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A Preliminary Study of the Fracture Morphology of Acrylic Fibers

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Synopsis

A preliminary study has been made of the tensile and fatigue fracture morphology of acrylic fibers. Tensile breaks show a characteristic granular fracture surface which suggests the separate failure of fibrillar units in the fiber structure. In some instances, there are separate crack and final failure regions; in others, the fracture is in transverse steps linked by axial splits. The main characteristic in tensile fatigue is axial splitting of the fibers. The loading conditions for fatigue failure are less severe than in steady loading there is no zero minimum load criterion for fatigue failure as found in some other fibers.

INTRODUCTION

As part of a wide-ranging study of fiber fracture we have made some studies of acrylic fibers. As these show the essential character of the fracture morphologies in simple extension and in fatigue, and differ from the corresponding results for polyamide fibers reported by Hearle and Cross[1] and Bunsell and Hearle[2] and we are unlikely to be able to carry out a more detailed study for some time, we are reporting the initial findings here.

TENSILE FRACTURE OF COURTELLE

Figure 1 shows a scanning electron micrograph of the tensile fracture morphology of Courtelle (Courtauld's acrylic fiber); and the stress-strain curve of the fiber, as obtained on an Instron tester, at 65% R.H. at 20°C and a strain rate of 50%/min, is included in Figure 2. Normally, Courtelle is available only as a crimped staple fiber; but this study was conducted on 1.7 tex filaments from Courtelle tow obtained before the crimping process. The filaments as received are almost circular in cross section, with an irregular surface having nearly parallel grooves or striations in an axial direction. The tensile fracture is usually straight across the fiber, with moderate surface roughness, and shows little evidence of crack development. Sometimes, as in Figure 3, it is possible to see some distinction between what looks like an initial crack growth region and a catastrophic region. At some places, bundles of fibrils project above the main fracture surface.

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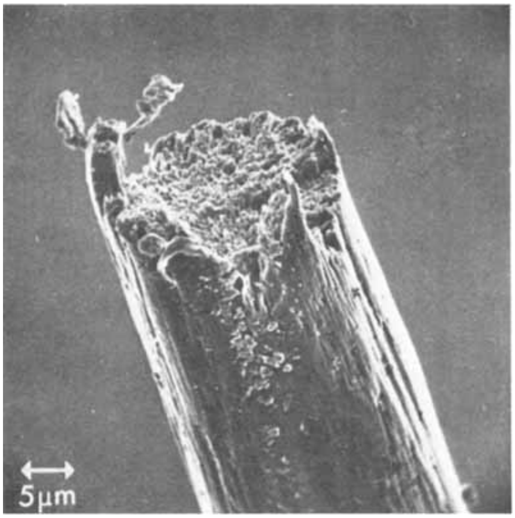


Fig. 1. Courtelle, 0.5 Tex, uncrimped tow. Tensile fracture.

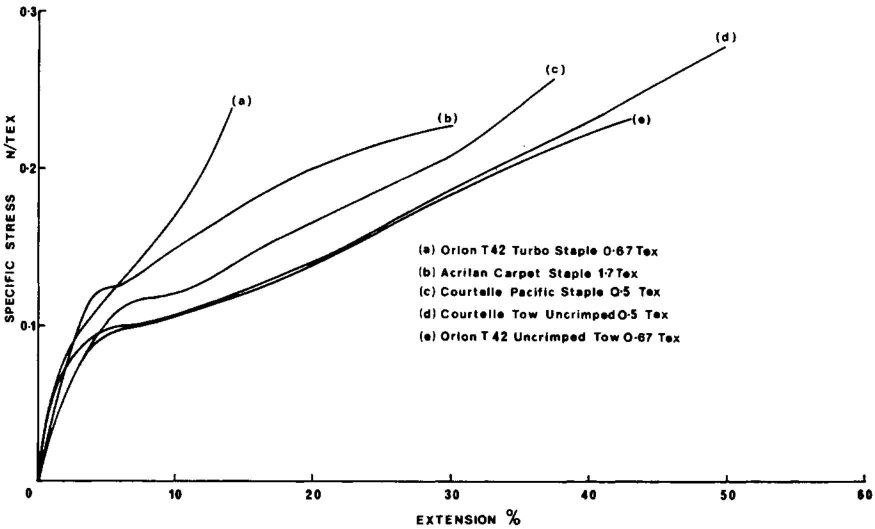


Fig. 2. Stress–strain curves of acrylic fibers.

