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FATIGUE DAMAGE GROWTH MECHANISMS IN CONTINUOUS FIBER REINFORCED TITANIUM MATRIX COMPOSITES

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The role of fiber/matrix interface strength, residual thermal stresses, and fiber and matrix properties on fatigue damage accumulation in continuous fiber metal matrix composites (MMC) will be discussed. Results from titanium matrix/silicon-carbide fiber composites will be the primary topic of discussion. Results have been obtained from both notched and unnotched specimens at room and elevated temperatures. The stress in the 0^{o} fibers has been indentified as the controlling factor in fatigue life. Fatigue of the notched specimens indicated that cracks can grow many fiber spacings in the matrix materials without breaking fibers.

INTRODUCTION

Titanium metal matrix composites are currently being considered as structural materials for high temperature applications where weight saving is a premium. Some potential applications of these materials are the National Aerospace Plane (hypersonic flight vehicle), advanced aircraft engines, missiles, supersonic transports, and the Advanced Tactical Fighter. All of these applications expose the material to repeated mechanical loadings and thermal cycles. Due to the coefficient of thermal expansion mismatch between the fiber and matrix materials, stresses are induced in the composite constituents as a function of temperature change. This, coupled with different strengths and failure modes in the fiber, matrix and fiber/matrix interface, contributes to a very complex problem in predicting and tracking damage progression in a laminated composite. Johnson (1) has summarized the damage initiation and progression process for a number of different metal

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matrix composites. This paper will show examples of fatigue damage and some of the controlling parameters. In particular the fatigue behavior of several laminates at room temperature in the notched and unnotched conditions will be discussed. The influence of the fiber/matrix interface strength and the thermal residual stresses on the fatigue damage propagation mode will be illustrated. Fatigue behavior at 650°C will be compared with room temperature behavior. This paper, for the most part, is a summary of previous research by the authors on titanium MMC.

MATERIALS AND TESTING TECHNIQUES

Ti-15-3, a shortened designation for Ti-15V-3Cr-3Al-3Sn, is a metastable beta strip alloy used where cold formability and high strength are desired (2). Ti-15-3 is currently under evaluation as a matrix material for high temperature metal matrix composites because it can be cold formed into relatively economical thin sheets while retaining good mechanical properties (2). The composite laminates were made by hot-pressing Ti-15-3 foils between unidirectional tapes of silicon carbide fibers. These fibers are designated SCS-6 by Textron Specialty Materials, the producer. The fiber diameter is 0.14 mm. A panel was made of each of the following lay-ups: $[0]_8$, $[0_2/\pm45]_s$, $[0/90]_{2s}$, $[0/90/0]$ and $[0/\pm45/90]_s$. The fiber volume fraction was approximately 0.325 for each laminate except for the [0/90/0] laminate where it was 0.38.

The tests were conducted on an 89 kN servo-hydraulic test stand. Load control was used with a loading rate of approximately 0.89 kN/second for the quasi-static tests and a cyclic frequency of 10 Hz for the fatigue tests. For room temperature tests, an extensometer with a 25.4-mm gage length was attached to the edge of the specimens to record strain. For the elevated temperature tests, a water cooled, quartz rod extensometer with a 25.4-mm gage length was used.

FIBER/MATRIX SEPARATION

Static loading of SCS-6/Ti-15-3 laminates containing off-axis plies resulted in a knee in the stress-strain curve well below the stress level anticipated for the onset of matrix plasticity (3). Figure 1 shows the stress-strain response of a $[90]_8$ laminate. The knee in the first cycle occurred at approximately 155 MPa, well below the matrix material's minimum proportional limit of 690 MPa. The unloading elastic modulus was also less than the initial elastic modulus, thus, indicating that some sort of damage had occurred in the laminate. After the first cycle, the unloading curve closely followed the loading curve, indicating an opening and closing phenomenon as shown in Figure 1 for the 11th loading cycle. This was due to failure of the fiber/matrix interface in the off-axis plies. This was determined using the edge replica technique (1,3). Reference (3) by Johnson, Lubowinski and Highsmith discusses in detail the fiber/matrix interface separation that occurred in these composites.

