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CHARACTERIZATION OF DAMAGE PROGRESSION AND ITS CORRELATION TO RESIDUAL STRENGTH IN A SIGMA/Ti-6242 COMPOSITE USING NONDESTRUCTIVE METHODS

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ABSTRACT

In this study, a novel approach of both global and localized damage assessment in metal matrix composites, by means of nondestructive evaluation and damage mechanics, was used to correlate NDE data and the residual tensile strength of a six ply, unidirectional BP Sigma-1240 SiC/Ti-6Al-2Sn-4Zr-2Mo composite after being isothermally fatigued. Baseline tension and fatigue curves were generated since minimal information on this particular metal matrix composite was available in the literature. Information obtained from these tests was used to pinpoint load levels and interruption points for subsequent interrupted fatigue tests. The following nondestructive evaluation techniques were used to evaluate the test specimens before and after fatigue testing: (1) High Frequency Scanning Acoustic Microscopy; (2) Oblique Incidence Shear Waves; (3) Global 'Reflector Plate' Ultrasonic Scanning; (4) Ultrasonic Surface Waves (10 MHz and less); (5) In Situ Surface and Longitudinal Waves; and (6) X-Ray Radiography. After the inspections were completed, the specimens underwent a tension test to determine the residual strength. Scanning electron microscopy was used throughout this study to examine fracture surfaces to gain a better understanding of the damage mechanisms present during isothermal fatigue loading. In addition to scanning electron microscopy, metallography and other destructive methods were used in the correlation and verification of fatigue damage. The work has demonstrated the need for developing quantitative correlations between nondestructive evaluation results and the material behavior of metal matrix composites.

INTRODUCTION

Continuous fiber metal matrix composites (MMCs) have a multitude of potential applications in situations requiring light weight, high stiffness materials possessing high temperature capability (Gabb, Gayda et al., 1990). Some of the potential applications for these materials are high performance aerospace vehicles, advanced aircraft engines, missiles, advanced supersonic transports, and advanced fighter aircraft (Johnson, 1991). Since all of these applications involve cyclic loads that can lead to a decrease in load carrying capability, frequent inspection and monitoring of these materials for detection and sizing of flaws or other types of damage are necessary to insure structural integrity (Nayfeh, et al., 1984; Larson, et al., 1993).

In the past, information regarding the damage mechanisms occurring in a material was obtained by observing the macroscopic mechanical response of material specimens subjected to forces (static or cyclic), temperatures (static or cyclic), and environments (oxidizing gas, turbine engine exhaust, etc.) representative of the target application. Typical mechanical responses monitored include changes in stiffness, elongation, and residual tensile strength. In addition to the mechanical response, metallographic examination of the material as well as microscopic inspection or photography of the specimen surface were used to reveal oxidation, cracking, or other accumulated damage. These traditional methods proved useful for understanding propagation of self-similar cracks in both aerospace and automotive structures (monolithic). In addition, information gained from inspections can be used to determine how often a component needs to be inspected to detect growing cracks before they reach a critical size and cause failure of the structure as a whole (Karpur, et al., 1993).

Unfortunately, many of the traditional inspection techniques provide somewhat limited information when applied to metal matrix composites because of the inhomogeneous, anisotropic nature of composites. Damage in the new advanced materials evolves in more subtle forms than a dominant crack that can be quantified primarily through measurements made on the surface of the material. In some tests, a dominant crack is observed on the surface of the composite, but distributed damage can also strongly influence the life of the composite (Johnson, 1989; Chan and Davidson, 1990; Castelli, et al., 1992; Jira and Larsen, 1993; Neu, 1993; Neu and Roman, 1993; Russ, et al., 1995). A crack can be bridged either by fibers or ductile material which at elevated temperatures can be degraded by environmental attack (Kortyna and Ashbaugh, 1991; Nicholas and Russ, 1992). In addition, fibers fail within the material, microcracks form in the matrix (John and Ashbaugh, 1992; Butkus, et al., 1993), and matrix/fiber

debonding occurs. Since these forms of damage are not readily observable or measurable, obtaining information on these typical forms of damage from bulk averaged measurements and other commonly used techniques for established materials is extremely difficult.

