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Parametric Studies to Determine the Effect of Compliant Layers on Metal Matrix Composite Systems

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PARAMETRIC STUDIES TO DETERMINE THE EFFECT OF COMPLIANT LAYERS ON METAL MATRIX COMPOSITE SYSTEMS

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ABSTRACT

Computational simulation studies are conducted to identify compliant layers to reduce matrix stresses which result from the coefficient of thermal expansion mismatch and the large temperature range over which the current metal matrix composites will be used. The present study includes variations of compliant layers and their properties to determine their influence on unidirectional composite and constituent response. Two simulation methods are used for these studies. The first approach is based on a three-dimensional linear finite element analysis of a nine-fiber unidirectional composite system. The second approach is a micromechanics based nonlinear computer code developed to determine the behavior of metal matrix composite system for thermal and mechanical loads. The results show that an effective compliant layer for the SCS 6 (SiC)/Ti-24Al-11Nb (Ti_3Al+Nb) and SCS 6 (SiC)/Ti-15V-3Cr-3Sn-3Al (Ti-15-3) composite systems should have a modulus 15 percent that of the matrix and a compliant layer coefficient of thermal expansion roughly equal to that of the composite system without the CL. The matrix stress in the longitudinal and the transverse tangent (hoop) direction are tensile for the Ti_3Al+Nb and Ti-15-3 composite systems upon cool down from fabrication. The fiber longitudinal stress is compressive from fabrication cool down. Addition of a recommended compliant layer will result in a reduction in the composite modulus.

INTRODUCTION

Metal matrix composite (MMC) are prime candidates for high temperature applications. They present a unique challenge to today's researchers. The large operating temperature range (greater than 2000 °F) and the mismatch between the thermal expansion coefficients (CTE) of the fiber and the matrix pose great difficulties in fabrication and low thermal cycling resistance. Both of these increase the matrix stress to critical proportions and often lead to failure. Many solutions to this problem have been proposed (e.g., matching CTE for fiber and matrix) with little success. One suggestion is to use a compliant layer (CL) as a buffer between the fiber and the matrix. The goal of this CL is to reduce the matrix stress without degrading the fiber, the matrix, or the composite. Finding a material to do this, however, may prove to be quite a challenge.

In an attempt to find such CLs, a parametric study is a natural first step. It is essential to assemble a working knowledge of which and/or how characteristic parameters of the constituent material effect composite behavior.

Two computational simulation approaches are used in this study to evaluate CLs in MMC systems for high temperature applications under thermal loads. The first is a three-dimensional linear finite element method. The other is a nonlinear micromechanics based numerical method.

In attempt to identify characteristics for suitable compliant layers, compliant layers are evaluated with two common but very different metal matrices. They are (1) Ti-15V-3Cr-3Sn-3Al (Ti-15-3) and (2) Ti-24Al-11Nb (Ti_3Al+Nb) reinforced with SiC (SCS 6) fibers. The SiC/Ti-15-3 composite system has been processed without matrix cracks (1-3). SiC/Ti_3Al+Nb, however, does develop matrix cracks during processing (5,6), making it a candidate for a CL. There will be some discussion on the Ti-15-3 system; but, the majority of the effort will concentrate on the Ti_3Al+Nb system.

The development of matrix cracks may be related to tensile stresses in specific directions. Large tensile hoop stresses in the matrix can cause the transverse tangent (hoop) cracks observed by MacKay (1) and Ghosn & Lerch (2). Similarly, large tensile longitudinal stresses may cause matrix cracking perpendicular to the fibers. These cracks have not been observed. A compliant layer should reduce the stress in all directions to be an effective method for preventing cracks during the fabrication and the thermal cycling of these systems. If the goal is to eliminate matrix cracking, a compromise may have to be made between stresses to eliminate matrix cracking.

METHODS

The FEM calculates the linear composite response at many locations in the constituents of the composite system that cannot be determined through experiments (6-8). The general purpose finite element code MSC/NASTRAN (9) is used to perform the analysis. The model uses eight-noded hexahedron and six-noded pentahedron elements to form a nine-cell nine-fiber unidirectional composite system (Fig. 1). The model provides constituent displacements, stresses, and forces due to thermal loading conditions.