Johnson et al (3) suggested that thermal residual stresses were responsible for the observed opening and closing behavior of the fiber/matrix interface. These laminates are consolidated at high temperatures, where the matrix and fiber are essentially stress free. However, as the composite cools, internal stresses are developed in the constituents due to the differences in the coefficient of thermal expansion of the fiber and the matrix. A simple cylindrical fiber model was used to estimate these stresses. For the silicon carbide/titanium system, coefficients of thermal expansion of 4.86×10^{-6} cm/cm/^{o}C and 9.72×10^{-6} cm/cm/^{o}C (2) were used for the fiber and matrix, respectively. It was assumed that any stresses that might develop during the fabrication process at absolute temperatures greater than one half of the melting point of the matrix would be relieved due to stress relaxation (4). Therefore, a temperature change of 555^{o}C was used. For the as-fabricated unidirectional lamina the analysis predicted the following stresses in the matrix material near the fiber/matrix interface: radial stress, -138 MPa; tangential stress, 276 MPa; and axial stress (fiber direction), 207 MPa. These compressive radial and tensile tangential (hoop) stresses cause the matrix to close on the fiber upon unloading. Even if the fiber/matrix interface has failed, these residual stresses must be overcome before the fiber and matrix will separate.

FATIGUE OF UNNOTCHED SPECIMENS

Fatigue at Room Temperature

S-N data was experimentally determined at room temperature (RT) for four different lay-ups containing 0^{o} plies as shown in Fig. 2 (3). The stress-strain response was monitored during the fatigue life. Laminates containing off-axis plies lost stiffness very early in the cycling history due to the fiber/matrix interface separations. After a few cycles, the stiffness stabilized and the cyclic strain range was recorded. This stabilized strain range was multiplied by the fiber modulus (400 GPa) to determine the cyclic stress range in the fiber. A plot of the 0^{o} fiber cyclic stress against life for the different laminates is shown in Figure 3. The fatigue data from the four different laminates was correlated very well by the 0^{o} fiber stress. Since the laminate will not fail until the 0^{o} fiber fails, it is reasonable to assume that the stress in the 0^{o} fiber will dictate fatigue life. The measured stabilized strain range is also plotted against the number of cycles to failure in Fig. 3. It is important to note that the fiber failures were not necessarily the first damage to occur in these composites The first damage that caused significant modulus changes was the failure of the fiber/matrix interface in the off-axis plies.

Similar stiffness losses and loading-unloading responses were found for boron/aluminum and silicon-carbide/aluminum composites (1). However, for these systems, it took thousands of cycles to develop an equivalent stiffness loss to that occurring in just a few cycles for the SCS-6/Ti-15-3 system. Figure 4 presents a plot of the elastic unloading modulus (E_{ul}) divided by the initial elastic modulus (E_I) versus the number of applied cycles for $[0/90]_{2s}$ laminates of boron/aluminum (B/Al) and the SCS-6/Ti-15-3 (1). The elastic unloading modulus is a good indicator of the amount of damage in a composite. The elastic unloading modulus would be equal to the initial elastic modulus if the composite was undamaged. Both laminates were loaded such that the ratio stress range/ultimate strength was approximately the same. In the case of the B/Al laminate, damage initiated in the matrix material of the 90^{o} plies and grew as a fatigue crack. Therefore, the B/Al stiffness did not drop during the number of cycles required for fatigue crack initiation. Once fatigue cracks were initiated the modulus slowly dropped with an increasing number of cycles until at 2 million cycles the unloading modulus had dropped by almost 20 percent. This is in sharp contrast to the SCS-6/Ti-15-3 composite for which the modulus dropped more than 20 percent in the first few cycles due to the fiber/matrix interface failure in the 90^{o} plies. The modulus then remained almost constant until just before failure at 10,000 cycles. This illustrates how the damage process can affect laminate stiffness.

Fatigue at High Temperature

Unnotched fatigue tests were conducted at $650^{o}C$ on the SCS-6/Ti-15-3 laminates discussed above. Once again the cyclic strain range stabilized after a few cycles. The cyclic stress range in the 0^{o} fibers versus number of cycles to failure is plotted with the room temperature data in Figure 5. The elevated temperature data is more scattered than the room temperature data but all the data fall within a reasonable band.

