. This trend was also seen for SiC/Ti-15V-3Cr-3Al-3Sn (28). However in reference 28, the data were presented on a maximum 0° fiber stress basis. The maximum 0 °fiber stress was determined from a Hookean relationship between the maximum applied strain of the composite and the modulus of the fiber. In essence, this approach is identical to the maximum strain based fatigue life diagram used in this study. The above observations suggest that for isothermal, strain based, LCF lives of cross-plys and 0° unidirectional composites will be similar, as long as there is at least one 0° ply in the cross-ply composite. Thus, it is reasonable to assume that cross-ply lives can be approximated with unidirectional data on a strain basis.

FATIGUE LIFE APPROXIMATION APPROACH

The choice of representing composite fatigue life on the basis of strain is two-fold in nature. First, historically strain based representation of fatigue life for monolithic metals has proven to be quite useful for both understanding fatigue mechanisms and life prediction techniques (15). This is especially true for practical high temperature applications where the material at a critical location is to some extent constrained which is reminiscent of a strain controlled situation. Secondly, during LCF tests of composites reinforced with 0° fiber orientations, the strains for both the fiber and the matrix are essentially the same, but the stresses in the composite constituents differ (26-27). With this in mind, it is logical to use a strain based method for life estimation.

The basic form of the equation used in this approach employs tensile properties similar to the Universal Slopes equation. The proposed life prediction relationship is:

$$N_p = A\left(\frac{\sigma_{ult}}{E}\right)^{\alpha}(\epsilon_f)^{\beta}(\epsilon_{max})^{\gamma} \qquad (2)$$

where N_p is the predicted life, ϵ_{max} is the maximum applied strain, A is a constant, and α, β and γ are exponents. Like the Universal Slopes method, equation 2 correlates composite's ultimate tensile strength (σ_{ult}), tangent loading modulus (E) and fracture strain (ϵ_f) to fatigue life. The ratio σ_{ult}/E can be thought as the maximum elastic strain that can be applied to composite. While ϵ_f is a measure of the composite's ductility and is comprised of a combination of the composite's maximum elastic and inelastic applied strains.

The composite's tensile properties are used in equation 2 rather than the constituents' tensile properties because the microstructure of this composite type is quite complex. Composed of different phases and interface regions, it is difficult at best to obtain the constituents' in-situ tensile properties and how they interrelate to one and other. By using the composite's tensile properties, the influence of aspects like different V_f's, temperature effects, and fabrication processes on fatigue life are incorporated into the model implicitly. Furthermore, it was anticipated that the fatigue lives of different ply lay-ups would correlate with their respective tensile properties as a function of equation 2.

To obtain the parameters A, α, β and γ, LCF data and corresponding tensile properties at various temperatures are used in a multiple regression analysis. The resultant parameters that were calculated for SiC/Ti-24Al-11Nb are presented in table 2. The LCF data used in the multiple regression were only the 425 and 815 °C data represented by filled symbols in figure 1.

The final form of equation 2 with calculated parameters for SiC/Ti-24Al-11Nb is:

$$N_p = 4.592\times10^{-31}\left(\frac{\sigma_{ult}}{E}\right)^{-14.718}(\epsilon_f)^{4.892}(\epsilon_{max})^{-5.420} \qquad (3)$$

By making simple algebraic manipulations equation 2 can be rewritten in a more conventional form with maximum strain as a function of tensile properties and life:

$$\epsilon_{max}=A^{-\frac{1}{\gamma}}\left(\frac{\sigma_{ult}}{E}\right)^{-\frac{\alpha}{\gamma}}(\epsilon_p)^{-\frac{\beta}{\gamma}}(N_p)^{\frac{1}{\gamma}} \qquad (4)$$

Using the values for the exponents and constants from table 2, equation 4 takes the following final form for SiC/Ti-24Al-11Nb:

$$\epsilon_{max}=2.527\times10^{-6}\left(\frac{\sigma_{ult}}{E}\right)^{-2.716}(\epsilon_p)^{0.902}(N_p)^{-0.1845} \qquad (5)$$

Equations 3 and 5 will be used for the rest of the paper making LCF predictions of both 0° unidirectional and cross-plied SiC/Ti-24Al-11Nb.