The whole fracture surface is strikingly reminiscent of views of the fracture of reinforced fiber composites at a magnification too low to resolve the individual fibers. The Courtelle fiber fracture thus appears to fit into a category of break of material characterized by moderate cohesion between individual axially aligned fibrous elements, which in the acrylic fiber must be fibrillar units of the fine structure. Twisted filament yarns, as studied by Hearle and Thakur,[3] show the same features except that the cohesion due to twist is lost when fracture occurs. The effects have been very clearly demonstrated in some studies of larger-scale models of blended yarns by

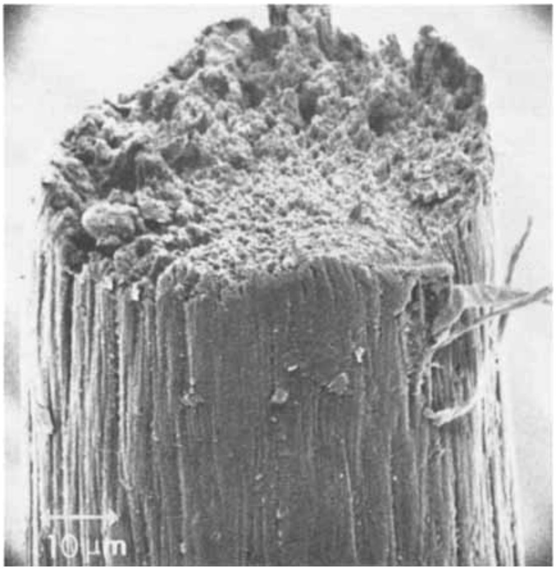


Fig. 3. Courtelle, 1.7 Tex, uncrimped tow. Tensile fracture.

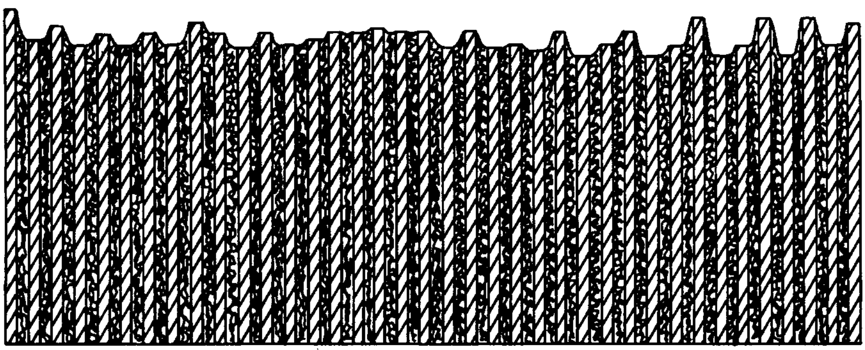
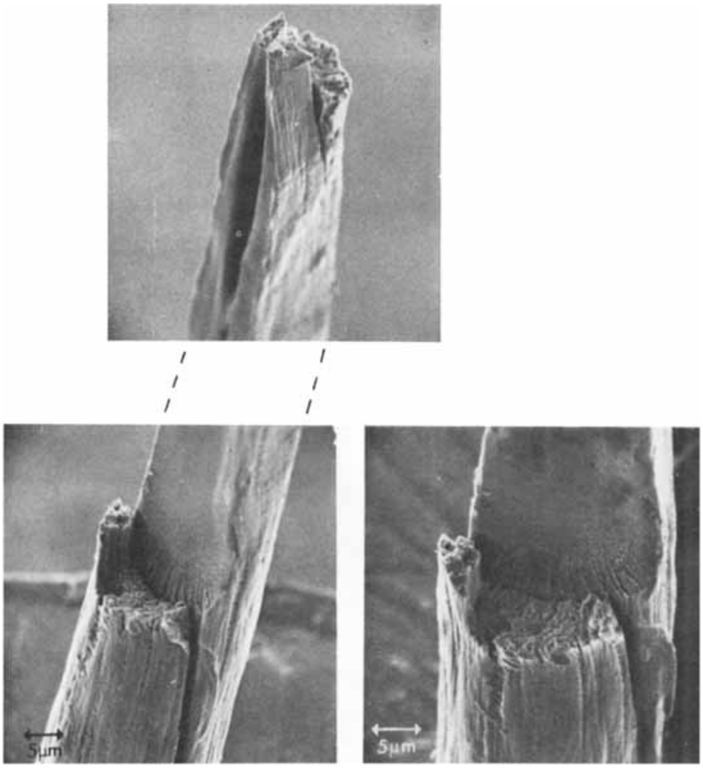


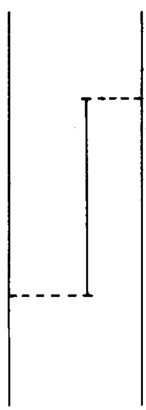
Fig. 4. Schematic representation of acrylic fiber fracture, based on fracture studies of yarns by Monego and Backer.[4]

Monego and Backer.[4] With little cohesion (low twist), the individual axial elements break separately at their weakest points which are distributed along the whole length of the test specimen; but with greater cohesion (moderate twist), the stress transfer which occurs near to an initial fracture is sufficient to cause the neighboring elements to break, and the whole system fails by successive fracture of individual elements in a narrow band across the specimen. This is illustrated in Figure 4 in a form which is more relevant to the Courtelle fiber, although the positions of the breaks of the individual fibrillar elements are based on the experimental observations of Monego and Backer on the large-scale yarn models. With very high cohesion within the structure, a well-defined crack propagation across the specimen would be expected to occur.

