JOURNAL OF MATERIALS SCIENCE 24 (1989) 167—172

Fractography of unidirectional CFRP composites

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The morphology of fracture surfaces of unidirectional carbon fibre reinforced plastic composites has been studied to categorize the fractographic characteristics for several types of loading. Specimens were tested in compression and in tension, both in the axial and the transverse direction, in bending and in interlaminar shear. The influence of prior exposure to moisture and to elevated temperature on the fracture morphology of specimens tested at elevated temperature has also been studied. Optical and scanning electron microscopy were used for the fracture surface analyses. Fractographic features characteristic of each mode of stressing and directionality of specimen were identified.

1. Introduction

In the last few years carbon fibre reinforced plastic (CFRP) composite materials have been increasingly applied in aerospace structures. The successful design, development and behaviour in service of these structures require an understanding of the mechanisms of the possible failures. These failures can occur during laboratory evaluation at stages in the development of manufacturing processes, they can occur during ground-testing of a component in simulation of service conditions and, of course, they can occur in service. The need for a reliable methodology of failure analysis of aircraft parts made from composite materials, as is available for metallic parts, is obvious. Accordingly it is most important to determine the fractographic features characteristic of different types of applied stress and for different directions and lay-ups of specimen.

The fractography of different CFRP unidirectional or multidirectional composite materials has been the subject of several studies [1-6]. Some specific fractographic characteristics were identified in these investigations. It was also established [1, 4] that in a multidirectionally layered material each ply has very much the same fractographic features as a unidirectional material for the same direction of fibres. Accordingly the fractography of unidirectional composites can serve as a basis for the fractography of multidirectional composites.

The effect of the absorption of moisture on the fractography of CFRP composites has been studied [7-9]. Moisture absorption in combination with an elevated test temperature has an adverse effect on the strength of the epoxy resin and of the fibre–matrix interface [7, 8].

2. Experimental procedure

The unidirectional laminates examined were manufactured from the commercial graphite–epoxy system Magnamite AS4/3502 (Hercules Corp., Magna, Utah) having ~ 65 vol % of fibres, the latter being of 7 μm diameter. This system is used extensively for the production of aircraft structures.

In order to produce a known mode of failure, standard test specimens were loaded in axial compression according to ASTM Standard D3410, in axial tension Standard D3039, in three-point bending Standard D790, in transverse compression Standard D3410, in transverse tension Standard D3039 and in interlaminar shear Standard D2344. All the above tests were carried out under ambient conditions of temperature and humidity. Some additional tests were carried out at 120° C after prior exposure for two months in an environmental cabinet at 70° C and 95% relative humidity.

The fractured specimens were examined visually and the fracture surfaces were examined with the aid of an optical stereoscopic microscope and with a scanning electron microscope (SEM). Prior to SEM examination the fracture surfaces were vacuum-sputter-coated with approximately 20 nm of gold. This minimized charging and improved resolution of the SEM imaging.

3. Results and discussion

3.1. Failure in axial compression

A typical view at low magnification of the surface of a fracture in compression is shown in Fig. 1. The fracture is transverse and is accompanied by extensive longitudinal cracking in the direction of the fibres within, and at the boundaries of the plies. The latter cracks are delaminations. The macroscopic surface of the fracture is stepped. Fig. 2 shows such a step as observed in the SEM. This feature is typical of failure of the fibres by microbuckling, which, as a rule, is the main mode of failure in compression [1, 2].

Purslow [1] has noted that the height of each step is a multiple of half the wavelength for fibre buckling. In our case the heights of the steps were found to be

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Figure 1 A typical fracture surface in an axial compression failure.

multiples of the smallest, so that the half-wavelength measured was 0.018 ± 0.001 mm and was independent of the absorption of moisture and the temperature of the test.

A detail of the fracture surface at relatively high magnification is shown in Fig. 3. Two distinct areas of compressive and tensile failure, respectively, can be identified on the fracture surfaces of individual fibres, all of which failed by buckling. A line drawn in Fig. 3, to separate these two areas, is the buckling axis. The fibres on each step had a common direction of buckling axis such as line A–A in Fig. 3. This direction changed from one step on the fracture to another. The fracture propagated through the individual fibres from the tensile to the compressive side in a direction perpendicular to the buckling axis. The fracture direction and height common to all the fibres in a step indicate localized crack propagation. Thus, the buckling axis can be used for determination of the direction of crack propagation through a region of the fracture and possibly for identification of the local failure origin. The arrow in Fig. 3 indicates the direction of crack propagation through the region shown.