PREDICTION RESULTS

Comparisons between actual and correlated fatigue lives of 3-ply 0° SiC/Ti-24Al-11Nb at 425 and 815 °C are presented in figure 3. The correlations were made by employing equation 3 and the appropriate tensile data from table 1. Since equation 3 was determined using this data, the good agreement between this data and the life approximation was not surprising.

Figures 4 and 5 present comparisons between LCF data and predictions determined from equation 3 and respective tensile data (table 1). Note that the agreement between the 650 and 760 °C LCF lives and predicted lives is remarkably good. The 650 °C data (fig. 4) generally falls above the predicted life line indicating a conservative prediction (i.e., the predicted lives are lower than actual lives). But still the predicted lives are within a factor of two from the data. On the other hand, the 760 °C data (fig. 5) appear to be more symmetrically scattered about the predicted life line.

An attempt was made to extend this approximation to incorporate cross-ply LCF data. Figure 6 shows the comparison of predicted $[0/90]_{2s}$ and $[0/\pm45/90]_s$ lives to test data. The approximation for the $[0/90]_{2s}$ data was within acceptable limits. As for the $[0/\pm45/90]_s$ data, the predictions were unsatisfactory with errors of several orders of magnitude in lives. An explanation for this inconsistency will be discussed in the next section.

An overall evaluation of the subject LCF life approximation technique for 0° unidirectional SiC/Ti-24Al-11Nb is shown in figure 7. In this figure, the observed life is plotted against the predicted life. A data point that lands on the solid line of this figure denotes a perfect prediction. For convenience, a factor of two life region is plotted on the graph. The boundaries of this region are denoted by two dashed lines. About ninety percent of the data points fall within a factor of 2 in life from the predicted values. All of the data fall within a factor of 3. Similarly, figure 8 compares the predicted maximum strain to actual maximum applied strain. Here too the agreement between predicted and actual maximum strain are remarkably good with all of the data falling within a factor of 1.2 in strain (factor of 1.2 region is denoted by the two dashed lines). This observation is not so surprising considering the range of strains is small compared to the range of lives which encompasses several orders of magnitude.

The cross-ply predictions are compared on a similar basis in figures 9 and 10. On a life basis, most of the $[0/90]_{2s}$ predictions were within a factor of 4 from the actual data with an exception of one test (fig. 9). The $[0/\pm45/90]_s$ predictions were off by several orders of magnitude. On a maximum strain basis, the $[0/90]_{2s}$ predictions were better with most data (with the exception of one) landing within a factor of 1.2 in strain (fig. 10). However, the $[0/\pm45/90]_s$ prediction was poor. Note, that some of the $[0/\pm45/90]_s$ predictions were so non-conservative that the data fell outside the upper bounds of figures 9 and 10.

DISCUSSION

When examining the data (fig.1) on a fatigue life diagram, certain observations about the fatigue trends of [0°] SiC/Ti-24Al-11Nb at elevated temperatures become obvious. First, there is a region where the strain-life relationship is a plateau with lives varying between one to thousands of cycles. This region seems to correspond to the scatter in tensile ductility of the composite from static tests (21 and 26). As a designer, the lower bound of the region would naturally become the upper most design limit on strain.

Another observation is the fact that there are no distinct differences between LCF lives of $[0]_3$ or $[0]_8$ SiC/Ti-24Al-11Nb. Remember the 425 and 815 °C data were obtained from 3-ply composites while the 650 and 760 °C were obtained from 8-ply material. Similarly, there seems to be little if no influence of fabrication process (foil vs powder), small differences in V_f (±5 percent) or laboratory procedures on LCF life trends. However, these factors might influence high cycle fatigue (HCF) trends where typically, the scatter in life is large (on the order of several orders of magnitude) and these factors can greatly influence this variance. This has been observed for monolithic materials but it still remains to be seen for MMC's.