Existing nondestructive evaluation techniques need to be evaluated, and new experimental capabilities need to be developed to inspect metal matrix composites and to provide quantitative data because quantitative data is essential for developing methodologies in life prediction studies (Johnson, 1991; John, et al., 1993; Neu, 1993). A review of the literature revealed only a few studies that quantitatively assessed the residual strength of metal matrix composites after expending a certain percentage of the proposed fatigue life (Reifsnider and Stinchcomb, 1986; Castelli, 1994). Therefore, the main objectives of this research effort were to evaluate various NDE methods to study the evolution of isothermal fatigue damage and to correlate this information with the residual strength of the composite. Such correlations between damage, as it evolves under simulated service conditions, and the characterization results from NDE techniques are necessary to produce successful life prediction methodologies.

Several nondestructive evaluation methods have been used in this study to evaluate the integrity of a material without compromising its mechanical properties. The NDE techniques used in this study are: (1) Scanning Acoustic Microscopy; (2) Oblique Incidence Shear Waves; (3) Global 'Reflector Plate' Ultrasonic Scanning; (4) Ultrasonic Surface Waves (10 MHz and less); (5) In Situ Surface and Longitudinal Waves; and (6) X-Ray Radiography.

MATERIALS AND EQUIPMENT

The material system evaluated during this study consists of unidirectional BP Sigma SM-1240 silicon carbide fibers in a Ti-6Al-2Sn-4Zr-2Mo matrix. The six-ply composite was manufactured by Howmet and was determined to have a fiber volume percentage of 24.5 ± 0.2%. Sigma SM1240 is a C/TiB_2 coated SiC fiber produced by BP Metal Composites Ltd. The SiC is chemical vapor deposited onto a tungsten filament substrate. The fiber has a nominal diameter of 100 microns (0.004 inch), and the duplex protective coating is approximately two microns thick. Due to the poor thermal shock resistance of the outer TiB_2 coating, which causes fiber degradation during composite manufacture, Howmet developed a protective coating for the fiber to reduce this problem. The matrix material, Ti-6Al-2Sn-4Zr-2Mo, is described as a near-α $\alpha + \beta$ alloy that has good mechanical heat resistance (Collins, 1984). The composite was produced by plasma melting the titanium alloy powder to deposit the matrix material around a fiber array precision wrapped on a mandrel. Monotape lay-ups were subsequently produced by cutting and arranging the fiber-reinforced "monotapes". Multilayered fiber-reinforced composite panels were produced by hot consolidation of monotape lay-ups using hot isostatic pressing. This method reportedly offers the advantage of improved fiber spacing control over conventional methods of TMC (titanium matrix composites) fabrication (Hartman, et al., 1988). Specimens were cut from the consolidated, unidirectional plate by abrasive water jet into dog-bone shaped, test specimens. All specimens were mechanically tested with the load applied in the longitudinal, or fiber, direction.

Isothermal fatigue tests were conducted on a horizontal test frame incorporating a pneumatic ram for load control. The test system was positioned horizontally to improve temperature control and to allow for proper extensometry mounting. A 25 kN load cell was used, and loads were controlled to within 0.1 kN. Specimens were positioned horizontally in precisely- aligned, hydraulically-actuated, rigid grips (Hartman, et al., 1988; Hartman and Russ, 1989; Hartman and Buchanan, 1993). Gripping pressure was approximately 60 MPa. A symmetric, triangular load cycle was generated by a personal computer using control software developed by the University of Dayton (Hartman and Ashbaugh, 1990). Axial strain was acquired throughout the tests with a 12.7 mm gage length, high temperature, MTS extensometer containing quartz extension rods.