When the fracture passes through a resin-rich area, it produces a relatively smooth fracture surface with flow lines in the direction of propagation of the fracture, resembling the "river" pattern observed in the cleavage fracture of metals, see Fig. 4. Such a surface indicates brittle fracture of the resin matrix.

The compressive fracture surface is also characterized by extensive post-failure damage resulting from the mutual rubbing of the fractured surfaces. Large areas of such surfaces are covered with debris composed of fibres and resin, such as shown in Fig. 5. Such debris was not removed by conventional ultrasonic cleaning.

The morphology of the transverse fracture surface is not significantly affected by the absorption of moisture or by elevated test temperature. However, there is an increase in the amount of fibre pull-out in specimens that absorbed moisture and were tested at an elevated temperature. This is due to weakening of the fibre–matrix bond.

Longitudinal cracks propagate along the fibre–matrix interfaces and along the layers of resin between adjacent fibres. The main features observed on the crack surface are exposed fibre surfaces and broken resin layers between the fibres. The latter exhibit a serrated shear fracture pattern, designated as "hackles" [3, 4], as in Fig. 6.

Cracks due to delamination propagate between the outermost fibres of the ply and the resin-rich interlaminar layer, jumping back and forth across this layer. Due to this jumping, each mating delamination surface exhibits alternate resin-poor and resin-rich regions. The former show fibre surfaces and the latter fibre imprints, both with "hackles" in the resin between them.

3.2. Failure in axial tension

On a macroscopic scale the contour of the fracture surface is irregular. The fracture is divided into

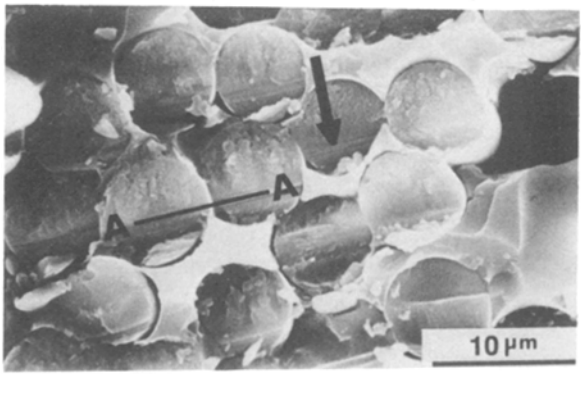

Figure 2 A step on the surface of a compressive fracture.

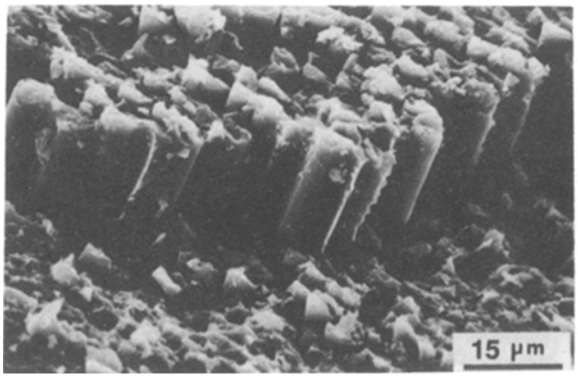

Figure 3 Fibre failure in a compression test. A–A is parallel to the buckling axis of the fibres in the area shown. The arrow denotes the direction of local crack propagation and is perpendicular to A–A.

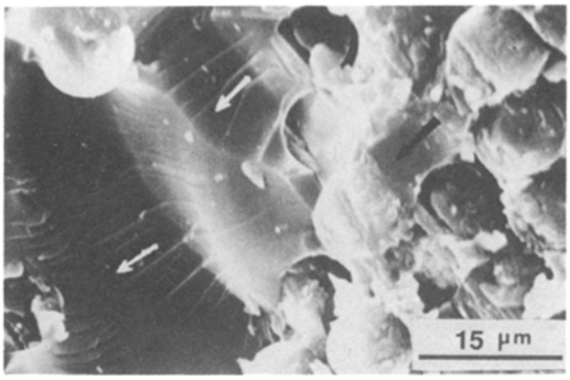

Figure 4 The compressive fracture of a resin-rich area on the left-hand side of the electron micrograph. The arrows show the direction of crack propagation through the fibres and resin.

