NONDESTRUCTIVE INSPECTION AND EVALUATION
OF METAL MATRIX COMPOSITES

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INTRODUCTION

A review is presented of work performed in our laboratory on the nondestructive inspection of metal matrix composites. In order to obtain damage representative of that which occurs in service, the specimens were mechanically loaded to intermediate load levels below that which causes final, catastrophic failure. Various nondestructive techniques were used both during and after the applied loadings to follow damage initiation and progress.

The objectives of both studies discussed here were to apply nondestructive testing and evaluation techniques to characterize the nature of internal damage and to correlate the observed damage with the actual mechanical properties of the material, such as strength, stiffness and life. Many different nondestructive test methods were investigated, including X-ray radiography, ultrasonic C-scan and attenuation, thermography, replication, acoustic emission, eddy current, and stiffness change. The specimens were inspected both initially and at intermediate load stages.

As a generalization, nondestructive test methods may be referred to as specific or general, depending upon their ability to identify the specific form of the damage. For example, X-ray radiography and replication would be specific techniques since

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they are capable of identifying the exact nature, location and orientation of matrix cracks, delaminations, and other types of damage. General methods such as ultrasonic attenuation and thermography, on the other hand, interact with the damage in an integrating fashion and yield results indicative of the total effect of the damage. From attenuation measurements alone, one is unable to say whether the damage is all transverse cracks, all delaminations, a combination of these, or something else entirely. We believe that both types of NDT methods provide useful information. In fact, for composite materials the general methods may be potentially more useful from an engineering viewpoint since they may provide quantitative information on the total damage state. Since composites in general develop very complex damage leading to different failure modes, general methods which yield information on the integrated damage state may be easier to interpret than specific methods which provide much microscopic information that is difficult to assimilate and integrate into failure prediction theories.

Two separate programs are discussed in the following. The first program investigated the behavior of Fp Al composite material while the second program studied boron-carbide coated, boron reinforced titanium vanadium alloy. These will be discussed separately.

FP ALUMINUM COMPOSITE MATERIAL

Coupon specimens of Fp Al unidirectional material were machined from a panel, Fig. 1. Prior to any testing, initial NDT was performed on the specimens using ultrasonic C-scan, x-ray radiographic, and surface replication techniques. Figure 2 presents an initial x-ray radiograph together with initial C-scans taken at several different trigger levels of one of this specimen. This was the only specimen, out of more than forty, for which a region was identified by the initial NDT screening procedures that appeared to correlate with the final failure location when the specimen was tested. The specimens were loaded in a standard three-point bend test as shown in Fig. 3. The initial C-scans and radiographs both indicate longitudinal striation patterns. Closer observation of the specimens under a microscope was unable to provide any reason for these patterns. That is, no obviously fiber-rich, matrix-rich, void, or other regions were discernible optically.

At intermediate stages of fatigue loading, the specimens were removed from the test fixture and subjected to the same round of NDT tests used initially. Figure 4 is a series of ultrasonic C-scans taken after various cycles of fatigue loading. These
Fig. 1. Schematic of Fp Al panel showing positions from which coupon specimens were cut (dotted lines).

Fig. 2. X-ray radiograph and C-scans taken of specimen prior to mechanical testing.
Fig. 3. Schematic illustration of three point bend test applied to specimen coupons.

Fig. 4. Ultrasonic C-scans made after various cycles of fatigue loading.
C-scans were all made with a calibration specimen present to duplicate, as closely as possible, instrumentation settings. Note that the C-scans were able to detect a region that grew and finally contributed to the failure surface. This specimen again was one of the few for which an obvious damage site was easily detected as it grew into final failure. For most of the specimens tested, the failure site occurred at a location which did not appear to be any different than the surrounding region as far as C-scan pictures or X-ray radiographs could detect. We believe that, in general, the damage regions which developed in these specimens during fatigue loading were confined to regions very near the edge where the tensile stresses were maximum. Because of edge effects, the C-scanning and radiography techniques are insensitive to damage at the edges.

In addition to these usual NDT methods, changes in longitudinal and flexural stiffnesses were also measured at intermediate stages of the fatigue tests. Typical changes in these moduli are shown in Fig. 5. Generally, the stiffnesses increased rapidly over the first 20% of the test and then showed a gradual decrease over the remaining cycles. Note in Fig. 5 the decrease in longitudinal stiffness around 100 kilocycles was attributable to an improperly calibrated extensometer.

Because of the difficulty of being able to distinguish developing damage in this material, a series of specimens were made with a single edge notch, Fig. 6. It was thought that this stress concentration would localize damage sufficiently so that the capability of NDT techniques to detect developing damage in this material might be evaluated better. Figures 7 and 8 are ultrasonic C-scans and X-ray radiographs, respectively, of damage developed in these single edge notch specimens at various intermediate load cycles. As can be seen, longitudinal cracks developed near the notch tip. These cracks grew with increasing cycles of loading. Surface replicas, Figs. 9 and 10 showed that the notch actually grew transversely a small distance before the longitudinal cracks began to grow. For this damage type, the three NDT techniques: C-scan, radiography, and replication were equally good in following and characterizing damage development. Figure 11 is a graph showing the crack length, as measured on the pictures produced by these three NDT methods, versus cycles of loading. As can be seen, each of these methods provided approximately the same degree of sensitivity to crack length.