For the 500° C fatigue tests, the specimens were heated using radiant energy, quartz lamp, heaters. Two heating units were used, each containing four tungsten filament quartz lamps. One heater was positioned above the top surface of the specimen and the other placed below, and each lamp was paired with another to form four controllable heating zones. A uniform temperature profile (±3°C) was maintained throughout a 25 mm region centered along the length of the specimen. The quartz lamp outputs were controlled by commercial four-zone, digital, temperature controllers. Four type K thermocouples welded to the top and bottom surfaces of the specimen were used for temperature sensing. A more detailed description is provided by Hartman et al. (Hartman, et al., 1988; Hartman and Russ, 1989; Hartman and Buchanan, 1993). This heating system produced a temperature of 500 ± 3°C in the specimen gauge section for the duration of the tests.

PROCEDURES

This section outlines the procedures employed during the NDE and material behavior experiments. Baseline experiments were conducted before the actual fatigue experiments were conducted. NDE was used in all cases.

Baseline Tension and Fatigue Tests

Since the literature contains minimal information on the Sigma/Ti-6242 composite system, baseline tension and fatigue curves were generated. Two tension tests were conducted at room temperature, and another two were tested at 500°C. This temperature was chosen since it represents the upper limit at which Ti-6242 is typically used (Collins, 1984). The tests were run in load control at a rate of 10 MPa/sec. Information obtained from these tests was used in the selection of load levels and interruption points for subsequent fatigue tests.

Baseline isothermal fatigue tests were conducted at room temperature and 500°C as depicted in Figure 1. All tests were tension-tension fatigue, run in load-control with a triangular waveform, a stress ratio of 0.1, and a frequency of 0.01 Hz. Six baseline fatigue tests were conducted at each temperature. The maximum applied stress for each

test was chosen as a percentage of the baseline ultimate tensile strength at that temperature: 60%, 65%, 72%, 80%, and 90% (with one sample at a repeated stress ratio). The stress ratio was chosen to ensure consistency with previous work done on similar titanium matrix composites, and the frequency was selected to ensure a uniform loading profile since pneumatic-actuated fatigue systems are limited in this regard at higher frequencies.

Interrupted Isothermal Fatigue Tests

The maximum applied tensile stress for all interrupted fatigue tests was 65% of the ultimate tensile stress at the corresponding temperature. This stress level was chosen to yield a fatigue life that did not exceed 10 days due to time constraints. The temperatures, frequencies, and stress ratios were consistent with the baseline tests. Baseline curves, changes in modulus, and *in situ* surface wave data were all used in the selection of appropriate interruption points for each specimen. The interruption points relative to fatigue lives of baseline specimens tested at the same stress level are shown in Figure 2. The *in situ* surface wave technique was used to monitor progressive damage throughout the room temperature tests (MacLellan, 1993). Some of the room temperature specimens were interrupted during testing, ultrasonically C-scanned in immersion tanks, and then reinstalled in the fatigue fixture for additional cycling if minimal damage was evident.

An isothermal fatigue test was conducted at room temperature to monitor longitudinal waves traveling the length of the specimen. A horizontal, servo-hydraulic test frame with specially machined grips for placement of the contact transducers at the ends of the specimen was used. This test was tension-tension fatigue, run in load-control with a triangular waveform at a stress ratio of 0.1 and a frequency of 1 Hz. As with the interrupted fatigue tests, the maximum applied tensile stress was 65% of the ultimate tensile strength.

Nondestructive evaluation of the interrupted specimens was performed to characterize damage such as matrix cracking, fiber bridging, or cracked fibers. The following methods were used to evaluate each specimen before and after fatigue testing: High Frequency Scanning Acoustic Microscopy, Oblique Incidence Shear Waves, Reflector Plate Ultrasonic Scanning, Immersion Surface Waves, and X-Ray Radiography.

Following the nondestructive evaluation of the test specimens, tension tests were conducted to determine residual strength. All tests were run in load control at a rate of 10 MPa/sec at room temperature.

Failure Analysis

After testing, scanning electron microscopy, metallography, and other destructive methods were used to characterize fatigue damage. Qualitative and quantitative data obtained from fatigue tests, nondestructive evaluations, and residual tensile tests were correlated with the observations made during destructive analyses.