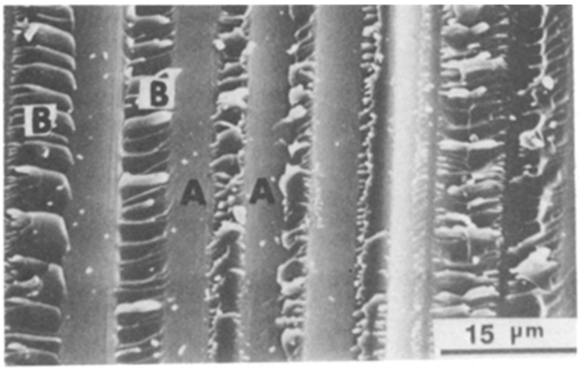

Figure 6 The surface of a crack in a compression test in the fibre direction. Letters A indicate uncovered fibres and B the hackles.

separate segments such as those numbered 1 to 3 in Fig. 7. Such a fracture shape indicates several origins.

SEM examination of a typical segment reveals radial lines, as in Fig. 8, that emanate from a point on the surface, the crack origin, marked O. The failure clearly occurs by the merging of such surface cracks. According to Purslow [1], such radial lines are a characteristic of brittle fracture.

A typical area of the fracture is shown at higher magnification in Fig. 9. It can be seen that the fracture propagates through the fibres in regions of different height. Each region consists of a few dozens of fibres. Closer examination reveals microscopic radial lines on the fracture surface of the individual fibres, as shown in Fig. 10. The centres of these lines are marked by an arrow on each fibre. These lines start from a point on the fibre–matrix interface, indicating the origin of the failure of the individual fibre. This implies that the fibres fail in a sequence, the fracture propagating from Fibre A in the figure to Fibre B, then to C and so on, the direction indicated by the larger arrow. Accordingly the radial lines on the fracture of the individual fibres allow one to locate the fracture origin and follow its direction.

In most of the regions the local direction of crack propagation through the fibres coincides with the general direction of failure that was determined from the radial lines observed on the fracture surface at relatively low magnification, such as those shown in Fig. 8. There are, however, a few regions where the local direction of crack propagation through the fibres differs from the general direction. Most probably, the local fracture in these regions started before the arrival of the front of the main crack and at a point of local weakness. In addition to the fracture across the fibres there are cracks in the fibre direction. The morphology of these cracks was found identical to that of similar cracks in the compression specimens, as described in the previous section.

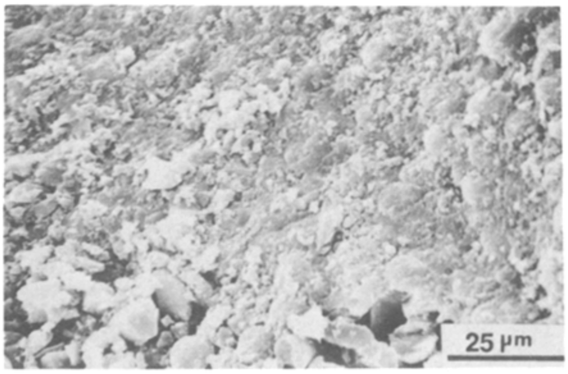

Figure 5 Debris on a mutually rubbed compressive fracture surface.

With respect to specimens which absorbed moisture and were tested at an elevated temperature, the morphology of their fracture surfaces was, in general, similar to that of specimens without absorption of moisture. It seemed, however, that the macroscopic radial lines, such as those in Fig. 8, were less accentuated in the specimens which had absorbed moisture. Also, the number of regions with a local direction of crack propagation differing from the general direction of failure, and the number of fibre pull-outs, was greater in specimens which had absorbed moisture and were tested an an elevated temperature.