The data correlation for both room and high temperature data indicates that it is the stress in the 0^o fibers, and not the matrix, that controls the fatigue life. In fact, for a given strain range the stress state in the matrix material is completely different for each of the laminates tested. Indeed, the matrix stress state is different in each lamina orientation. Further, the matrix properties at 650^oC are significantly different from those at room temperature, thus, the stresses in the matrix material would be significantly different at the two temperatures for the same laminate strain range. While the first fatigue damage may be at the fiber/matrix interface or in the matrix material, it is clear that laminate failure is controlled by the stress in the 0^o fiber. However, the interfacial and matrix damage may well contribute to increasing the stresses in the 0^o fibers.

Effect of Interface Strength and Residual Stresses on Fatigue

Naik, Johnson, and Pollock (5) investigated the effect of a high temperature conditioning cycle on the mechanical properties of a [0/90/0] lay-up of SCS-6/Ti-15-3. Essentially the high temperature cycle (SPF/DB) increased the strength and stiffness of the matrix material, had little or no effect on the fiber properties, but significantly reduced the static and fatigue strength of the laminate as shown in Figure 6. Studies of the fracture surfaces in Figure 6 showed a change in the failure mode. In the as-fabricated (ASF) specimen the fiber/matrix interface was weaker and the thermal residual streses were lower than in the SPF/DB specimen, thus the damage tended to grow around the fibers, debonding along the fiber/matrix interface. This produced a tortuous crack path in the matrix and extensive fiber pull-out. In the SPF/DB specimen the residual stresses were sufficiently high and the fiber matrix interface strong enough to cause the matrix cracks to grow directly through the fiber causing a very planar failure surface with little or no fiber pull-out. This latter failure mode resulted in a greater stress concentration in the fiber ahead of the crack, thus, explaining the reduction in strength of the SPF/DB specimen.

These results (5) indicate that for a high strength matrix material, such as titanium, one can make the fiber/matrix interface too strong, thus, sacrificing laminate strength by changing the mode of failure. On the other hand if the interface is too weak, the required load transfer between fiber and matrix necessary for optimum moduli and shear properties will not be available.

FATIGUE OF NOTCHED SPECIMENS

Understanding the fatigue behavior around local stress concentrations can be complex. The initiation process may be very different from the damage growth process. Depending on the design philosophy adopted, one process may be more important than the other, however both damage initiation and growth should be understood.

Fatigue Crack Initiation

Naik and Johnson (6) recently reported fatigue test results from several laminates containing either double edge notches or center holes. The data shown in Figure 3 was used with a stress analysis to predict the remotely applied stress level required to initiate fatigue damage at a notch tip (6). The stress level for fatigue initiation was successfully predicted for a double edge notched $[0]_8$ laminate and for a $[0/90]_{2s}$ laminate containing a circular hole. This approach was also successfully used to approximate the number of cycles required to initiate fatigue damage for applied stress levels above the fatigue limit.

Fatigue Crack Growth

Fatigue cracks were observed in the $[0]_8$, $[0/90]_{2s}$, and [0/90/0] laminates at cyclic stress levels above those required for crack initiation but well below the laminates' net section static strength. In each case the specimens were periodically radiographed during the tests to monitor fiber breaks. After the tests (but prior to specimen failure), the specimens surfaces were either polished or acid etched to reveal the matrix cracks and the fibers in the surface lamina. Multiple matrix cracks initiated and grew from the notches. Harmon and Saff (7) reported similar results. Figure 7 shows a matrix crack growing from the edge of a hole in a $[0/90]_{2s}$ specimen. The polished surface clearly shows that the matrix crack grew around and past the fibers. Also notice that next to the hole there is a long debond between the fiber next to the hole and the matrix on the side toward the hole. This type of debonding can significantly reduce the stress concentration at the edge of the notch. One can nominally predict the stress level at which the fibers next to the notch should fail, based on the applied loading and calculated stress concentration for the undamaged state. However, because of the type of initial damage shown in Figure 7 the stress concentration may be reduced to a level such that only the matrix would fail and not the fibers.

SUMMARY

This paper summarizes notched and unnotched fatigue data of composite laminates made of titanium matrix with silicon-carbide fibers (SCS-6/Ti-15-3). In the unnotched laminates damage starts as fiber/matrix interface failures in the off-axis plies. This results in a stiffness loss early in the fatigue life. The fatigue life of the unnotched laminate was shown to be a function of the stress in the 0^{o} fibers both at room and elevated temperatures. The strength of the interface and the magnitude of the thermal residual stresses can play a significant role in the laminate failure process. The higher interface strength and residual stresses can reduce the laminate's static and fatigue strength.