RESULTS AND DISCUSSION

Reflector Plate Ultrasonic Scanning

Reflector plate C-scans of the specimens obtained before and after fatigue cycling indicated that the method was unsuccessful in identifying fatigue cracks; however, regions of attenuation of the ultrasound oriented perpendicular to the specimen axis were detected in all the specimens at all stages of testing. These indications are possibly associated with the plasma spraying operation. No other anomalies were evident in the reflector plate scans.

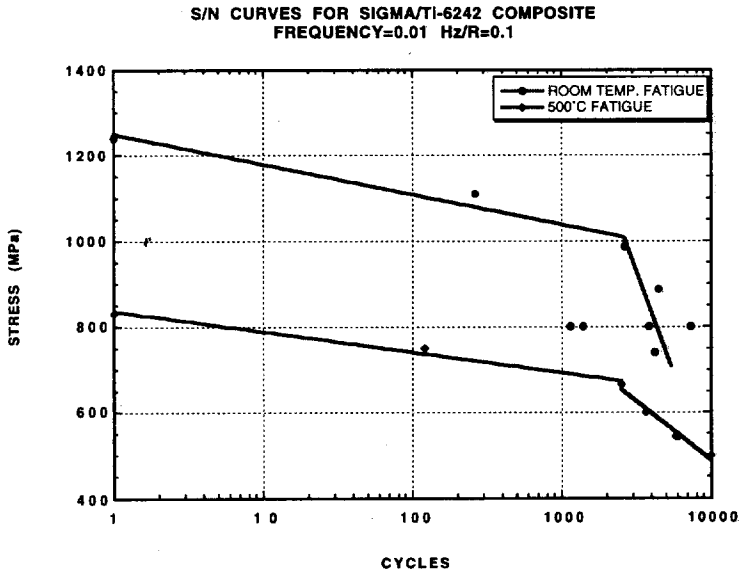

Figure. 1--Baseline isothermal fatigue curves for Sigma/Ti-6242 composite at room temperature and 500°C. Solid lines are drawn to show the change of trend in the data only (not a curve fit).

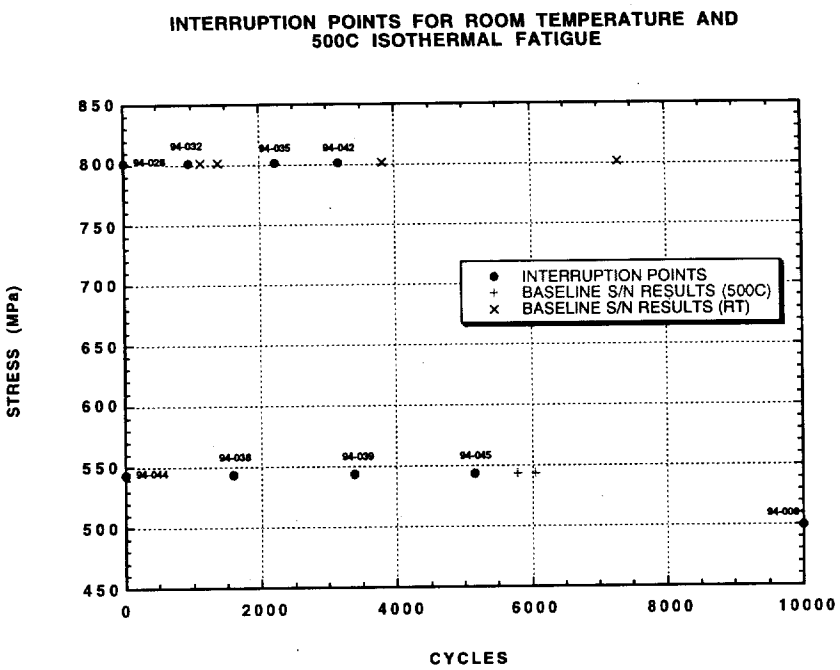

Figure 2 Cycles accumulated prior to interruption or failure for fatigue specimens used in this study.