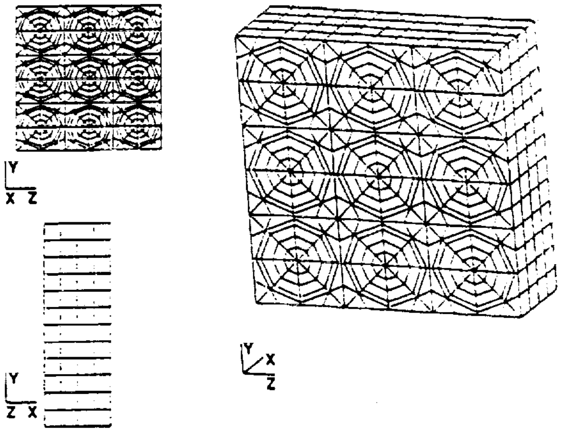

FIGURE 1. - MULTICELL 3-D FINITE ELEMENT MODEL FOR LOCAL DETAILS.

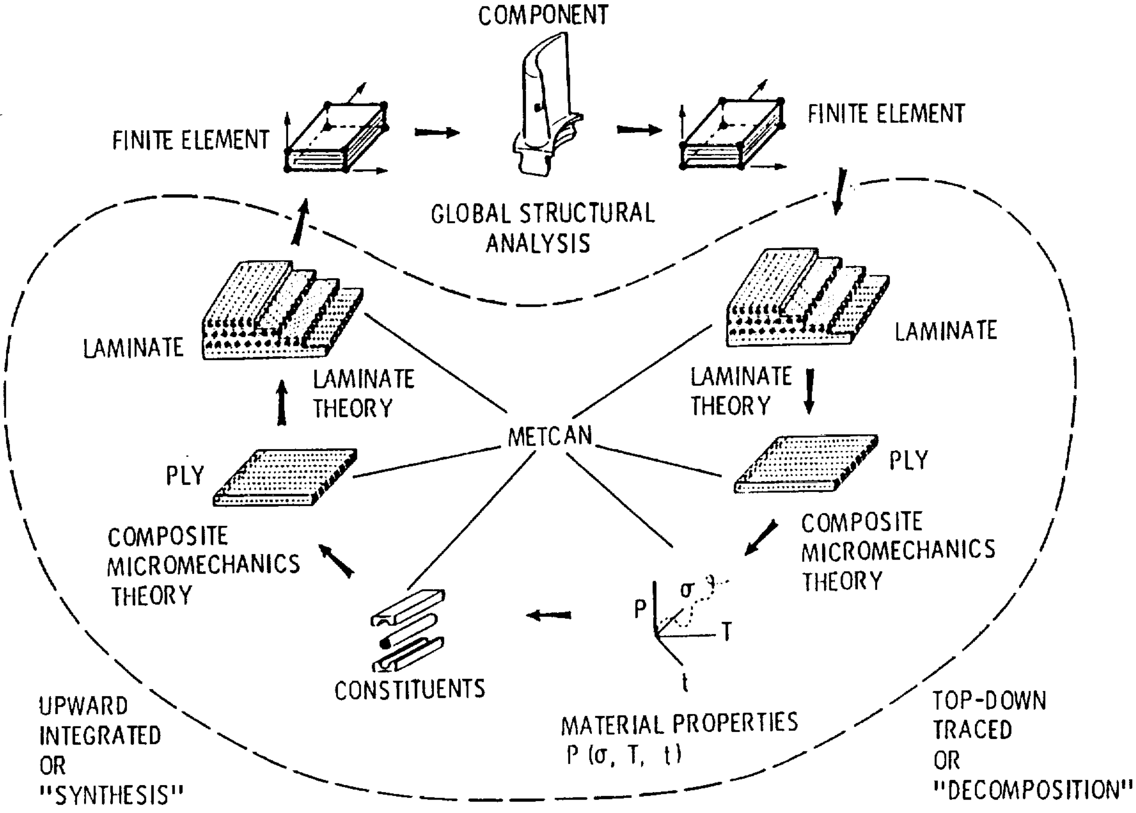

FIGURE 2. - HIGH TEMPERATURE COMPOSITE BEHAVIOR COMPUTATIONALLY SIMULATED.