The schematic view in Figure 4 should not, of course, be taken as a realistic representation of the fiber structure of Courtelle. The fibrillar units can be regarded as more highly ordered regions and the matrix as less ordered, but in many ways one would expect the structure to be much less



(a) (b)



(c)

Fig. 5. (a) Courtelle, 0.5 Tex, uncrimped tow. Tensile fracture, showing tip and base of split. (b) Courtelle 0.5 Tex, uncrimped tow. Tensile fracture, detail of break. (c) Representation of linking of two fractured regions.

well-defined than that in Figure 4. The boundary between fibrils and matrix may be blurred; fibrils may vary in size, may terminate, may branch, or, perhaps most probably, may really be a fibrillar network. These uncertainties would not affect the main argument. It is possible that more

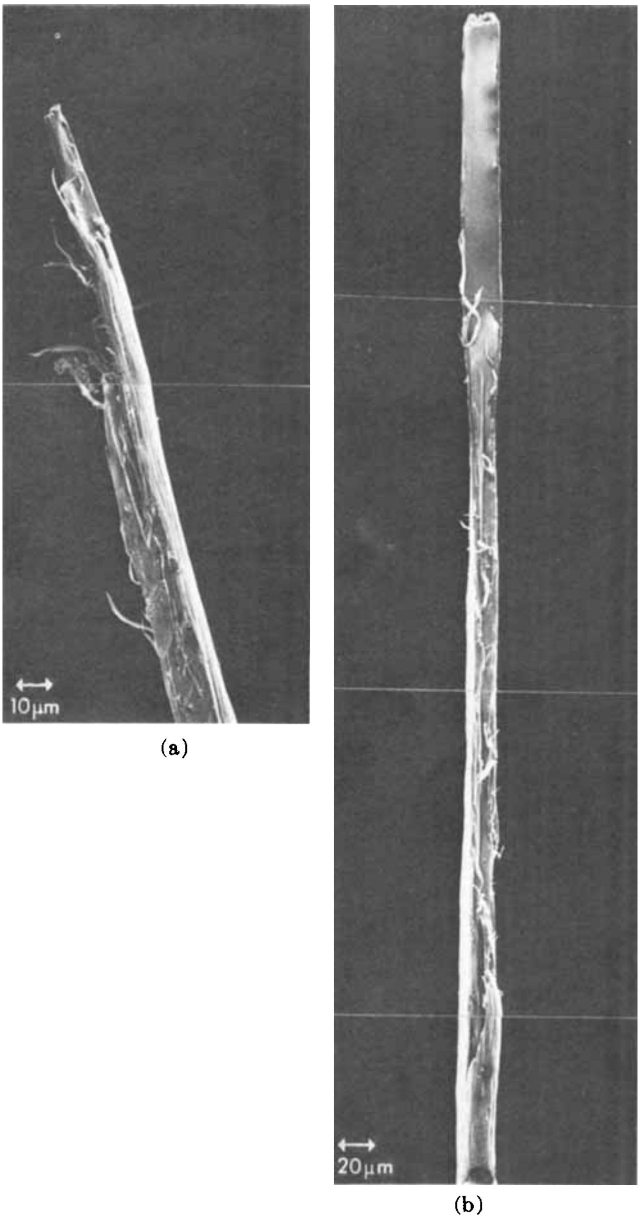
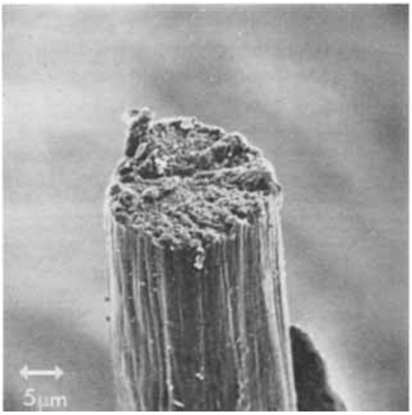
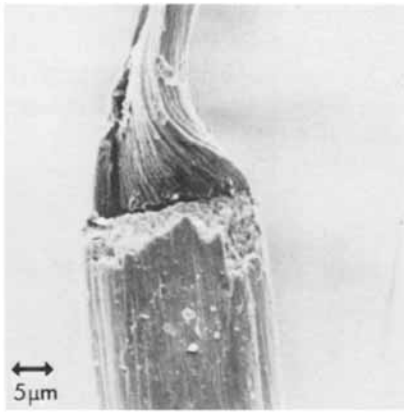


Fig. 6. (a) Courtelle, 0.5 Tex, uncrimped tow. Tensile fracture showing fibrillar end of long split break. (b) Courtelle, 0.5 Tex, uncrimped tow. Opposite end of (a) showing the considerable length of split.