Immersion Surface Waves

An immersion surface wave C-scan of a 500°C baseline sample tested at a maximum applied stress of 500 MPa reveals several surface and subsurface cracks as shown in Figure 3. This particular sample (94-008) was removed from the fatigue fixture after exceeding 10,000 cycles due to time constraints. This scan was calibrated such that the full scale amplitude (black in this C-scan) in the color coded scale represents the level of reflection from the polished edge of a Sigma/Ti-6242 calibration block. None of the specimens showed any evidence of surface or subsurface damage prior to testing. However, cracks formed during room temperature fatigue cycling in specimens 94-035 (2237 cycles) and 94-042 (3168 cycles) as evidenced by the immersion surface wave scans (Benson, 1995). The 500°C interrupted fatigue samples tested at a maximum applied stress of 540 MPa, on the other hand, revealed no signs of significant damage after being removed from the fatigue fixture.

Scanning Acoustic Microscopy

The 100 MHz transducer used during this study produced Rayleigh waves that penetrated the composite to a depth of approximately 0.03 mm; however, the outer layer of matrix material for this composite measured 0.160 mm. Since the imaging of fibers was desirable, longitudinal waves produced by the acoustic microscope were monitored instead. Since the full scale amplitude (black in these C-scans) represents high levels of reflection, the fibers in the first ply of the gauge section appear as dark lines in the C-scan of a room temperature fatigue specimen. Fiber alignment in the first ply was successfully evaluated using this method.

Oblique Incidence Shear Waves

The oblique incidence shear wave technique was somewhat successful in evaluating fiber alignment and detecting some surface cracks; however, details were far less apparent than those attained with acoustic microscopy. This method failed to identify any changes in the fiber-matrix interface during fatigue cycling. The shortcomings of this method may be attributed to the small diameter of the Sigma fiber (104 mm) used in the composite. Other studies that have been successful in using this technique typically involved fibers with larger diameters such as SCS-6 (142 mm). Lower frequency transducers (25 MHz) were originally used in this study; however, since the wavelength of the resulting shear wave was larger than the Sigma fiber diameter, good resolution was difficult to attain. As the transducer frequency was increased to 50 MHz, the wavelength decreased to 92 mm, but attenuation of the shear wave signal increased which hindered data acquisition. In addition to these difficulties, the undulating nature of the fibers made detection and proper gating of the ultrasonic signal extremely difficult.

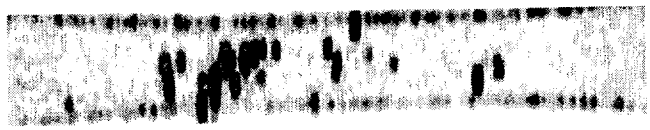

Figure 3--Immersion surface wave C-scan of specimen 94-008 (500°C, 500 MPa, 10 000 cycles).