The second approach, the METCAN computer code (Fig. 2), is used to determine the nonlinear average composite response of unidirectional and laminate composite systems (10). The code's computational simulation begins with the cool down of the consolidation process and includes any thermal and/or mechanical processes which occur after consolidation. The changes in constituent materials resulting from environmental variations are taken into account. In this study a unidirectional MMC system is evaluated to determine the fiber, matrix, and CL stress. These stresses are used to determine whether the composite system will survive fabrication and, if so, the thermal cycles to failure of the system. METCAN also computes composite properties in an attempt to determine the effect of a CL on them.

TABLE 1 ROOM TEMPERATURE CONSTITUTIVE
MATERIAL PROPERTIES

		SiC Fiber	Ti_3Al+Nb Matrix	Ti-15-3 Matrix
E	psi	62.0×10^6	11.0×10^6	14.5×10^6
G	psi	23.8×10^6	4.23×10^6	5.50×10^6
ν		0.300	0.300	0.320
α	in./in. °F	2.70×10^{-6}	6.50×10^{-6}	4.72×10^{-6}
S_{oxxt}	ksi		65.0	130.0

RESULTS AND DISCUSSION

Finite Element Method The first phase of this study is to find, using the FEM, the longitudinal stresses in the SiC/Ti_3l+Nb (Table 1) for selected CL's. The first selected CL (2) has a CTE of 4.67 ppm/°F and a modulus that varies from 1.1 to 22 Msi. Figures 3(a) and (b) shows that the CL stress is lower than the matrix stress throughout the range of CL modulus. In Fig. 3, the stress is normalized per degree Fahrenheit. (Table 2 summarizes the figures for the readers' benefit). The fiber is in compression for the composite system in a fabrication cool down through the range. The longitudinal stress in the matrix is low on the surface (Figs. 4(a) and (b)) and increases as the X/D ratio increases, where X is the distance from the free surface of the composite and D is the fiber diameter. As X/D increases, the matrix stress does not decrease until the compliant layer modulus has decreased to 40 percent of the matrix modulus. In all cases the matrix stress does not significantly decrease until the CL modulus is 15 percent of the matrix modulus. For the Ti_3Al+Nb system the CL modulus would be 1.7 Msi.

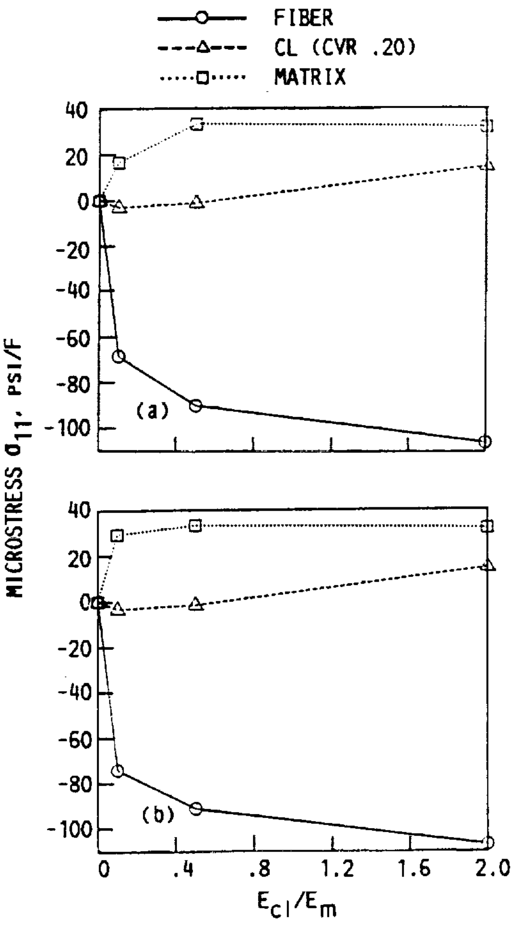

FIGURE 3. - ROOM TEMPERATURE LONGITUDINAL CONSTITUENT MICROSTRESS ($\sigma_{\ell 11}$) FOR A 20 PERCENT FVR SC26/Ti_3-Al + Nb AT L/D = 2.21.