Fatigue damage initiation at notches were predicted using unnotched data with an appropriate stress analysis. Matrix fatigue cracks can grow for long distances in the laminate without breaking the 0^{o} fibers in the crack path. Matrix cracking and fiber/matrix interface debonding early in the fatigue life result in a significant reduction in the stress concentration at a notch tip. Therefore, material scientists must work with mechanicians in an interdisciplinary program to pursue the optimum interfacial strength to achieve the desired laminate properties, realizing a trade-off will be necessary.

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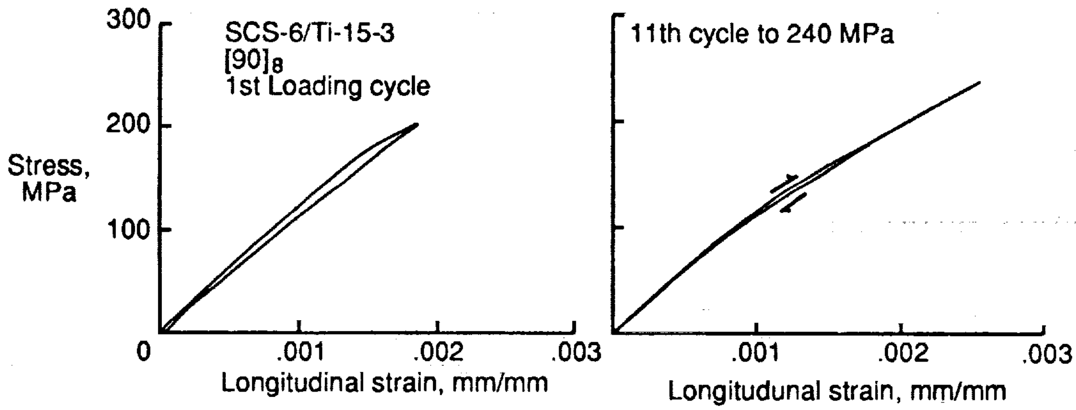

Figure 1. Stress-strain response showing nonlinearity due to fiber/matrix separation (3).

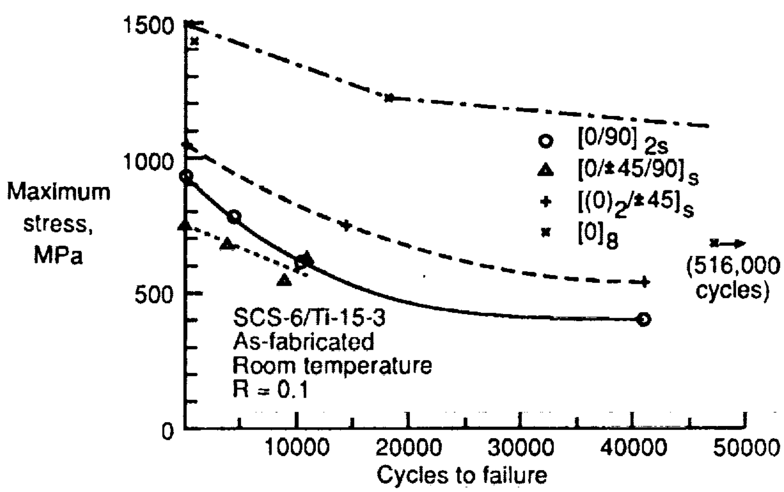

Figure 2. S-N curves for SCS-6/Ti-15-3 laminates containing 0° plies (3).