Finally, there is a certain temperature dependence with respect to fatigue lives of SiC/Ti-24Al-11Nb. The fatigue trends of the higher temperature data, 760 and 815 °C, are grouped closely together with significantly lower lives than the 425 and 650 °C data that are also grouped together. This coalescing of higher life and lower life trends can be attributed to the matrix temperature dependence. It can be argued that the SiC fiber properties remain essentially constant throughout the practical use temperature range for the SiC/Ti-24Al-11Nb composite system. Thus fiber temperature dependence should have no effect on fatigue life. This leaves only the temperature dependence of either the fiber/matrix interface, the ß-depleted zone, the Ti-24Al-11Nb matrix or any combination of the above that would influence these life trends. It would be interesting to investigate these factors and provide rational explanations. A recent study (29) provided some useful insight towards an explanation of this temperature dependent dichotomy of fatigue lives. One conclusion of this study (29), showed that bulk Ti-24Al-11Nb has a definite embrittlement problem at temperatures above 650 °C in an air environment. It was further presumed that the embrittlement was due to oxygen diffusion into the alloy. Thus, it is reasonable to assume that the most likely dominating factor influencing the fatigue life temperature dependence of SiC/Ti-24Al-11Nb is matrix oxygen embrittlement. This phenomena would affect matrix crack growth behavior and ultimately life.

In general, the unidirectional SiC/Ti-24Al-11Nb life predictions made with equation 3 were quite remarkable, considering they were made using only tensile properties. However, the cross-ply predictions were not as respectable with the worst case being the $[0/\pm45/90]_s$ predictions. An explanation of the poor cross-ply predictions along with an alternative method to predict life will be addressed later.

The general form of the life prediction equation (eqn. 2) was chosen in an attempt to implicitly incorporate life controlling factors such as temperature, V_f, differences within and between fiber lots, number of plys and cross-plys. Temperature, V_f and cross-ply effects are incorporated into the prediction approximation via the ratio σ_{ult}/E. Obviously, the parameters σ_{ult} and E will decrease as temperature is increased but, the ratio (σ_{ult}/E) might increase with respect to temperature as in the case of this composite. Both V_f and cross-plys will influence σ_{ult} and E by either increasing or decreasing the number of 0° fibers along the loading direction. By far the cross-ply factor has the most affect on these tensile properties. For instance, compare the $[0]_8$ and the $[0/90]_{2s}$ tensile data of reference 22 (table 1). With the $[0/90]_{2s}$ having only 4 plys in the loading direction (0°), instead of 8 plys, the tensile properties are quite lower than the $[0]_8$. There should be no differences in tensile properties between $[0]_3$ and $[0]_8$ because σ_{ult} and E are engineering quantities that account for geometrical effects. It has been observed that for unidirectional SiC/Ti-24Al-11Nb, ϵ_f is dominated by the properties of the fiber (18). Also found was that the SCS-6 SiC fiber has a large amount of scatter in tensile strength both within and between fiber lots (18). The SiC fibers with less defects will have higher σ_{ult} and ϵ_f, since the fiber response is linear elastic up until fracture. Therefore, composites made from fibers with less defects will have higher σ_{ult} and ϵ_f.

The mathematical implications between σ_{ult}, E, ϵ_f and N_p are critical for predicting life (eqn. 2). For the SiC/Ti-24Al-11Nb life equation (eqn. 3), an increase in E or ϵ_f will increase the predicted life. An increase in σ_{ult} will result in a decrease in predicted life. One conclusion that becomes evident is the need to use tensile properties from the same lot of composite material that the component will be fabricated from. The tensile test temperature needs to be identical to the application and the tensile specimen should have similar V_f with similar fiber lot strengths. For these factors can affect the accuracy of the prediction.

Perhaps, the main advantage of this type of approach is in its simplicity. That is, for a given high temperature application, a designer can take a life equation (i.e., equation 3) and tensile properties of a particular composite system, and evaluate the material without a costly investment of time or money. Then if the composite system is a viable option, a more robust fatigue characterization program could be started. The intent of this approach is to give an approximate life under isothermal LCF conditions and provide a basis from which other aspects of LCF can be incorporated similarly into the method.