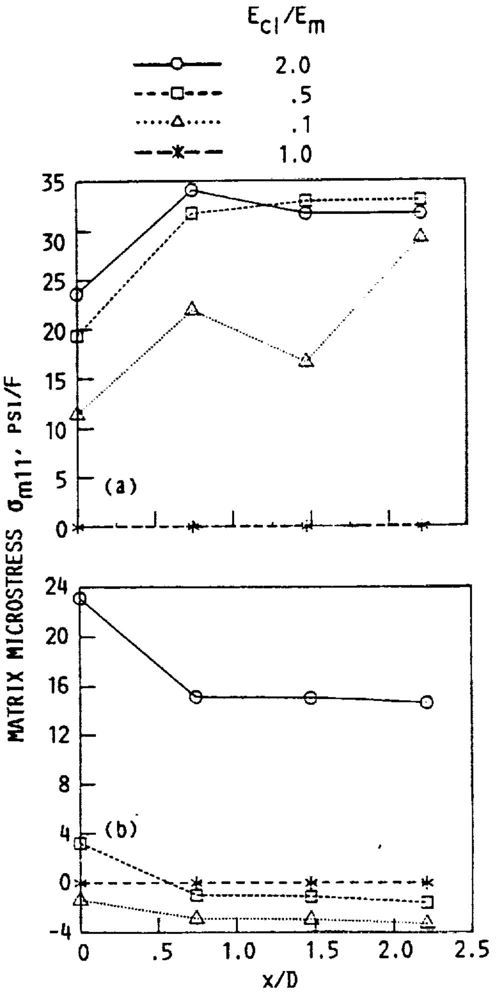

FIGURE 4. - RT LONGITUDINAL CONSTITUENT MICROSTRESS ($\sigma_{\ell 11}$) FOR 20 PERCENT FVR, 20 PERCENT CVR SCS-6/Ti_3-Al + Nb.

The second specific CL has a higher CTE of 7.5 ppm/°F but the same range for the modulus (1.1 to 22 Msi). Figure 5 shows the longitudinal stress in the constituents of the SiC/Ti_3Al+Nb composite system. At a high CL modulus, the CL stress is much larger than the matrix stress. As the CL modulus decreases, the compliant layer stress decreases. The matrix stress

TABLE 2 TEST MATRIX

[Stresses are due to thermal loading (excluding Fig. 9).]

Figure	FVR	Composite system	CVR	Compliant layer	Test
3(a)	0.20	SCS6/Ti$_3$Al	0.20	Ti$_3$Al w/ var. Ecl	Longitudinal constituent microstress CL CTE = 4.67 ppm, X/D = 1.47
3(b)	↓	↓	↓	↓	Longitudinal constituent microstress CL CTE = 4.67 ppm, X/D = 2.21
4(a)	↓	↓	↓	↓	Longitudinal matrix microstress as X/D increases
4(b)	↓	↓	↓	↓	Longitudinal CL mictrostress as X/D increases
5	↓	↓	↓	↓	Longitudinal constituent microstress CL CTE = 7.55 ppm, X/D = 2.21
6	.46	SCS6/Ti15	.01 .16	Ti15 w/ var. Ecl	Longitudinal constituent microstress var. CL CTE X/D = 2.94
7	.20	SCS6/Ti$_3$Al	0 .20 ↓	---- Gd Nb Zr Test	Maximum constituent hoop microstress due to CL type
8	↓	↓	Repeat CL from Fig. 7		Maximum longitudinal constituent microstress due to CL type
9	↓	↓	0.20 ↓	Gd Nb Zr Test	Change in composite modulus due to CL type
10	↓	↓	.03 0 .05,.1,.2	Carbon ---- Gd	Thermal cycles to failure as CTE mismatch increases

remains constant throughout this range of the CL moduli. The longitudinal matrix stress does not vary with the two CL CTEs shown in Figs. 3 and 5.

Constituent longitudinal stresses are predicted from the FEM for a composite system that contains several CLs for which the CTE varies inversely with the modulus. For example, when the CL modulus is halved, the CTE is doubled. As the CTE decreases and the modulus increases, the CL stress grows until it is significantly larger than the matrix stress (Fig. 6). The CL, even with a high CTE, does not significantly reduce the matrix stress until the modulus is 15 percent that of the matrix. Unfortunately, the CL stress is very high at this point. Since the CL stress is large the CL strength must also be high. A good rule of thumb for the SiC/Ti-15-3 composite system is to have the CL strength twice the matrix strength. Finding a CL that meets this is obviously not very practical since it may be impossible to find a material with a low modulus and high strength.