3.3. Failures in bending

The failure in the three-point bending test occurred at that point in the specimen opposite the central roller. Fig. 11 shows an area of the bend fracture surface. It

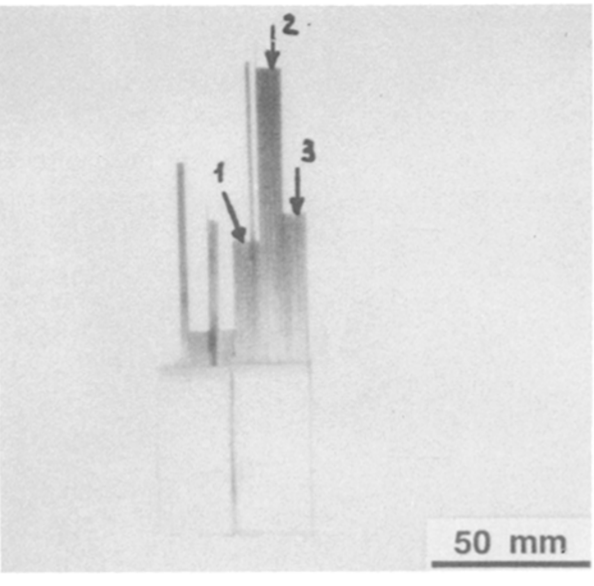

Figure 7 Two fractured tensile specimens. The numbers 1 to 3 mark separate segments of the fracture of the right-hand sample.

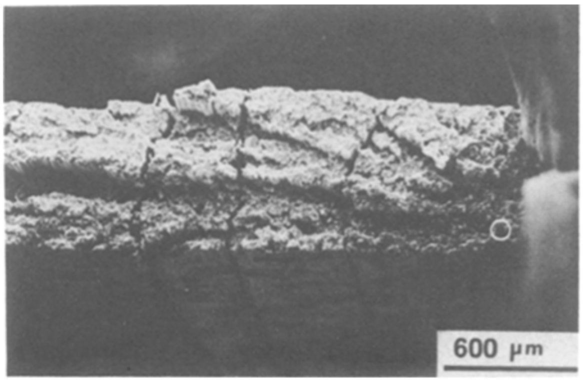

Figure 8 The segment of the fracture surface marked 2 in Fig. 7. The local crack origin is marked O.

will be seen that the transverse fracture surface consists of two morphologically different areas with a distinct boundary between them. A closer examination reveals that the morphologies of these fracture areas are identical to those of axial compressive and tensile fractures as described in Sections 3.1 and 3.2, respectively. In Fig. 11 the letters A and B indicate the tensile compressive fracture areas, respectively.

The fact that the tensile fracture region is considerably larger than the compressive one indicates that the failure started from the tensile surface [1]. The fracture flow lines visible on the tensile fracture area, and arrowed in Fig.11, indicate that the crack started from the full width of the external tensile surface and propagated into the specimen. The tensile propagation results in an increase of the flexural deformation and of the interlaminar shear stresses, the latter resulting in a large delamination crack, marked C in Fig. 11. After delamination the failure of the specimen is completed by partially tensile and partially compressive fracture of the remaining intact thickness. The new tensile failure initiates at the surface of the delamination and the compressive fracture initiates at the outside surface of the specimen. These two different fracture areas extend over approximately the same thickness of material and the boundary between them is clearly seen in Fig. 11. Some longitudinal cracks, marked D, can also be observed in the compressive fracture area.

The direction of crack propagation through the tensile fracture area, as determined from the radial flow lines on the fractures of individual fibres, is the same as the general direction of crack propagation, namely from the external surface to the interior of the specimen.

The fibres in the compressive fractured area, like those in the axial compressive failure, have fractured by microbuckling, and the buckling axes are clearly seen on the fractures of the individual fibres. These axes, which are perpendicular to the direction of crack propagation, are all parallel to the specimen surface save for those at the edges of the specimen. This fact indicates that the compressive fracture propagates from the surface over the full width of the specimen.

3.4. Failures in transverse tension and compression

The direction of failures in transverse tension and compression is parallel to the fibres as observed also by Purslow [1] and Liechti *et al.* [4]. We likewise found that the failure in transverse tension occurs on a plane perpendicular to the direction of the applied load. However, the failure in transverse compression occurred on a plane tilted at 30° to the loading direction, presumably due to resolved shear stress.