Limitations do exist in this life approximation approach. Fundamental LCF aspects that plague monolithic materials are not addressed by this method nor by the Universal Slopes method. The LCF data that were predicted in this paper are tensile fatigue with typical R_σ and R_ϵ (min/max) values of 0.0 and 0.1 respectively. Thus, issues like applicability to mean stress effects and fully reversed cycling (with R_σ and R_ϵ equal to -1.0) are not addressed. Also this method is limited to brittle fiber composites at elevated temperatures and does not account for ductile fibers or residual stresses in the composite due to thermal expansion mismatch of the fiber and matrix. In the same train of thought, the approach needs be extended to include creep-fatigue interaction and thermomechanical fatigue (TMF).

As for cross-plys, the predictions were reasonable for the $[0/90]_{2s}$ but, was far short of being successful for the $[0/\pm45/90]_s$ data. A possible explanation is that the stiffness of $[0/\pm45/90]_s$ will rapidly degrade with tensile cycling (23). The rapid stiffness degradation is typically the result of extensive microcracking both within and between the plys due to the complex multiaxial stress state of the matrix. This is contrary to the 0° unidirectional composite which maintains most of its stiffness for over 90% of its life (21-23). By using the static modulus, E, in equation 3, the tacit assumption is made that the stiffness is maintained throughout the test, thus resulting in an over-prediction of cross-ply lives. Figure 2 suggests a possible solution to this problem. Here, $[0]_8$, $[0/90]_{2s}$ and $[0/\pm45/90]_s$ data are collapsed by plotting them on a maximum strain basis. Thus, the life prediction of undirectional $[0]_8$ composite can be used to approximate the cross-ply lives as shown in fig. 11. Whether or not this trend holds for real world applications where the principal loads will be multiaxially applied along all fiber directions still remains to be addressed. However, for the case of cross-plys that are loaded along one fiber direction, this approach appears to be reasonable.

CONCLUSIONS

1) Presenting LCF lives of composites on a maximum strain basis has many advantages. Among them is the ability to

collapse LCF data of cross-plys onto unidirectional which can aid in life prediction of cross-plys (note: the cross-ply requires a ply with fibers along loading direction)

2) A strain-based life approximation method which uses tensile properties to predict fatigue life in a "Universal Slopes" manner was proposed.

3) The proposed life approximation technique for SiC/Ti-24Al-11Nb composite* at elevated temperatures performed quite well with 90% of all unidirectional predictions falling within a factor of two from the actual lives.

4) Cross-ply predictions using cross-ply tensile properties were inadequate except for the $[0/90]_{2s}$ that were within a factor of five on life. However, by using conclusion 1 and the life prediction of the unidirectional at the same temperature, predicted lives for 80% of the cross-plys were within a factor of two on life and all were within a factor of four.

5) The life approximation method has the following limitations:
   a) It has been only used for the brittle fiber composite system, SiC/Ti-24Al-11Nb, at elevated temperatures

   b) It cannot account for mean stress effects, fully reversed cycling, TMF, creep-fatigue interaction and multiaxially loaded cross-plys.

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TABLE 1 MEAN TENSILE PROPERTIES OF SiC/Ti-24Al-11Nb

Ref.	Plys	Lay-up	Fabrication Method	Temp. (°C)	σ_{ult} (MPa)	E (GPa)	σ_{ult}/E (m/m)	ϵ_f (m/m)
21	3	$[0]_3$	Powder Cloth	425	1100	180	0.0061	0.0080
21	3	$[0]_3$	Powder Cloth	815	900	130	0.0069	0.0080
22	8	$[0]_8$	Foil	650	1040	159	0.0065	0.0082
23	8	$[0]_8$	Foil	760	916	142	0.0064	0.0069
23	8	$[0/90]_{2s}$	Foil	760	581	93	0.0063	0.0077
23	8	$[0/\pm45/90]_s$	Foil	760	380	73	0.0052	0.0083