(a)



(b)

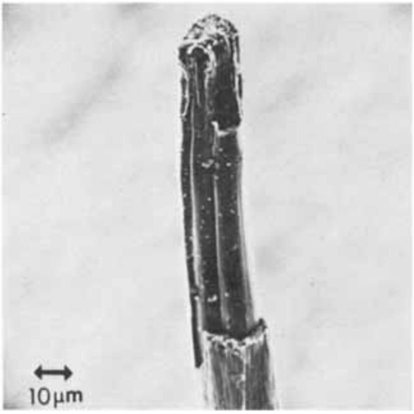
Fig. 7. (a) Courtelle, 0.5 Tex, staple made commercially by the Mackie Process. Tensile fracture perpendicular to fiber axis. (b) Courtelle, 0.5 Tex, staple Mackie Process. Tensile fracture showing fiber splitting up.

detailed studies of acrylic fiber fracture at higher magnification would yield useful information about the scale and form of the fine structure.

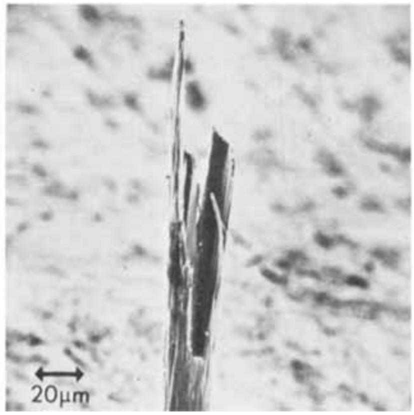
In tensile fracture of melt-spun fibers such as the polyamides, polyesters, or polypropylene, the break almost invariably starts at the surface, before proceeding by crack propagation. It has not usually been found possible in examining the breaks of Courtelle to identify the point at which break starts, but it seems possible that it is internal. We thus imagine a situation in which fibrillar units all over the structure are on the verge of failure, and as soon as one goes, the effects are transmitted to the neighbors and so across the fiber. The matrix between the individual fibrillar fractures is probably drawn out and then fractures as the molecules are pulled straight. In a low cohesion system, the matrix would fail by shear along the lines joining individual fibril breaks. The separate bundles projecting from the main fracture surface in Figure 1 will represent a situation where the fracture is displaced, and so this matrix shear has to occur.

In some instances, the fracture is divided into widely separated regions joined by a split, as in Figures 5a and 5b. Presumably, this arises because two different fracture regions are linked by a shear failure along the line joining them, as indicated in Figure 5c. There is often considerable fibrillation in these circumstances, as shown in Figure 6a. Another example of extreme splitting is shown in Figure 6b, which is the opposite end to that of Figure 6a. The break in the Courtelle fiber has presumably started simultaneously at two widely separated points in the fiber, and the separate fracture regions have then been joined by the long axial split.

We also examined the fracture of Courtelle fibers which had been converted to staple by the Mackie and the Pacific processes for conversion of continuous filament tow into staple fiber. Examples are shown in Figures 7 and 8, respectively. Those converted by the Mackie process mainly



(a)



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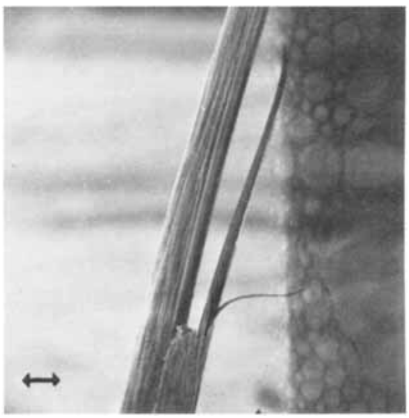


(c)

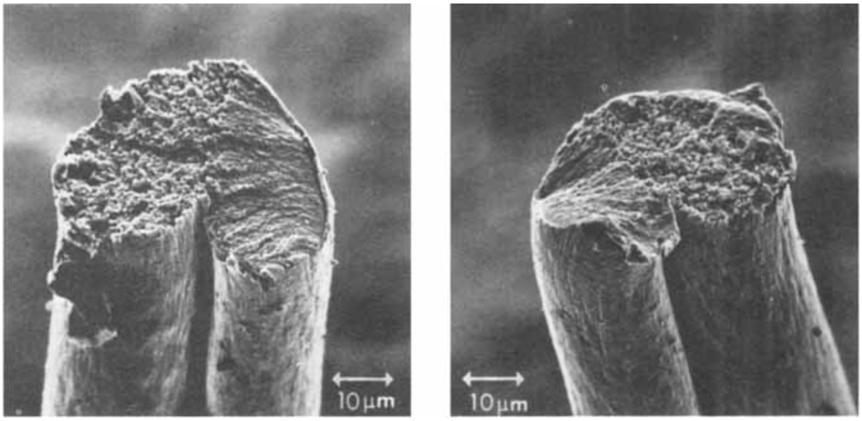
Fig. 8. (a) Courtelle, 0.5 Tex, staple made commercially by Pacific converter. Tensile fracture. (b) Courtelle, 0.5 Tex, staple-Pacific converter. Tensile fracture showing fiber splitting up. (c) Courtelle 1.7 Tex, uncrimped tow. Tensile fracture.

broke (under simple tensile loading) straight across the fiber, whereas the Pacific type showed marked splitting sometimes into layers which revealed a smooth internal surface (Fig. 8a).