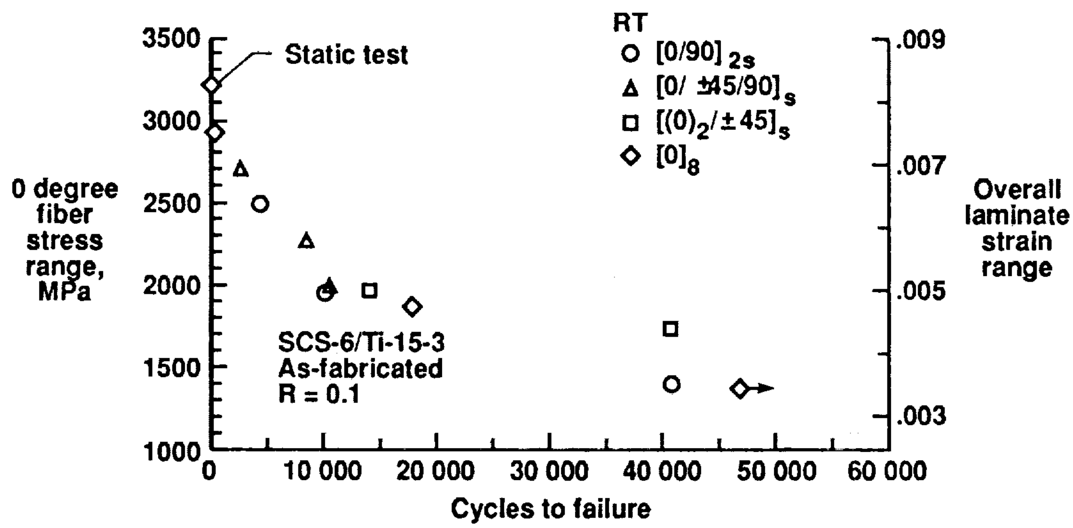

Figure 3. Cyclic stress range in 0° fiber versus number of cycles to laminate failure (3).

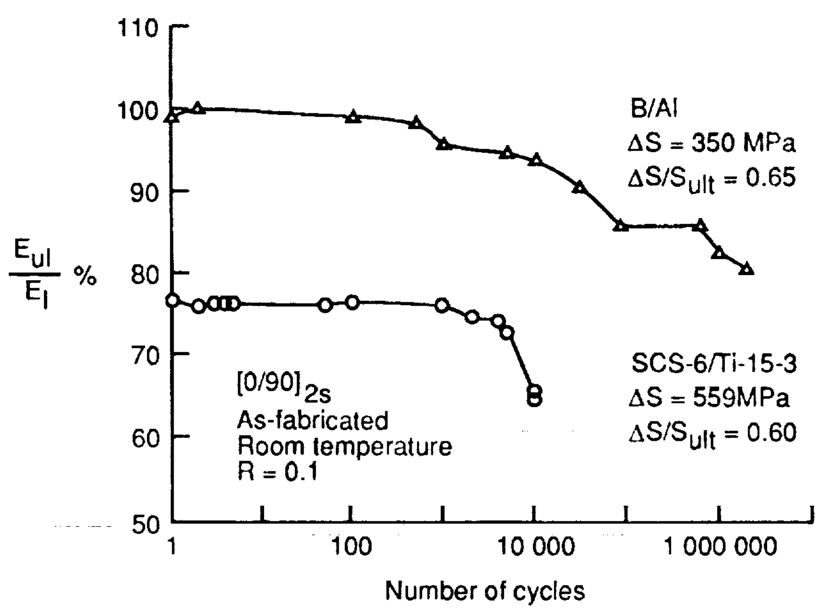

Figure 4. Change in the elastic unloading modulus for $[0/90]_{2s}$ layups of B/Al and SCS-6/Ti-15-3 (1).