TABLE 2 CORRELATION PARAMETERS

A	α	β	γ	1/γ	-α/γ	-β/γ
4.592×10^{-31}	-14.718	4.892	-5.42	-0.1845	-2.716	0.902

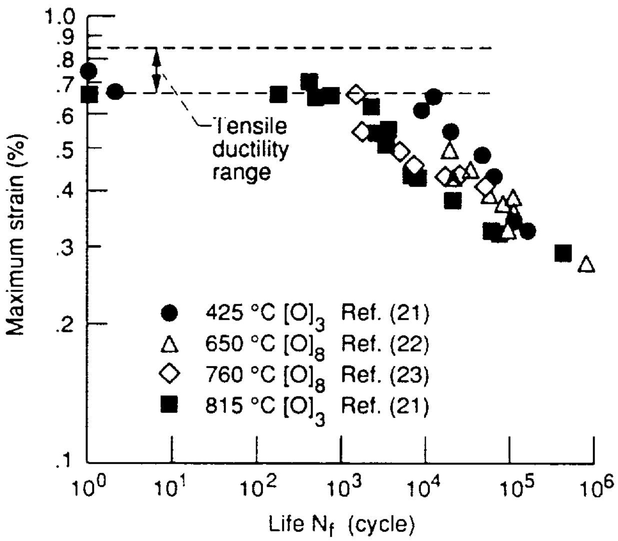

Figure 1.—Fatigue life diagram of SiC/Ti-24Al-11Nb at elevated temperatures from three independent studies.

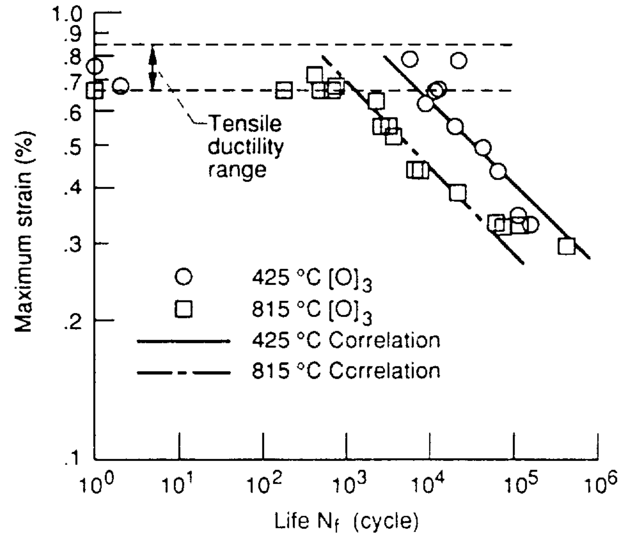

Figure 3.—Comparisons between actual and correlated fatigue lives of SiC/Ti-24Al-11Nb at 425 and 815 °C.

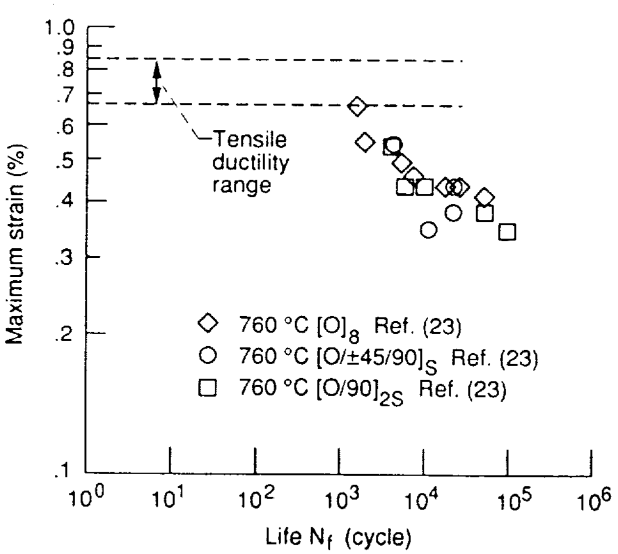

Figure 2.—Fatigue life diagram of $[0]_8$, $[0/\pm45/90]_S$, and $[0/90]_{2S}$ SiC/Ti-24Al-11Nb LCF data at 760 °C.