TENSILE FRACTURE IN OTHER ACRYLIC FIBERS

Most other acrylic fibers show tensile fractures which are generally similar in form, although with some significant differences which must result from the different minor components and spinning methods. There are distinct differences in the mechanical properties of the different fibers as indicated by the stress–strain curves in Figure 2.

The 1.7 tex Acrilan (Monsanto's acrylic fiber) carpet staple, in contrast to all the other results so far, does show a well-developed crack region. The



(a) (b)

Fig. 9. Opposite ends of Acrilan 1.7 Tex carpet staple, broken in tension.

opposite ends of a broken fiber, in Figure 9, show a V-notch, which is similar in shape to that occurring in the tensile fracture of nylon and polyester fibers. The notch region leads to a region of catastrophic failure. The finer detail of both the crack and catastrophic region do, however, show the same rather granular sort of texture that is found in the tensile breaks of the other acrylic fibers. Presumably, in this instance the spacing and cohesion of fibrillar units is such that break is initiated at or very near to the fiber surface and transmitted from one fibrillar unit to the next, thus giving crack formation, while the material in the remainder of the cross section extends plastically (draws) so as to open the crack. Finally, catastrophic failure occurs on the reduced cross section. There is some evidence of the existence of a skin on the Acrilan fiber, and it is not uncommon for portions of the fiber in the skin, or at least near the surface, to be broken separately and appear as a projection on one end with a matching region stripped from the other end.

Orlon (du Pont's acrylic fiber) type 42, which is a dry-spun fiber, in contrast to the wet-spun Acrilan and Courtelle, commonly shows a fracture which is usually broken up into separate portions over lengths of the order of a fiber diameter or more (Figs. 10a and 10b). Sometimes, the fiber splits considerably on breaking, as in Figure 10c (similar in some characteristics to certain Courtelle breaks, e.g., Figs. 7b and 8c), and the breaks are divided into widely separated regions linked by a split. As with some of the Courtelle breaks, the inner surfaces of the splits are relatively smooth, as shown in Figure 10d. Not all Orlon fibers break by splitting, and some fractures are perpendicular to the axis of the fiber (Fig. 10e). The fine detail of the Orlon fracture surface usually shows the granular appearance found in other acrylic fibers (Fig. 10f).

The bicomponent Orlon Sayelle 21 and 23 behave in a similar manner on fracturing. Figure 11a shows a split break in Orlon Sayelle 21, and Figure

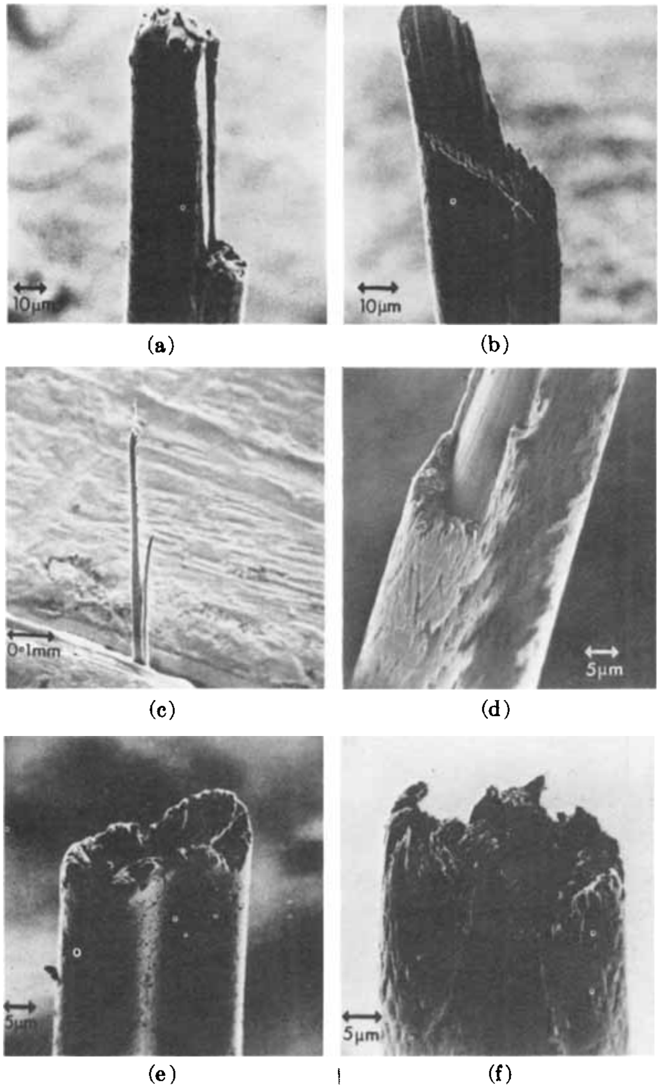
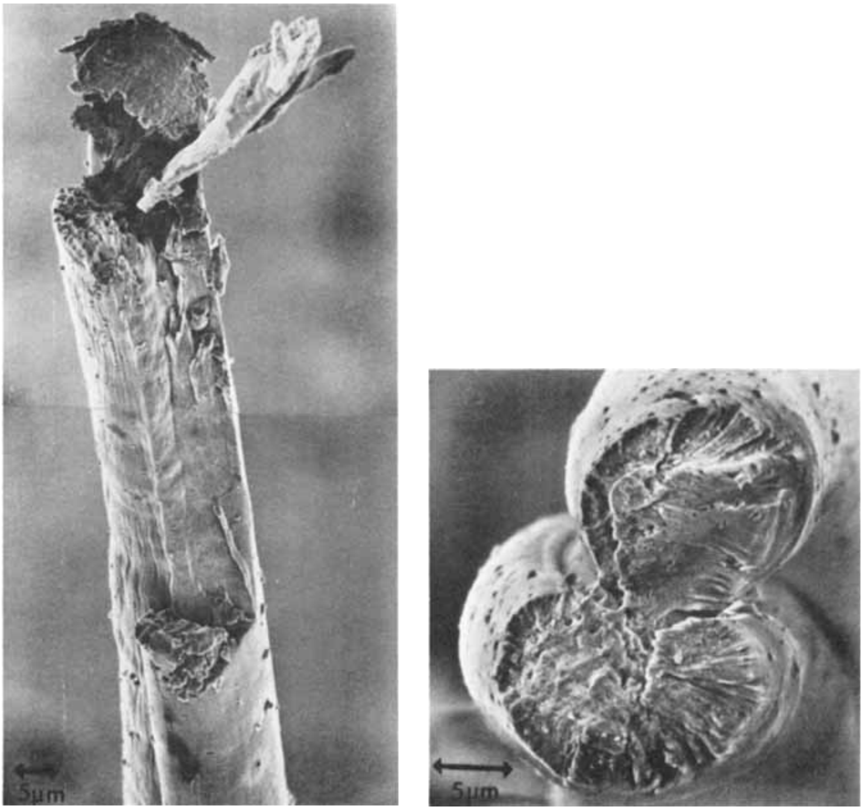