The microscopic morphology of the fracture surface for the two types of failure is very similar. In both cases the failure occurs either at the fibre–matrix interface or in the matrix itself with some additional fracture in the fibres. Accordingly, the following features are observed on the fracture surfaces: (a) exposed fibres free of resin, or imprints of the fibres in the matrix; (b) cleavage of the epoxy matrix; (c) hackles, indicative of shear fracture of the matrix; and (d) some fractured fibres. The fracture surface is similar to those observed by Liechti *et al.* [4]. Fig. 12 shows a fracture surface in transverse tension. The surface consists mostly of fibres free of all matrix. A few fractured fibres are visible.

Fig. 13 shows a detail of Fig. 12 at higher magnification. An area of cleavage in the matrix is shown at A. The cleavage is characterized by a relatively smooth fracture surface and shows river markings which indicate the local direction of propagation of the fracture. These river markings are arrowed. The local directions vary from region to region. At magnifications above × 5000 fine flow lines can be seen between these river marks. B in Fig. 13 indicates the hackles formed

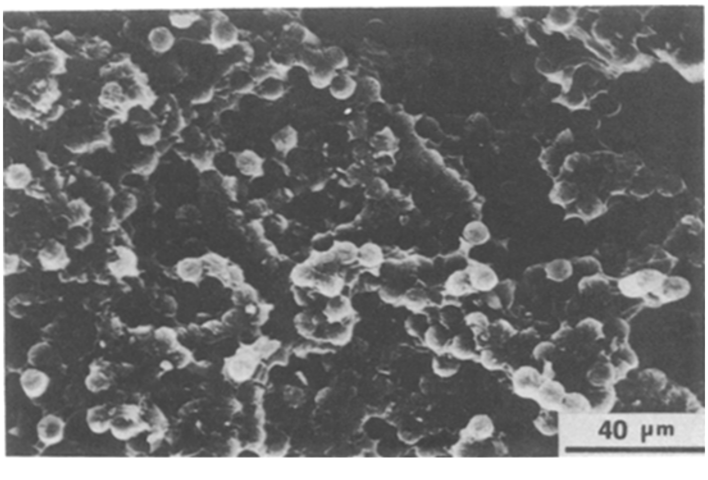

Figure 9 An area of a tensile fracture surface at higher magnification.

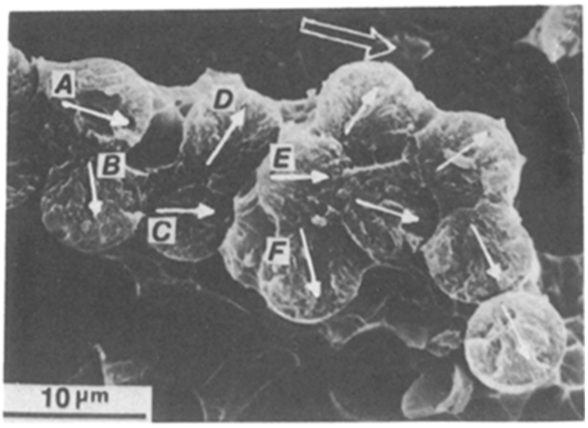

Figure 10 Propagation of a tensile fracture through individual fibres. The large arrow indicates the general direction of propagation of the fracture in the specific area selected.

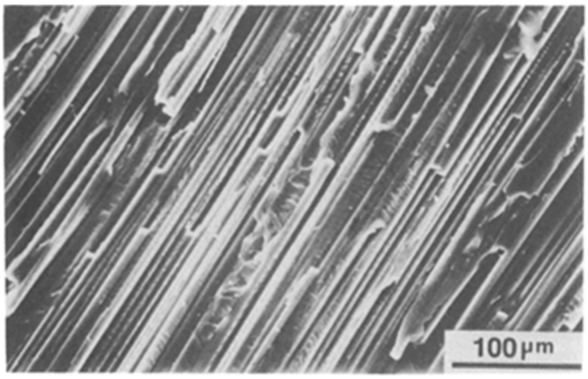

Figure 12 A fracture surface in transverse tension.

by shear fracture of the matrix. The river markings, mentioned above, can be observed only in those regions of failure in the matrix which were wider than the diameter of a fibre, and they are more frequent on the tensile fracture surface. On the compressive failure surface the matrix cleavage regions usually show finely spaced, parallel flow lines. This difference tends to support a hypothesis that the failure in transverse tension originates at several internal sources, while the failure in transverse compression is due to propagation of macrocracks formed perpendicular to the fibre direction and to the loading direction.