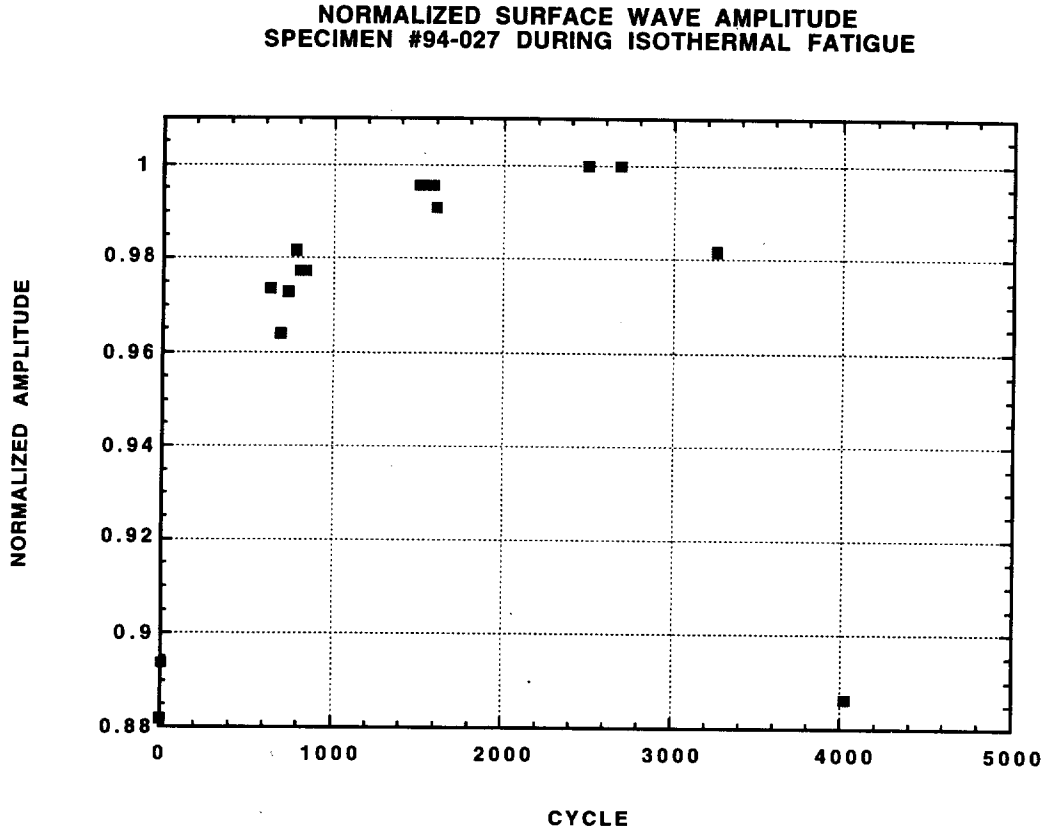

Figure 4 *In situ* surface wave amplitude plot for specimen 94-027.

In situ Surface Waves

In situ surface wave results were similar to those obtained before by other researchers (MacLellan, 1993). A large, initial decrease of the pitch-catch ultrasonic amplitude was typically seen during the first few cycles and may be an indication of fiber/matrix debonding. Some specimens subsequently displayed an increase in amplitude. This observation was also made by MacLellan (Testa and Burger, 1982), although the actual cause of the observation is still being investigated at this time. Following this slight increase, the transmitted amplitude gradually decreased until failure occurred. The gradual decrease in surface wave amplitude is believed to be due to reflection and scattering of the ultrasound from damage developing in the material as cycles are applied. A surface wave amplitude plot for specimen 94-027 is shown in Figure 4. This specimen, which was cycled at a maximum applied stress of 740 MPa at room temperature, failed after 4191 cycles.

Some difficulties encountered when using this technique may have affected the results. First of all, the transmitted surface wave amplitude was extremely sensitive to slight movements of the ultrasonic transducer wedges. In addition, the potential for error exists during the manual alignment of wedges to maximize the transmitted signal. These practices may have contributed to the variability present in the surface wave amplitude plots of specimens tested under identical conditions. An alignment fixture is recommended for future testing to ensure standardization.

In situ Longitudinal Waves

In situ longitudinal wave results for specimen 94-046 tested at room temperature at a frequency of 1 Hz are shown in Figure 5 (note the different y-axis scales). A comparison between changes in longitudinal wave amplitude and modulus (measured using extensometer displacement measurements) yielded similar results; however, the normalized results show that the modulus decreased by about 3% prior to failure, whereas the longitudinal wave amplitude decreased by 17% prior to failure. The longitudinal wave amplitude method,therefore, appears to be more sensitive to property changes and/or damage occurring in the material under study.

X-Ray Radiography

Regions of fiber displacement were easily detected in the X-ray radiographs taken during this study. Additionally, cracks were apparent in the Sigma/Ti-6242 unidirectional composites using magnification. The cracks were detectable because the fiber breaks appeared as gaps in the tungsten core, and all specimens were unidirectional which facilitated detection.