Fig. 10. Tensile fractures of Orlon 42. (a) 0.7 Tex, high bulk staple, split break. (b) 0.7 Tex, crimped tow, split break. (c) 0.7 Tex, Turbo process staple, split break. (d) 0.7 Tex, Turbo process staple, smooth surface in split region. (e) 0.7 Tex, Turbo process staple, break perpendicular to fiber axis. (f) 0.7 Tex, Turbo process staple, rough appearance of fracture surface.

11b, a perpendicular break (the only type of break found so far) in Sayelle 23.

FATIGUE FAILURE OF COURTELLE

Courtelle fibers, of the type described above, have also been tested on the tensile fatigue tester developed by Bunsell, Hearle, and Hunter.[5] Under



(a) (b)

Fig. 11. (a) Orlon Sayelle 21, bicomponent fiber, 0.7 Tex. Tensile break. (b) Orlon Sayelle 23, bicomponent fiber, 0.7 Tex. Tensile break.

dynamic loading at 65% R.H. and 20°C, Courtelle fibers were found to fail after about 10^5 cycles at 50 Hz when the maximum load was only 70% of the steady load needed to cause fracture. The effective "fatigue tenacity" of the fiber was thus less than about 0.15 or 0.2 N/tex in comparison with the ordinary tenacity of 0.25 N/tex. Much more extensive testing would be needed to establish the detailed relations between fatigue life and test conditions, but sufficient repetition has been done to justify the above comment. In contrast to the behavior of nylon reported by Bunsell and Hearle,[2] it is not a necessary condition of fatigue failure in the acrylic fibers that the minimum load should be zero or less. Any dynamic loading pattern will lead to fatigue failure, provided its level is high enough, though not so high as to induce immediate tensile failure. Even a small dynamic load superimposed on an appropriate steady load will cause fatigue failure to occur. Figure 12 shows the steady load and the oscillatory load amplitude for Courtelle fibers which have failed by fatigue. As can be seen from this graph, fatigue failure occurs over a wide range of oscillatory loads, and the