The transverse tensile and compressive failures also result in fracture of both single fibres and of groups of fibres. The morphology of the fracture of these fibres is compressive or tensile, as described in Sections 3.1 and 3.2, irrespective of the mode of loading.

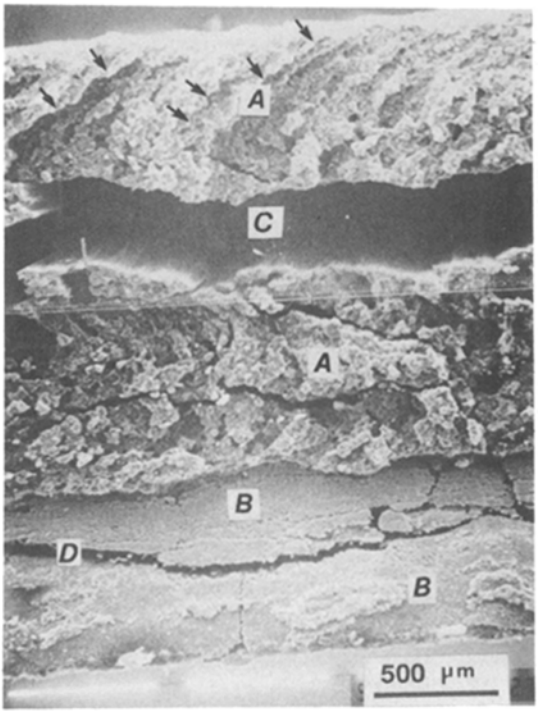

Figure 11 An area of the bend fracture surface. The letters A and B mark the tensile and the compressive fracture regions, respectively. The letter C marks a delamination crack in the tensile fracture region and the letter D marks a longitudinal crack in the compressive fracture region. The arrows indicate the fracture flow lines.

The transverse compressive fracture surface, like that in the axial compressive fracture, contains areas covered with debris of crushed fibres and the resin. This debris is due to damage caused after the failure and it was not removed by conventional ultrasonic cleaning.

The morphology of the failure surface in the specimens that were tested after absorption of moisture at an elevated temperature showed an increase in the fraction of failure at the fibre–matrix interface.

From all the above it follows that the characteristics of the fracture surfaces in transverse tension and compression are quite similar to those of the crack surfaces in the fibre direction in samples loaded in axial tension and compression. The main differences are in the presence of regions of cleavage in the matrix in the transverse loaded specimens, and in the fracture areas being covered with debris in the transverse compressive failures.

3.5. Failure in interlaminar shear

The interlaminar shear failure investigated was generated by the short-beam method of testing according to ASTM Standard D2344, which is an acceptance test for the laminate.

The failure in this case is by multiple cracking of the matrix in the fibre direction. The cracks are formed either opposite the central roller or at the edges of the

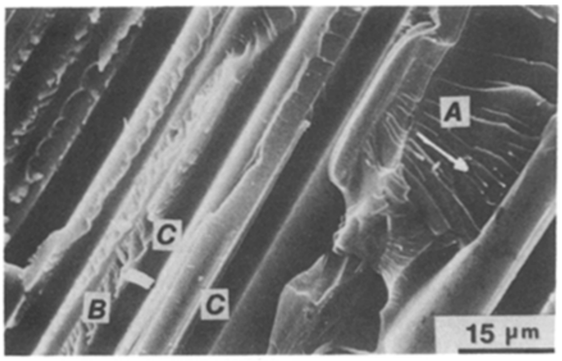

Figure 13 A detail of Fig. 12. Letter A indicates a region of matrix cleavage, B of hackles and C of imprints of the fibres in the matrix. The arrow indicates the local direction of cleavage in the matrix.