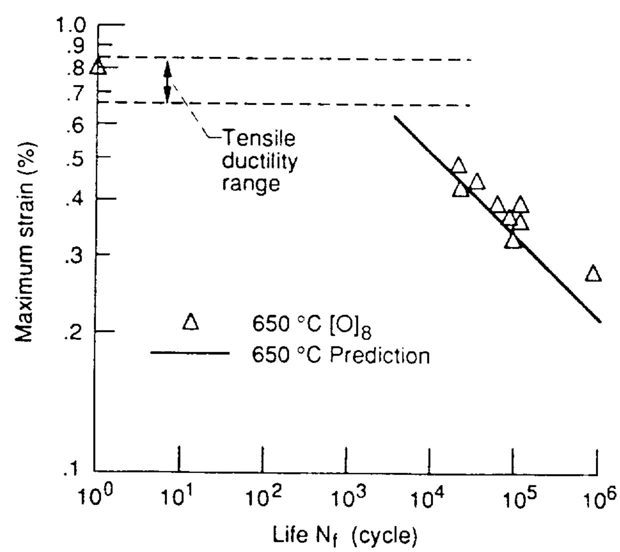

Figure 4.—Comparison between actual and predicted fatigue lives of SiC/Ti-24Al-11Nb at 650 °C.

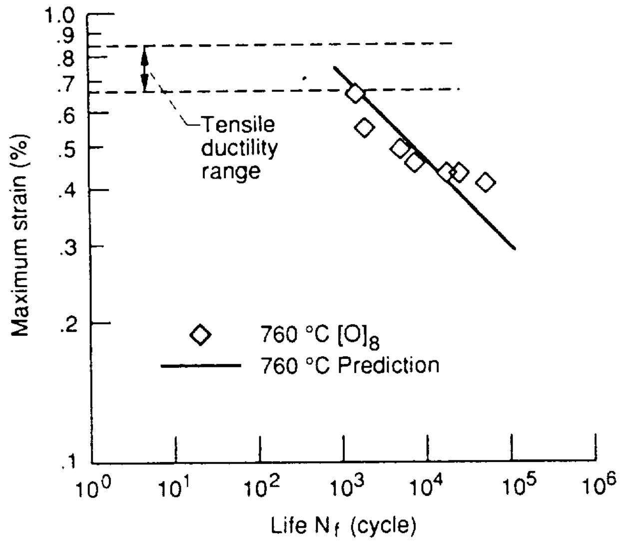

Figure 5.—Comparison between actual and predicted fatigue lives of SiC/Ti-24Al-11Nb at 760 °C.

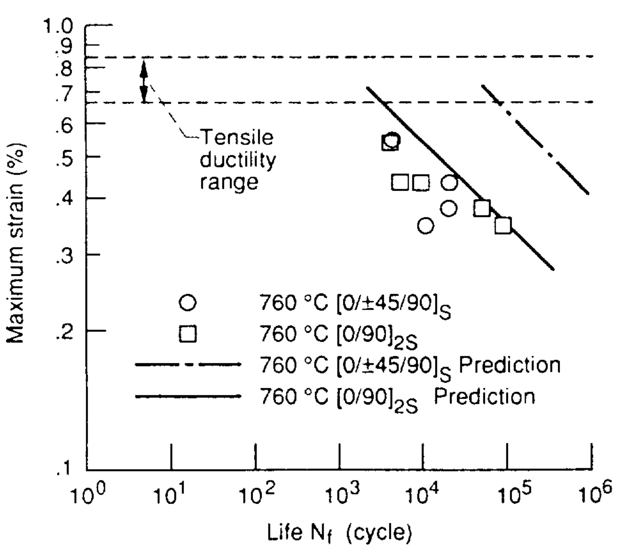

Figure 6.—Comparison between actual and predicted fatigue lives of $[0/\pm45/90]_S$ and $[0/90]_{2S}$ SiC/Ti-24Al-11Nb at 760 °C.