Next, the effect of select CL materials on the SiC/Ti$_3$Al+Nb system is examined. Four of the many CL materials evaluated by Ghosn and Lerch (2) were

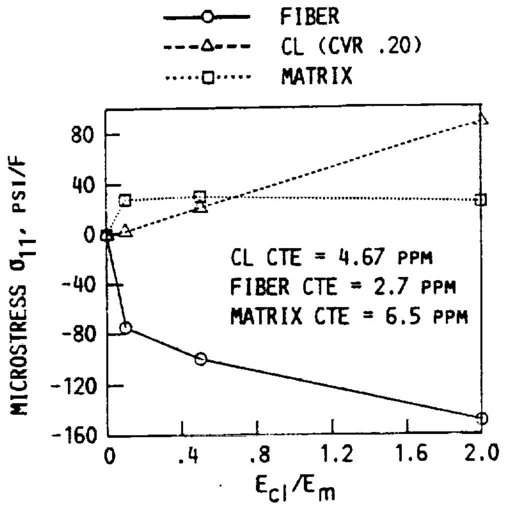

FIGURE 5. - ROOM TEMPERATURE LONGITUDINAL CONSTITUENT MICRO STRESS ($\sigma_{\ell 11}$) FOR A 20 PERCENT FVR SCS6/Ti$_3$-Al + Nb AT L/D = 2.21.

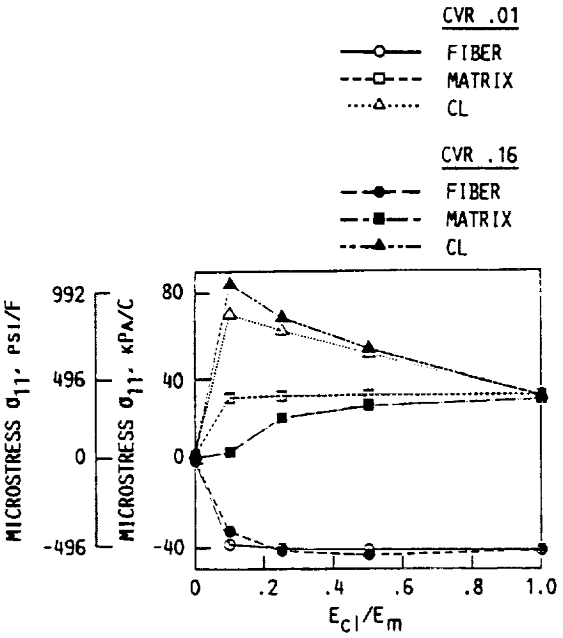

FIGURE 6. - ROOM TEMPERATURE CONSTITUENT MICROSTRESS $\sigma_{\ell 11}$ WITH VARYING CL CTE FOR 46 PERCENT FVR SCS6/Ti-15-3 AT L/D = 2.94.

chosen for this study (Table 3). Three of the CLs are actual materials, Gd (gadolinium), Nb (niobium), and Zr (zirconium). One is a fictitious material designed to find optimum CL properties (called the test case in the present study). This test case has a CTE of 4.67 ppm/°F and a modulus varying form 1.1 to 2 Msi. The composite systems containing CLs are compared to a reference case of SCS 6/Ti$_3$Al+Nb having no CL, both at a fiber volume ratio (FVR) of 20 percent. In this study the FVR is the fiber volume ratio of the fiber without the CL.

The FEM is used to predict the hoop microstress SiC/Ti$_3$Al+Nb system. For most CLs the matrix hoop stress is less (about 20 percent) than the matrix stress of the reference case with no CL (Fig. 7). A CL of Zr, however, increased the stress in the matrix slightly; while the CL stress went into compression. The CL stresses are significant for the fabrication cool down and, because of this, the CL strength may need to be close to that of the matrix or larger.

The longitudinal microstresses in the SiC/Ti$_3$Al+Nb system are determined from the FEM and plotted per degree Farenheit. The results show that the CLs examined increase (about 11 percent) the longitudinal matrix stress from the reference case with no CL (Fig. 8). This increase in longitudinal matrix stress may induce matrix cracking during fabrication and thermal cycling. The increase in matrix stress may also reduce fatigue life, provided the composite system survives fabrication.

