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The flex fatigue of polyamide and polyester fibres

Part II *The development of damage under standard conditions*

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Polyamide and polyester fibres have been subjected to flex fatigue by pulling to and fro over a pin, in order to investigate the alternative damage modes, namely cracks along kink-bands due to compression, and axial splitting due to shear stresses. Initial studies determined the conditions that were sufficiently severe to give a short enough test time but not so severe that abrasion on the pin was dominant. Fibres were then cycled for varying periods, the damage viewed in a scanning electron microscope, and the change in tensile properties, including residual strength, determined.

1. Introduction

The previous paper, Part I [1], described a test method for flex fatigue of fibres, which involved pulling a fibre backwards and forwards over a pin under controlled tension with the same side of the fibre always maintaining contact with the pin. Earlier work at UMIST, reviewed in a book on fibre failure [2], had shown that three forms of damage could occur in this sort of test.

Firstly, it is well known that the compression of oriented polymer fibres, for example on the inside of a bend, leads to the formation of kink bands, which can be seen in a polarized light microscope or in a scanning electron microscope (SEM). A single bend does not lead to any loss of strength, but under repeated bending the damage becomes more pronounced and may eventually lead to a complete breakdown of the kink band into a crack.

Secondly, axial splitting is observed. This results from the shear stress associated with variable curvature, as described in text-books of the mechanics of materials [3], or, possibly, from the shear stress at the tip of the kink band crack.

Thirdly, wear at the contact between fibre and pin may remove material, in which case the effect is one of abrasion and not of flexing.

The first part of this paper describes flex fatigue tests on commercial nylon 6, nylon 66 and polyester (polyethylene terephthalate) fibres, in order to determine conditions that avoid the dominance of abrasion but give an acceptable time for each fatigue test. SEM studies of fatigued filaments were used to identify which mechanisms were operative. The results were used to select conditions for a set of tests intended to rank the fibres in order of durability and evaluate the statistical variability. The same conditions were used in tests to investigate the effect of temperature and humidity, which have already been reported [1]. The second part of the paper describes experiments designed to observe in more detail the progressive development of damage as a way of studying the two flex effects and the sequence in which they occur. Further details of the instrumentation and the fibres tested have been given elsewhere [1, 4].

2. Experimental procedure

2.1. Test conditions

The principal parameters determining the result of a flex fatigue test are listed below. The first two have a major influence on the fatigue damage and are varied in the exploratory tests. The others were held constant.

(i) Bending curvature: the radius of curvature of the fibre axis equals the sum of the radii of pin and fibre; the nominal bending strain (tensile on the outer edge and compressive on the inner edge; assuming the neutral plane remains central) equals the ratio of fibre radius to pin radius.

(ii) Tension: the specific tensile stress equals the tension divided by the linear density; this is expressed in N/tex, equal to GPa g^{-1} cm^3.

(iii) The nature of the pin surface: hypodermic needles were used because of their high durability and smooth surface.

(iv) Frequency of cycling: the vibrator was run at 50 Hz.

(v) Amplitude of movement over the pin: this was set at 2.5 mm.

(vi) Environment: the tests were run in a standard laboratory atmosphere of 65% R.H. and 20 °C.

(vii) The fibre type: the fibres studied were commercial nylon 6 hosiery monofilament (Courtaulds), and

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filaments from high-tenacity industrial multifilament nylon 6.6 and Dacron polyester yarns (DU PONT), as made in the early 1980s.

(viii) The fibre shape and dimensions: the fibres were circular with the following linear densities and diameters, 22 dtex, 48 μm for nylon 6, 13.6 dtex, 39 μm for nylon 6.6, and 13.3 dtex, 35 μm for polyester. (1 dtex = 0.1 $g\,km^{-1}$ or 0.9 denier.)

(ix) The fibre surface. The fibres had the commercial finish as applied by the manufacturers; information is proprietary and not disclosed.

In the first series of tests, the bending strain was held constant, but the tension was varied. In the second series, different pins were used to change the curvature, keeping the tension constant. It was decided that 3 h (about 500 000 cycles) was a practical time limit, and when the fibre had not failed the test was stopped and the conditions regarded as insufficiently severe. Fibres that failed were examined in the SEM.

The test conditions used and the results of the tests are shown in Table I. Although the boundaries are not sharp, Fig. 1 summarizes the test conditions suitable for fatigue testing. Below the marked ranges, tests take too long; above the marked ranges, abrasion is severe. The conditions selected for further studies are marked in Table I.