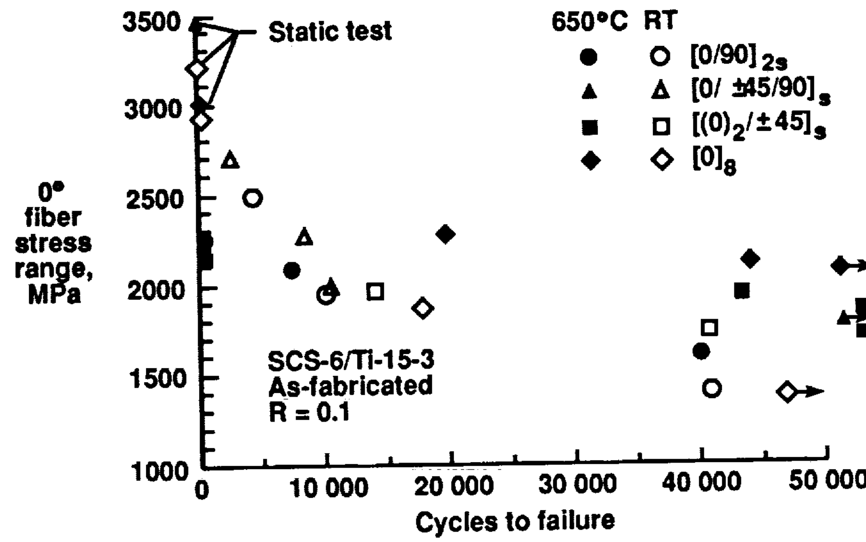

Figure 5. Fiber stress versus number of cycles to failure at 650°C and RT.

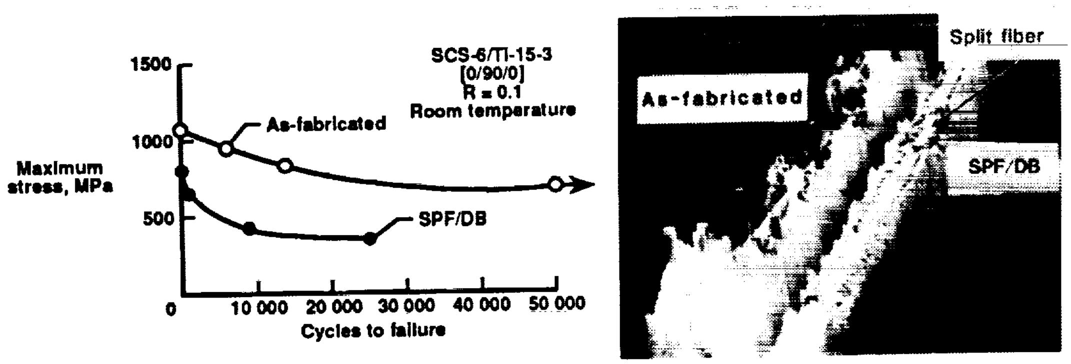

Figure 6. S-N curve for the laminates and their failure surface (5).

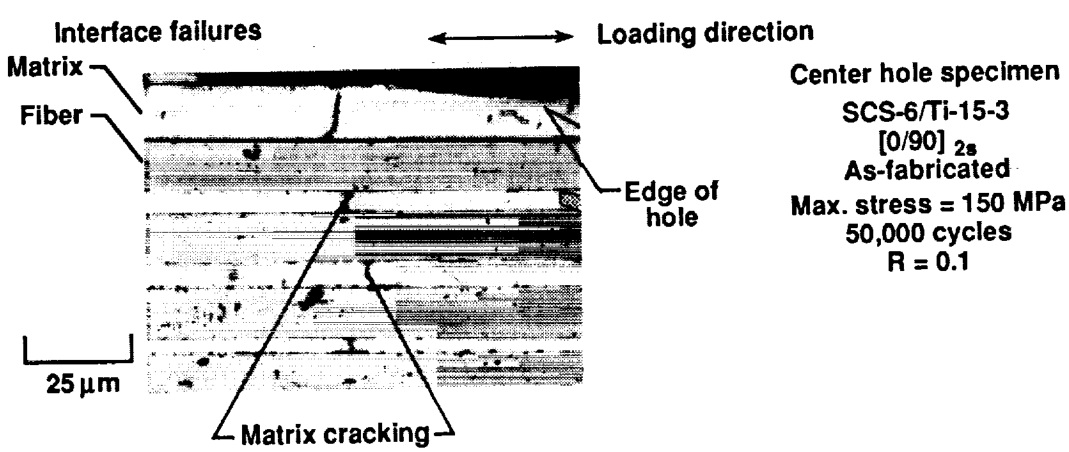

Figure 7. Matrix crack growing past fibers (6).

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16. Abstract

The role of fiber/matrix interface strength, residual thermal stresses, and fiber and matrix properties on fatigue damage accumulation in continuous fiber metal matrix composites (MMC) will be discussed. Results from titanium matrix/silicon-carbide fiber composites will be the primary topic of discussion. Results have been obtained from both notched and unnotched specimens at room and elevated temperatures. The stress in the 0° fibers has been identified as the controlling factor in fatigue life. Fatigue of the notched specimens indicated that cracks can grow in the matrix materials without breaking fibers.

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