TABLE 3 ROOM TEMPERATURE COMPLIANT
LAYER MATERIAL PROPERTIES

		Gd	Zr	Nb
E	psi	8.30×10^6	13.6×10^6	14.9×10^6
G	psi	3.30×10^6	5.10×10^6	5.31×10^6
ν		0.260	0.332	0.402
α	in./in. °F	5.60×10^{-6}	2.90×10^{-6}	4.40×10^{-6}

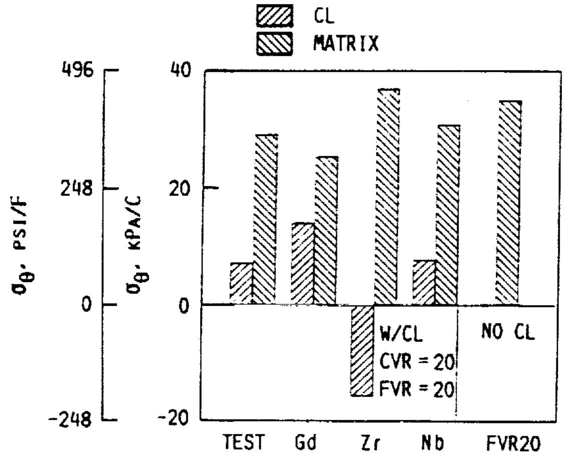

FIGURE 7. - MAXIMUM CONSTITUENT HOOP MICROSTRESS (σ_θ) DUE TO CL TYPE FOR SCS6/ Ti_3-Al + Nb.

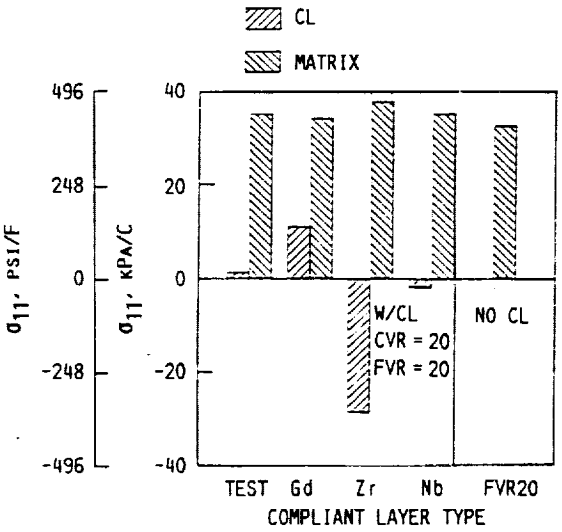

FIGURE 8. - MAXIMUM LONGITUDINAL CONSTITUENT MICROSTRESS ($\sigma_{\ell 11}$) DUE TO CL TYPE FOR SCS6/ Ti_3-Al + Nb.

The composite modulus may be affected by the use of CLs. The five systems from the FEM study have a very small decrease in the longitudinal modulus. Hence, the composite modulus variation is small (±4 percent) (Fig. 9). The two compliant layers that performed the best in this study (Gd, Test) have a slightly lower modulus than the reference. The change in composite modulus could be significant when using the recommended CL with a modulus 15 percent that of the matrix.

METCAN

The thermal cycling resistance is critical because of the large temperature envelopes in which MMC systems operate. The multifactor interaction relationship (MFI) is used to calculate the thermal cycles to failure. The MFI is shown for the SiC/Ti_3Al+Nb composite system. The exponents are determined from monolithic matrix experimental data. The matrix material is fabricated as a composite system is fabricated.

$$\frac{S}{S_f} = \left[\frac{T_m - T_u}{T_m - T_o}\right]^{0.55} \left[\frac{S_o - \sigma_p}{S_o}\right]^{0.66} \left[\frac{S_o - \sigma_c}{S_o}\right]^{0.33} \left[1 - \frac{N}{N_f}\right]^{0.5} .$$

Where S/S_f is the remaining ultimate tensile strength of the composite after thermal cycling over the original ultimate strength of the composite, T_m is the melting temperature (2730 °F), T_u is the maximum temperature of the thermal cycle (1200 °F), T_o is the reference temperature (70 °F), S_o is the room temperature reference ultimate tensile strength of the matrix (65 ksi), σ_p is the longitudinal residual matrix stress at the end of cycling, σ_c is the longitudinal residual matrix stress at the end of consolidation, N is the number of cycles at which there is 10 percent remaining strength, and N_f is the number of cycles to failure. This equation is evaluated for the number of cycles to failure with a 10 percent remaining strength S/S_f.