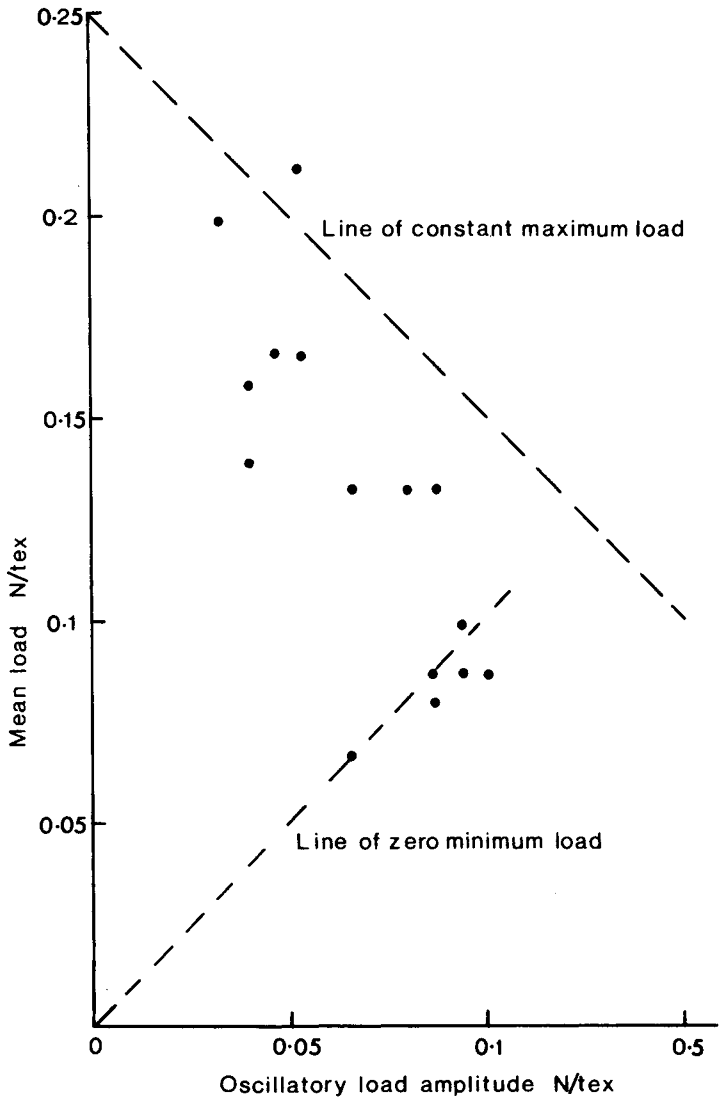
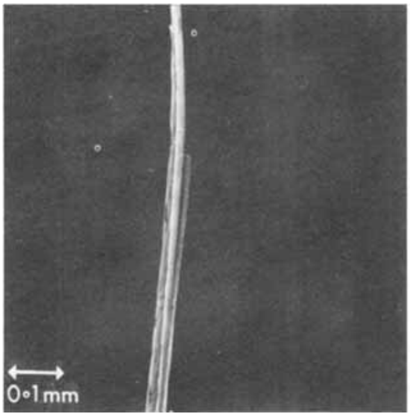


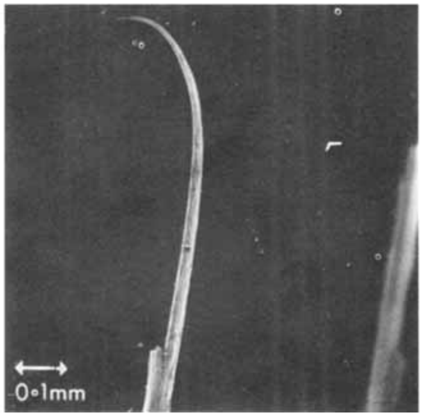
Fig. 12. Failure conditions for tensile fatigue of Courtelle fibers.

points are neither related to the line of constant maximum load nor zero minimum load, as they are in some melt-spun synthetic fibers.

The fracture morphology of the fatigued Courtelle fiber is illustrated in Figure 13. The predominant consequence of the dynamic loading is axial splitting in the fiber: there is no evidence that this starts on the surface, and indeed the cracks may be wholly internal. Any slight deviation of the crack from perfect alignment with the fiber axis will then lead to the situation shown in Figure 14. The whole load on the fiber has to be taken by a reduced cross section represented by A B and C D. Eventually, when the



(a)



(b)

Fig. 13. Opposite ends of Courtelle, 1.7 Tex, uncrimped tow, broken in tensile fatigue.

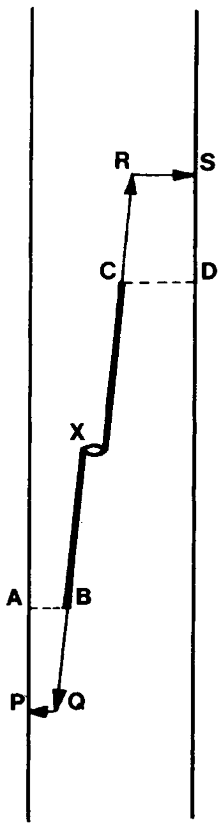


Fig. 14. Schematic representation of nature of axial splitting in fatigue.