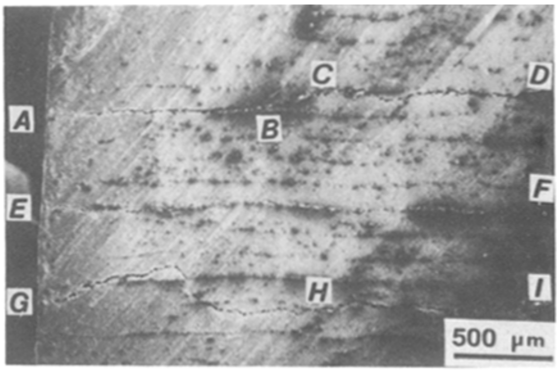

Figure 14 The LT–ST edge of a failed specimen in a short-beam interlaminar shear test. ABCD, EF and GHI indicate the paths of three cracks. LT = long transverse, ST = short transverse directions.

specimen. Usually they tend to develop and propagate between the plies as a delamination crack and sometimes inside a ply. Fig. 14 shows the LT–ST edge of a failed specimen. Three equally spaced cracks are seen on the specimen surface. For the greater part the cracks propagate between the plies, such as crack paths AB, CD, EF and HI. There are also crack paths that do not follow the boundary between the plies but penetrate the plies and propagate there, such as crack paths BC and GH.

The micromorphology of the delamination cracks, and that of the cracks running in the fibre direction within the laminates, is the same as that described in Section 3.1.

4. Conclusions

From this systematic experimental study of the fractographic characteristics of a CFRP unidirectional composite system, AS4/3502, subjected to different types of loading, the following conclusions can be drawn:

1. The main characteristic features unique to the axial compression fracture are due to the microbuckling of the fibres resulting in (a) steps on the fracture surface of the specimen of height corresponding to the half-wavelength of the buckling and (b) the appearance of distinct compressive and tensile fracture areas, respectively, on the fracture surface of the individual fibres.

2. In specimens loaded in axial tension the unique features of the resulting transverse fracture were as follows: (a) macroscopic radial flow lines were observed on the fracture surface, which emanated from a crack origin; (b) the crack origins were always on the external surface of the specimen; (c) radial lines with origins on the fracture surface of the individual fibres can be used to trace the general direction of propagation of the fracture.

3. The unique fracture characteristic of the bending failure is the formation of distinct tensile and compressive fracture areas on the transverse failure surface. The failure originates over the full width of the external tensile surface and propagates into the specimen. The compressive fracture starts later from the opposite side of the specimen.

4. The above-mentioned transverse fractures in specimens loaded in compression, tension and bending respectively are all accompanied by longitudinal cracking in the fibre direction within, and at the boundary of the plies. The morphology of these two types of crack is very similar. Where cracking occurred at the boundary of the plies it constituted a delamination crack. The fractographic characteristics of these crack surfaces are as follows: (a) exposed fibres or smooth imprints of fibres in the epoxy matrix; (b) the formation of hackles due to shear fracture of the matrix.

5. For specimens loaded in transverse tension, the failure occurs on a plane perpendicular to the direction of the applied load, whereas the failure in transverse compression occurs on a plane tilted at 30° to the loading direction, probably due to the resolved shear stress. The fractographic characteristics of transverse tensile and compressive failures are similar to those of longitudinal cracks forming in the fibre direction in axial tensile and compressive loading. In addition some areas of matrix cleavage are also to be seen on the fracture surface in transverse loading. These areas are characterized by river markings and fine flow lines which can be seen between them at high magnification.

6. Both transverse and axial compressive fracture surfaces contain areas covered with debris made up of crushed fibres and of the resin, which was formed by damage after the main failure.

7. In interlaminar shear testing the failure is due to cracks running in the fibre direction and which propagate mainly in the interply regions and to a lesser extent within the plies.

8. The morphology of failure of specimens which absorbed moisture before being tested at an elevated temperature is in general similar to that of "dry" specimens tested at room temperature. The absorption of moisture does, however, increase the fraction of failure occurring at the fibre–matrix interface.

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Received 1 October 1987
and accepted 26 January 1988