METCAN is used to investigate the thermal cycles to failure of FVR 20 SiC/Ti$_A$l+Nb and variations of this system. In four of the composites the protective carbon coating is removed from the fiber, three fibers have the coating replaced with a CL of Gd of different thicknesses and one without a coating or CL. The fiber without a coating was assumed to have the same strength as one with a coating (i.e., SCS 6). One additional composite system is analyzed with the coating. As the CTE mismatch between the fiber and the matrix grows, the composite system became less tolerant of the cycling (Fig. 10). The worst case is the composite system that contains the fiber with the coating. The CL slightly delayed the failure as the CTE mismatch increased.

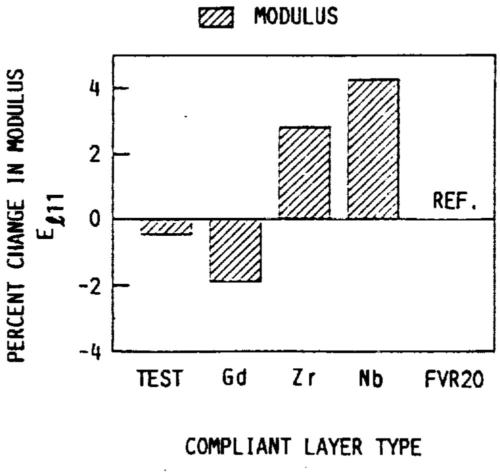

FIGURE 9. - CHANGE IN COMPOSITE MODULUS FOR VARIOUS COMPLIANT LAYER MATERIALS FOR SCS-6/ Ti$_3$-Al + Nb.

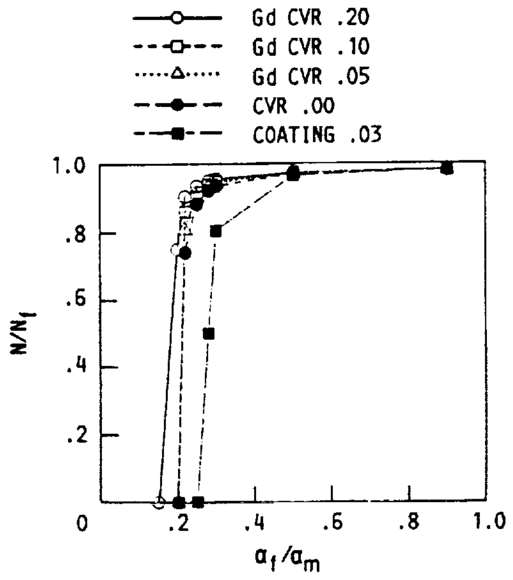

FIGURE 10. - EFFECT OF CTE MISMATCH ON THERMAL CYCLES TO FAILURE OF 20 PERCENT FVR SiC/Ti$_3$-Al + Nb WITH DIFFERENT COATINGS.

CONCLUSION

The compliant layers studied appear to be ineffective in reducing the longitudinal stress in the Ti_3Al+Nb composite system except with very low CL moduli (on the order of 15 percent of the matrix modulus). The reduction in hoop stress may eliminate the cracking in the hoop direction. It does not significantly increase the thermal cycles to failure of the system. The fiber stress is in compression and is currently not considered the weak link in this type of failure.

The best performing compliant layer has a low modulus (around 15 percent of the matrix) and a CTE lower than the matrix but higher than the fiber. High CTE CLs cause high stresses in the CL which require high CL strengths. Low modulus and high strength are not compatible properties for a material to have. The reduction in matrix stresses due to high CTE are not realized until the CL modulus is 15 percent that of the matrix modulus.

The compliant layer generally reduces the modulus of the composite but not by an appreciable amount. If a low modulus compliant layer (15 percent of the matrix) were used, the reduction could be much greater.

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