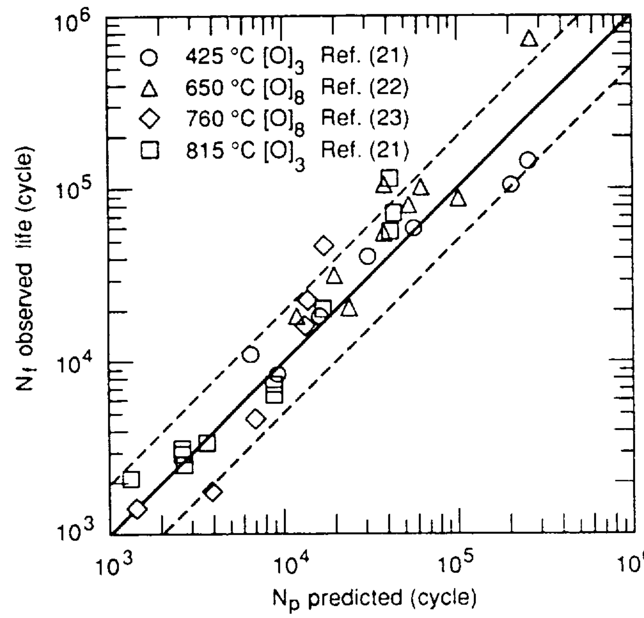

Figure 7.—Observed versus predicted fatigue lives of 0° unidirectional SiC/Ti-24Al-11Nb at elevated temperatures.

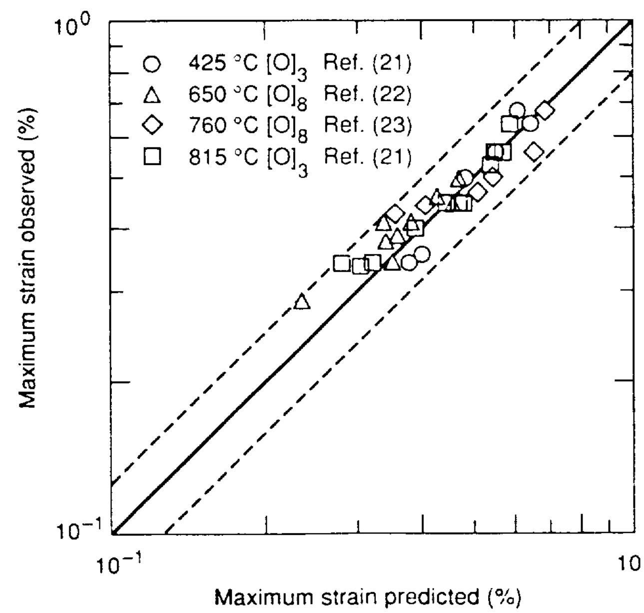

Figure 8.—Observed versus predicted maximum strains of 0° unidirectional SiC/Ti-24Ai-11Nb at elevated temperatures.

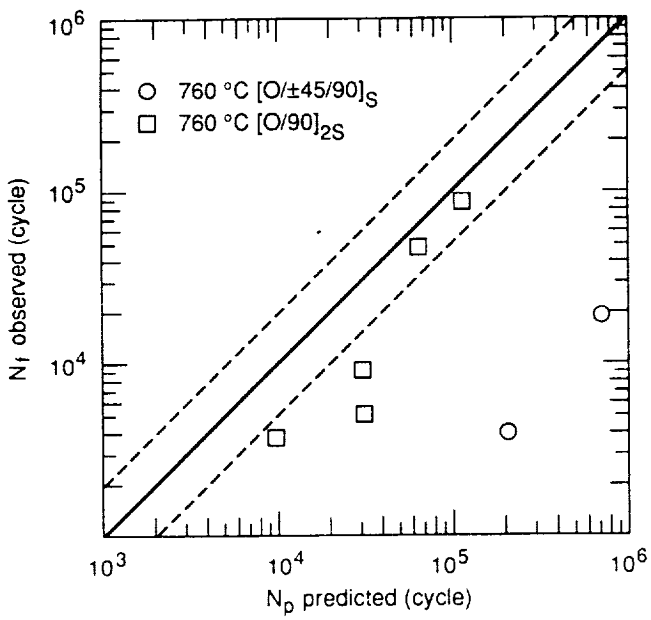

Figure 9.—Observed versus predicted fatigue lives of $[0/\pm45/90]_S$ and $[0/90]_{2S}$ SiC/Ti-24Al-11Nb at 760 °C.