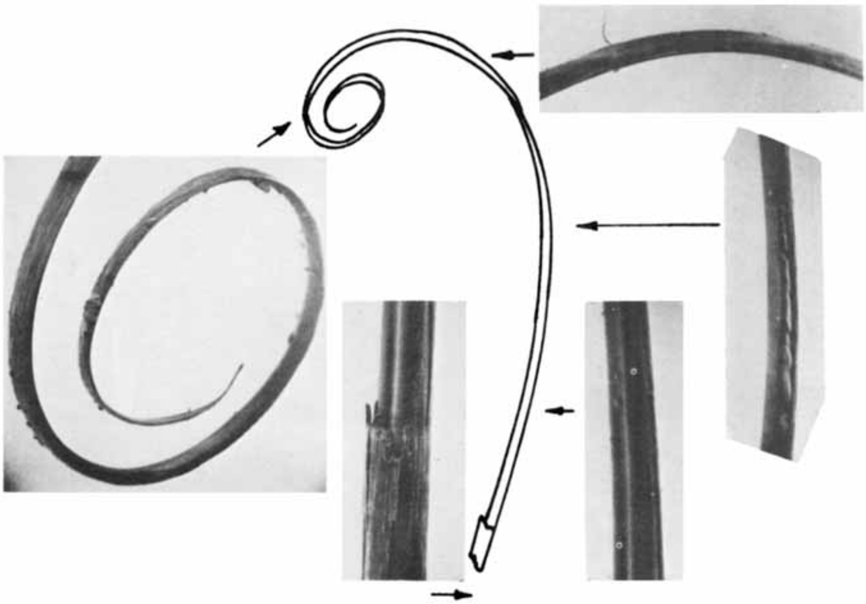
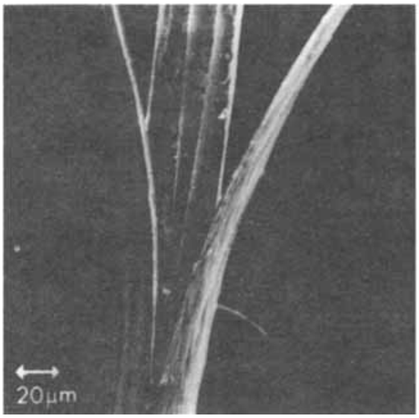


Fig. 15. Courtelle, 1.7 Tex, uncrimped tow, broken in tensile fatigue. Inserts illustrate various sections of the long split region.

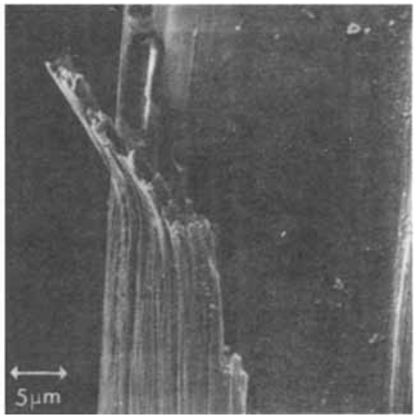
crack has extended to Q and R, the stress is sufficient to cause tensile failure over the reduced area P Q and R S. The fatigue life will thus be determined by the relation between the rate of crack propagation, the deviation from the axis in each cycle, and the extent of area reduction needed to cause the stress resulting from the applied load to reach the tensile strength of the fiber.

It is fairly easy to see how the axial splitting would occur in a fibrillar structure. As illustrated in Figure 14, any nonuniformity at X, such as a local void, a fibril end, a fibril branch, or even slight variation in fibril or matrix dimensions or structure, would lead to shear stress in the matrix between fibrils. A cyclic shear stress, which necessarily implies tension–compression cycling, is a form of deformation which seems particularly likely to cause fatigue failure and thus cause a split to start. When the split has started, the shear stress will be located at the ends of the split and may be greater, and so the fatigue splitting will continue. Local structural variations will cause the slight deviation of the split from the axial direction.

As shown in Figure 14, details of the fracture morphology, while conforming to the above general description, do show interesting variations. The split can be very long, extending over many fiber diameters, and these long breaks tend to curl as shown in Figure 15; the inserts show the surface features at various places along the split region. The fiber may separate into three or more strips on breaking (Fig. 16a), and often the exposed internal surface is smooth (Fig. 16b) compared with external surface of the fiber.



(a)



(b)

Fig. 16. (a) Courtelle 1.7 Tex, uncrimped tow. Fiber split into three parts during tensile fatigue testing. (b) Courtelle, 1.7 Tex, uncrimped tow, tensile fatigue. Smooth inner surface of split region.

CONCLUSIONS

The most characteristic feature of acrylic fiber fractures is the apparent dependence on a fibrillar fine structure. This is shown up by the marked splitting which occurs, particularly in fatigue failure and in fibers which have previously been highly stretched. Crack development does not occur in tensile fracture as clearly as it does in nylon and other melt-spun synthetic fibers.

The other marked difference from the melt-spun synthetics is the granular appearance of the fracture surface, which almost certainly reflects a failure of fibrillar bundles within the fiber. Similar granular surfaces can be seen in parts of cotton fiber fracture as reported by Hearle and Sparrow,[6] and in the fracture of rayon and wool fibers.[7]

The appearance of tensile fracture of a carbon fiber (made from an acrylic precursor material) shown by Whitney and Kimmel[8] is also very similar to the acrylic fractures.

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