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W.L. Morris
Rockwell International

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INITIATION, AND DISPLAY OF DELAMINATION FAILURE DURING FATIGUE OF GRAPHITE FIBER-EPOXY COMPOSITES

W. L. Morris
Rockwell International Science Center
Thousand Oaks, California 91360

ABSTRACT

Laminar microdiscontinuities which lead to the delamination of two unidirectional layup graphite fiber-epoxy composite materials during fatigue have been characterized, and discontinuity geometry and type related to the fatigue lifetime of specimens in which they occur. Two types of discontinuities were commonly observed: voids and organic inclusions consisting of regions of excess hardener. A stress intensity range based analysis applied to discontinuities found on the fatigue fracture place demonstrates that the several orders of magnitude scatter in fatigue life found for a series of test specimens is a result of a variation in the type and size of discontinuities present from specimen to specimen. A non-destructive acoustic pulse-echo system used to study the progress of crack propagation from the discontinuities during fatigue is also described.

Scatter in the values of mechanical properties of graphite fiber-epoxy composites is substantially larger than that typically found for metallic structural materials. This has required the use of large safety factors in the design of structural components using such composite materials. A purpose of the present study was to determine the cause for scatter in the lifetime of two graphite fiber-epoxy materials subjected to fatigue loading. The failure mode of particular interest was delamination, that is, the disbonding between layup plies. Delamination is the principal failure mode of fiber-epoxy composites loaded in shear, and is often a weak link in the failure sequence of such materials loaded in both tension and compression. The study was done using beam specimens loaded in 3-point bending, for an

\[ R = \frac{\text{minimum load}}{\text{maximum load}} = 0 \text{ loading condition.} \]

The materials characterized were 3501-5 epoxy/AS graphite and 934 epoxy/T300 graphite, a low and medium curing temperature material, respectively. Unidirectional fiber orientation 50 ply thick construction was used, providing a 0.63 cm thick specimen. Specimens where load in fatigue normal to the layup plane, with the fibers positioned parallel to the specimen axis as shown in Fig. 1. The specimens failed due to subcritical crack growth along a plane between plies, followed by a final tensile failure of the outer fibers due to loss in specimen stiffness with the delamination.

Fatigue lifetime data for the materials are shown in Fig. 1, in comparison to the peak shear stress experienced at the neutral plane of the specimen, resulting from the 3-point loading condition. The several orders of magnitude scatter in fatigue lifetime is typical of such materials.

Specimens were examined optically, after failure, to characterize areas on the delamination plane which might have acted as initiation sites for crack propagation. Principally, two types of microdiscontinuities were observed: voids and organic inclusions. The voids were apparently formed as the result of displaced fibers in the prepreg tape used to manufacture the composite panels. The organic inclusions were regions of excess hardener and were easily visible owing to their bright yellow color. General observations were that, typically, there was only one discontinuity of any appreciable size on the fracture surface, and for specimens with longer fatigue lifetimes the discontinuities tended to be smaller. To quantify the relationship between discontinuity size and fatigue life a mode two stress intensity range, \( \Delta K_2 \), was associated with each discontinuity. It was the fracture surface of a specimen, and the largest value of \( \Delta K_2 \) found was compared with the specimen fatigue life.

The analysis entailed approximating the shape of each discontinuity as an ellipse, on the basis of the location of the preponderance of the area of the discontinuity. Major (2a) and minor (2b) axes of the ellipse were assigned by ignoring small appendages such as illustrated for the void in Fig. 2. A stress intensity solution by Kassir and Sih was then used to determine \( \Delta K_2 \) for the discontinuity. The cyclic shear stress at the site of the discontinuity, needed to complete the calculation, was determined from the cyclic applied load and the distance of the discontinuity from the neutral plane.

Results of such an analysis are shown in Fig. 3. For the 3501-5 epoxy/AS graphite, for instance, one finds that the lifetime data fall into two groups, one describing the effect of inclusions, the other of voids. The scatter in lifetime is substantially reduced by the analysis, demonstrating that it is a variation in type, size and location of the planar microdiscontinuities from specimen to specimen that is principally responsible for the lifetime scatter. The better fatigue properties of the 934 epoxy/T300 graphite is attributed to a smaller average size of discontinuity in the material tested, as also illustrated in Fig. 3.

The longer lifetime of specimens containing inclusions, as compared to voids having the same \( \Delta K_2 \), is attributed to a longer interval of crack initiation at the inclusion sites. This was confirmed by a subsequent investigation in which the growth of cracks from the discontinuities was mapped, at increments in the fatigue life, using a computer controlled acoustic pulse-echo facility. The technique used is illustrated schematically in Fig. 4. A specimen was emersed in a water bath and an acoustic C-scan made using a 15 MHz broad-band focussed transducer, with a point-to-point resolution of better than 0.05 cm. The X, Y position of the transducer over the specimen was computer controlled and echo samples were taken for a
square grid on the specimen at intervals of 0.025 cm. Because of the high acoustic attenuation and the acoustic echoes from each laminate, even in the absence of defects, it was necessary to make the acoustic amplitude for which a discontinuity was "recognized" a function of depth in the specimen. This procedure is also illustrated in Fig. 4.

Figures 5 and 6 show the results of such mapping for a specimen of 934 epoxy/T300 graphite. The display in Fig. 5 is of defect location as a function of depth normal to the layup plane in a sample, and shows that the principal discontinuities responsible for crack initiation in that particular specimen lay in poorly manufactured plies on either side of the center of the specimen. Figure 6 is a map of a limited area in depth taken normal to the layup plane. The discontinuity shown before fatigue was in this case a void, and subsequent crack growth from the defect after 1000 fatigue cycles is also illustrated. Test specimens were mapped, transferred to a loading apparatus for fatigue and then returned to the mapping facility. The procedure was continued until a specimen failed, at which time the acoustic map was compared to the actual discontinuities present. Using this technique, it was demonstrated that crack propagation from the voids began almost immediately, but there was a substantial time required for crack initiation at the void sites.

In summary, the major findings are:

1. Microdiscontinuities inadvertently introduced during manufacture of graphite fiber-epoxy materials are a major source of scatter in lifetime of the materials subjected to fatigue loading.
2. The principal discontinuities observed in a 3501-5 epoxy/AS graphite and a 934 epoxy/T300 graphite are voids resulting from displaced fibers in the prepreg tape, and organic inclusions consisting of regions of excess hardener.
3. The type, size and location of such discontinuities are the principal factors which determine fatigue life of the materials.
4. Discontinuities as small as 0.05 cm in diameter can affect composite fatigue life, and can be detected in specimens 0.63 cm thick using acoustic pulse-echo techniques.

REFERENCES

Fig. 3 Results of analysis.

Fig. 4 Experiment technique for observing discontinuities; a, b, c.

Fig. 5 Location of fatigue damaged areas in composite structure.

Fig. 6 Crack initiation and propagation during fatigue.