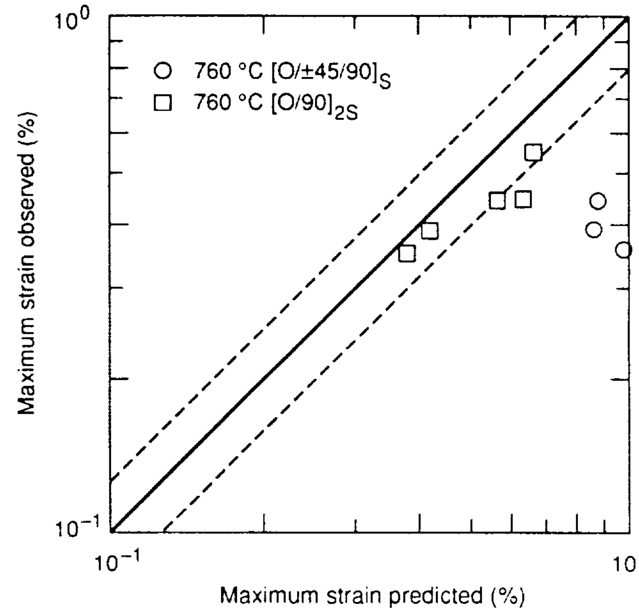

Figure 10.—Observed versus predicted maximum strains of $[0/\pm45/90]_S$ and $[0/90]_{2S}$ SiC/Ti-24Al-11Nb at 760 °C.

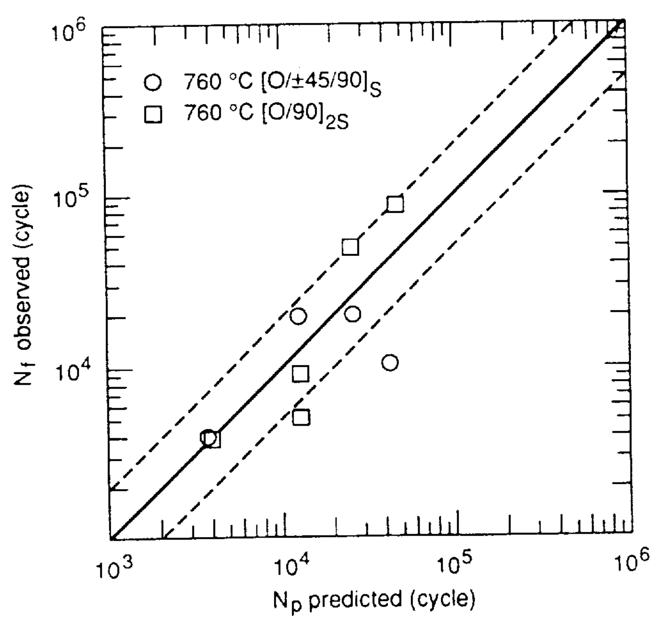

Figure 11.—Observed $[0/\pm45/90]_S$ and $[0/90]_{2S}$ versus predicted $[0]_8$ fatigue lives of SiC/Ti-24Al-11Nb at 760 °C.

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15. Supplementary Notes

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16. Abstract

A strain-based fatigue life prediction method is proposed for an intermetallic matrix composite (IMC) under tensile cyclic loadings at elevated temperatures. Styled after the "Universal Slopes" method, the model utilizes the composite's tensile properties to estimate fatigue life. Factors such as fiber volume ratio (V_f), number of plies and temperature dependence are implicitly incorporated into the model through these properties. The model constants are determined by using unidirectional fatigue data at temperatures of 425 and 815 °C. Fatigue lives from two independent sources are used to verify the model at temperatures of 650 and 760 °C. Cross-ply lives at 760 °C are also predicted. It is demonstrated that the correlation between experimental and predicted lives is within a factor of two.

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