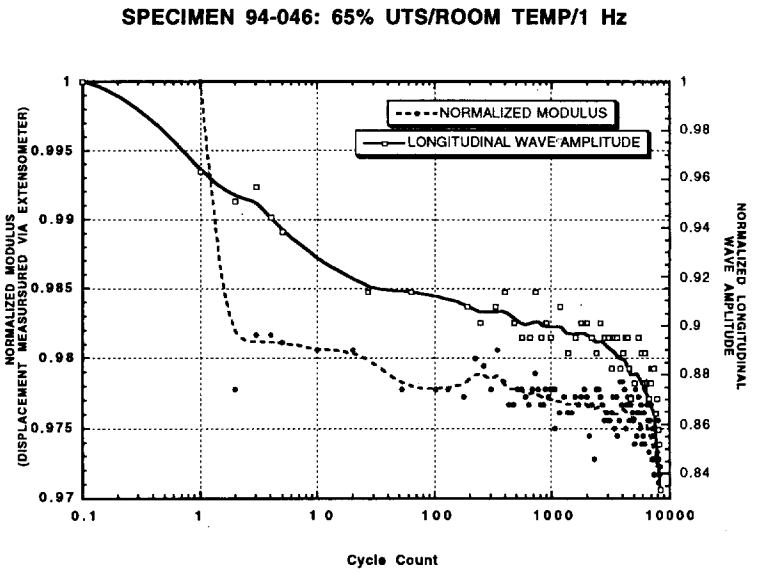

Figure 5 *In situ* longitudinal wave amplitude versus mechanically measured modulus of specimen 94-046.

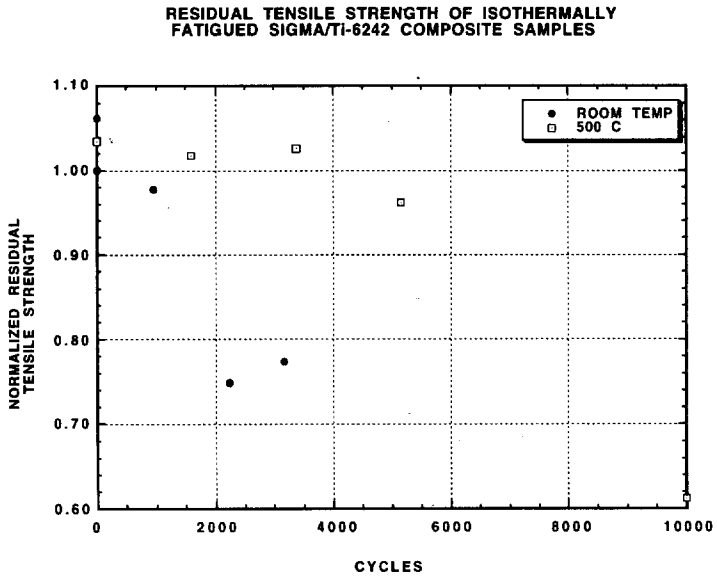

Figure 6 Residual tensile strengths of the interrupted fatigue specimens.

Correlating Observed Damage With Residual Tensile Strength

Figure 6 shows the residual tensile strengths and moduli of the interrupted specimens. The only specimens showing significant reductions in tensile strength were 94-035 (2237 cycles), 94-042 (3168 cycles), and 94-008 (10 000 cycles). These results correspond well with the findings of the immersion surface wave scans which revealed the presence of surface and sub-surface cracks in these samples. Specimens showing no evidence of surface or sub-surface cracking possessed residual tensile strengths comparable with the baseline values.

Damage Mechanisms Involved in Producing Indications During Nondestructive Evaluation

Scanning Electron Microscopy (SEM) of the fracture surfaces of baseline specimens revealed fatigue that initiated at the fiber/matrix interface and propagated radially outward. This failure mechanism was detected in both the room temperature and 500°C specimens. Failure of the

matrix surrounding some fibers apparently preceded fiber failure and subsequent overload. Fibers near the edges are more susceptible because constraints to failure are reduced once the matrix crack reaches an edge. Metallographic analyses of damaged regions were consistent with SEM findings. Cracks propagating away from the fiber/matrix interface are evident.