BORON TITANIUM COMPOSITE MATERIAL

Again as was the case with the Fp Al, the purpose of this study was to initially characterize the condition of the material
Fig. 5. Change in longitudinal and flexural moduli with fatigue cycles.

Fig. 6. Schematic diagram of specimen with machined edge notch.

in question, boron-carbide coated boron fiber reinforced Ti6Al4V, and determine the nature of damage development resulting from mechanical loading. Several techniques were employed, including ultrasonic C-scan, X-ray radiography, vibrothermography and eddy current testing. Examination of the as-received panel and specimens cut from it provided no indication of any existing imperfections. Subsequent metallographic work did show that the fiber distribution was not very uniform and that some fibers were not completely surrounded by the matrix material. Re-examination of the results of these techniques subsequent to testing of the
specimens did not reveal this or differences between the failure site and other unfailed regions. Using these techniques to periodically examine the test specimens at intermediate points in loading them to failure was equally unproductive. However, through the application of two continuous monitoring techniques during loading, ultrasonic attenuation and acoustic emission, an indication of the early initiation and development of damage was obtained.

**Ultrasonic Attenuation Monitoring**

For specimens having fibers oriented both parallel (longitudinal) or perpendicular (transverse) to the direction of applied load, ultrasonic attenuation indicated that changes in the material condition occurred at low load and continued until failure. Figure 12 indicates the procedure used for monitoring. Careful consideration reveals that if successive echoes from the back surface of the delay block are monitored, no attenuation change should occur. Hayford and Henneke\(^3\) have shown that changes which are observed by monitoring in this way can be explained by considering diffraction of the sound waves by damage in the specimen. Figures 13 and 14 show how the attenuation changes for
Fig. 8. X-ray radiographs of specimen showing damage development at tip of notch.

typical longitudinal and transverse specimens, respectively. However, since no description of the deformation mechanism(s) responsible for these changes is obvious, consideration of other techniques both nondestructive and destructive was necessary.

Acoustic Emission Monitoring

Continuous monitoring of acoustic emission resulting from quasi-static tensile loading of both longitudinal and transverse specimens was performed and recorded by a high speed tape recorder. The general nature of the behavior agreed with the results of the ultrasonic attenuation monitoring. Acoustic emission activity began to occur early during the loading and increased with increasing load. In order to better understand the cause(s) of this AE, and perhaps thereby the damage development, a very careful examination of the recorded AE signals was performed. Three distinct types of AE waveforms were observed, as seen in Fig. 15, and their time of occurrence during the test was
determined. Although for both types of specimens the same three signal types were observed, their times of occurrence were quite different; Figs. 16-18, and Figs. 19-21 are for longitudinal and transverse specimens respectively. The spectra of the various signal types as well as the fact that for both specimens the signal types were the same suggested that the waveforms are related to specimen resonances. Nevertheless, for either the
Fig. 11. Longitudinal crack size, as measured by three different NDI techniques, versus load cycles.

Fig. 12. Schematic diagram of system used to monitor ultrasonic attenuation.

Longitudinal or transverse specimens, different signal types ought to be associated with different damage modes. Such speculation can only be verified by destructive analysis of damaged specimens.
Fig. 13. Load and attenuation versus strain for a unidirectional specimen, load applied parallel to fibers.

Fig. 14. Load and attenuation versus strain for a unidirectional specimen, load applied perpendicular to fibers.

Scanning Electron Microscopy and Auger Depth Profiling

Extensive examination of the failed specimens by means of a scanning electron microscope revealed a number of mechanisms which
could have been responsible for the observed AE signals and ultrasonic attenuation. Figure 22 shows how, for a longitudinal specimen, the fibers have fractured, split and separated from the surrounding material. Further examination of the surrounding material, Fig. 23, and separated fibers by depth profiling using Auger electron spectroscopy (AES) revealed, Fig 24, that the separation occurred between fiber and fiber coating and not between the coating and matrix. Together the SEM and AES results provide considerable insight into understanding the results of the nondestructive monitoring techniques, which in turn help to describe the nature of damage development in this material.
Fig. 16. Frequency of occurrence for three types of AE signals observed for longitudinal specimen. Type I.

Fig. 17. Frequency of occurrence for three types of AE signals observed for longitudinal specimen. Type II.
Fig. 18. Frequency of occurrence for three types of AE signals observed for longitudinal specimen. Type III.

Fig. 19. Frequency of occurrence for three types of AE signals observed for transverse specimen. Type I.
Fig. 20. Frequency of occurrence for three types of AE signals observed for transverse specimen. Type II.

Fig. 21. Frequency of occurrence for three types of AE signals observed for transverse specimen. Type III.
CONCLUSIONS

In general, nondestructive inspection of metal matrix composites presents an even more difficult problem than examination of organic matrix composites. Because of the ductile nature of the metal matrix, transverse and longitudinal matrix cracks and delaminations, which are important failure modes in organic matrix composites, are not observed in metal matrix composites. Whatever damage develops prior to catastrophic failure of the material is either microscopic or not easily observable by many of the usual NDT techniques. However, as shown by the results reported in this paper, there are some techniques, such as ultrasonic attenuation, acoustic emission, and stiffness measurements, which give results potentially useful for NDE of metal matrix composites. It is obvious that a great deal of further study in this area is required.
Fig. 23. SEM photograph showing fractures in material surrounding a fiber which has been pulled away.
Fig. 24. Auger electron spectroscopy showing material remaining bonded to matrix after fiber has pulled away is rich in boron and carbon.

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