In order to verify damage detected during nondestructive evaluations, scanning electron microscopy and metallography were used to evaluate all interrupted specimens after the residual tension tests. Little, if any, fatigue damage was detected on the fracture surfaces of specimens that possessed a residual tensile strength near 100%. Minimal fatigue damage was observed near the fiber/matrix interface of specimen 94-045 (5114 cycles, 500°C) which displayed a slight decrease in tensile strength. On the other hand, significant fatigue damage was detected on the fracture surfaces of specimens that displayed a reduction in tensile strength after fatigue: 94-035 (2237 cycles, RT), 94-042 (3168 cycles, RT), and 94-008 (10,000 cycles, 500°C, 500 MPa). Most of the visible fatigue damage was located near the outer surface of the specimens; however, fatigue damage at the fiber/matrix interface was also present. These findings correspond well with the NDE results as well as the residual tension tests.

SUMMARY

The immersion surface wave technique proved to be the one of the most promising methods for correlating fatigue crack damage with the residual tensile strength for this composite. The only interrupted specimens showing significant reductions in tensile strength were those found to contain surface or subsurface cracks during scanning. Other NDE techniques were useful in evaluating fiber alignment and detecting some favorably oriented cracks; however, each method had its own limitations when applied to this material. Since fatigue crack damage typically developed at the fiber-matrix interface of fibers located near an edge or exterior ply, immersion surface wave scanning was an ideal NDE technique for this particular composite. Different modes of failure in other composite systems may dictate the use of the other NDE methods to detect damage.

Crack length measurements made from immersion surface wave C-scans were compared with information obtained during mechanical testing. The reduction in tensile strength does not appear to be related to the number of cracks detected; rather, the total length of cracks in the gage section seems to be more indicative of residual tensile strength in this composite. Specimens showing no evidence of surface or subsurface cracking possessed residual tensile strengths comparable with the baseline values. Other three specimens tested under different conditions (2237 cycles, 23°C; 3168 cycles, 23°C; and 10,000 cycles, 500°C) displayed reductions in the ultimate tensile strength of 25%, 22%, and 39%, respectively.

CONCLUSIONS

The usefulness of ultrasonic nondestructive evaluation to assess fatigue crack damage in a six-ply, unidirectional Sigma-1240/Ti-6242 composite has been demonstrated through correlation of immersion and *in situ* ultrasonic data with residual tensile strength. This study was conducted because correlations between damage, as it evolves under simulated service conditions, and the results from nondestructive evaluations are necessary to produce successful life prediction methodologies.

Of the eight NDE methods evaluated, immersion surface wave scanning best correlated fatigue crack damage with the residual tensile strength for this particular composite. The only interrupted specimens showing significant reductions in tensile strength were those found to contain surface or sub-surface cracks during scanning. However, acoustic microscopy, oblique incidence shear wave, and X-ray radiography techniques also proved to be extremely useful in evaluating fiber displacement and locating favorably oriented cracks. Although reflection plate inspection was unsuccessful in identifying fatigue crack damage, slight variations in material density, possibly related to composite processing, were detected prior to testing. The *in situ* longitudinal wave method was more sensitive to property changes and/or damage occurring in the material than the mechanically measured modulus. The *in situ* surface wave technique, on the other hand, was less successful detecting damage in this particular composite when compared to work done on SCS-6/Beta 21-S metal matrix composites (MacLellan, 1993). Different modes of failure in the two composite systems may explain the *in situ* surface wave results.

Scanning electron microscopy and metallography were useful for verifying fatigue damage detected using the NDE methods. Little, if any, fatigue crack damage was detected on the fracture surfaces of specimens that possessed a residual tensile strength near 100% of ultimate tensile strength (UTS). On the other hand, significant fatigue damage was detected on the fracture surfaces of specimens that displayed a reduction in tensile strength after fatigue.

Information obtained from nondestructive evaluations augmented the mechanical test data and facilitated early detection of damage. This work demonstrated that these findings can be used for developing quantitative correlations between nondestructive evaluation findings and material behavior of metal matrix composites.

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