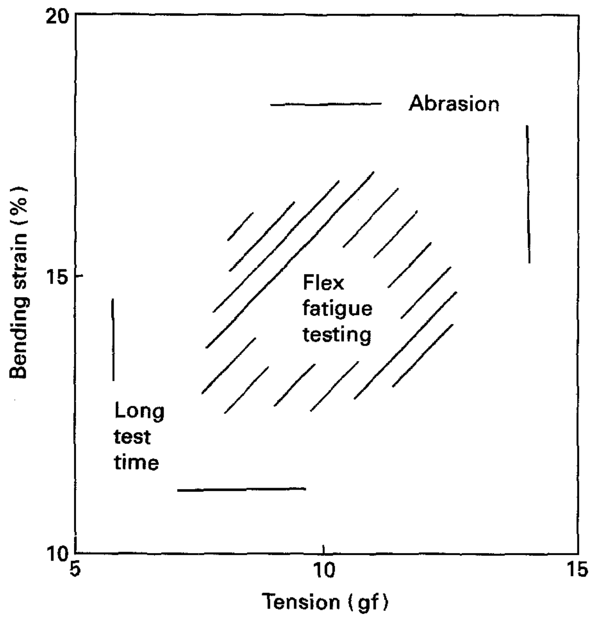


Figure 1 Test conditions for fatigue testing.

2.2. SEM examination

Fig. 2a–f contrasts failures (a, c, e) under more severe conditions, with extensive surface abrasion, with those (b, d, f) under less severe conditions, dominated by axial splits and kink-band cracks. The peeling away of surface layers, most clearly shown in Fig. 2a, is similar to that occurring in some end-use situations, such as inter-strand and inter-yarn abrasion in nylon ropes. In Fig. 2c, the surface wear clearly shows up the kink-bands within the fibre.

In order to illustrate in more detail the form of flex fatigue failure, Fig. 3a–f gives examples of fibres tested in the standard laboratory atmosphere under the standard conditions marked in Table I. The nylon fibres show a combination of kink-band cracks with axial splits, but, in polyester, the kink-band cracks, if present, are completely obscured by the extensive fibrillation. Changes in the form of damage with temperature and humidity will be reported in another paper.

2.3. Fatigue lifetimes

Fig. 4 gives the survivor diagrams for fibres tested under standard conditions and statistical parameters are given in Table II. The nylon 6.6 and polyester fibres have been drawn and heat treated in manufacture to give similar high strengths and low extensibilities, as required for industrial uses. Consequently, the differences in lifetimes reflect the superior resistance of polyester to flex fatigue. The shorter life of the nylon 6 fibres is due to the fact that these are weaker and more extensible fibres intended for an apparel use. The variability of around 35% is typical of fatigue testing of fibres and results from the inherent variability of dimensions and structure and the random occurrence of weak places.

3. Development of fatigue damage

3.1. Experimental procedure

In order to observe the progressive effects of flex fatigue cycling, eight tests per fibre type were carried out under the standard conditions noted above for the following periods: 3, 6, 9, 12, 15 and 20 min; the numbers of cycles were thus 9000, 18 000, 27 000, 36 000, 45 000 and 60 000. At the end of each period, the instrument was switched off and the specimens were

TABLE I Tension and curvatures imposed on fibres in exploratory tests: *italic* entries lasted more than 3 h; **bold** entries showed severe abrasion

Pin diameter (mm)	Nylon 6						Nylon 6.6						Polyester					
	Bending strain (%)	Tension (g)					Bending strain (%)	Tension (g)					Bending strain (%)	Tension (g)				
0.20	19.4	**10**	**11**	**12**	**13**	**14**	16.4	8	9	10	11	**12**	15.5	**8**	**9**	10	**11**	**12**
0.22	17.9	10	11	12	13	**14**	15.1	8	9	10	11	**12**	13.8	8	9	10	11	**12**
0.25[a]	16.1[a]	10	11	12[a]	13	**14**	13.5[a]	8	9	10[a]	11	**12**	12.4[a]	8	9	10[a]	11	12
0.28	14.6	10	11	12	13	14	12.2	*8*	*9*	10	11	**12**	11.2	*8*	*9*	10	11	12
0.30	13.8	*10*	*11*	12	13	14	11.5	*8*	*9*	*10*	11	12	10.5	*8*	*9*	*10*	11	12

[a] Conditions selected for standard tests.

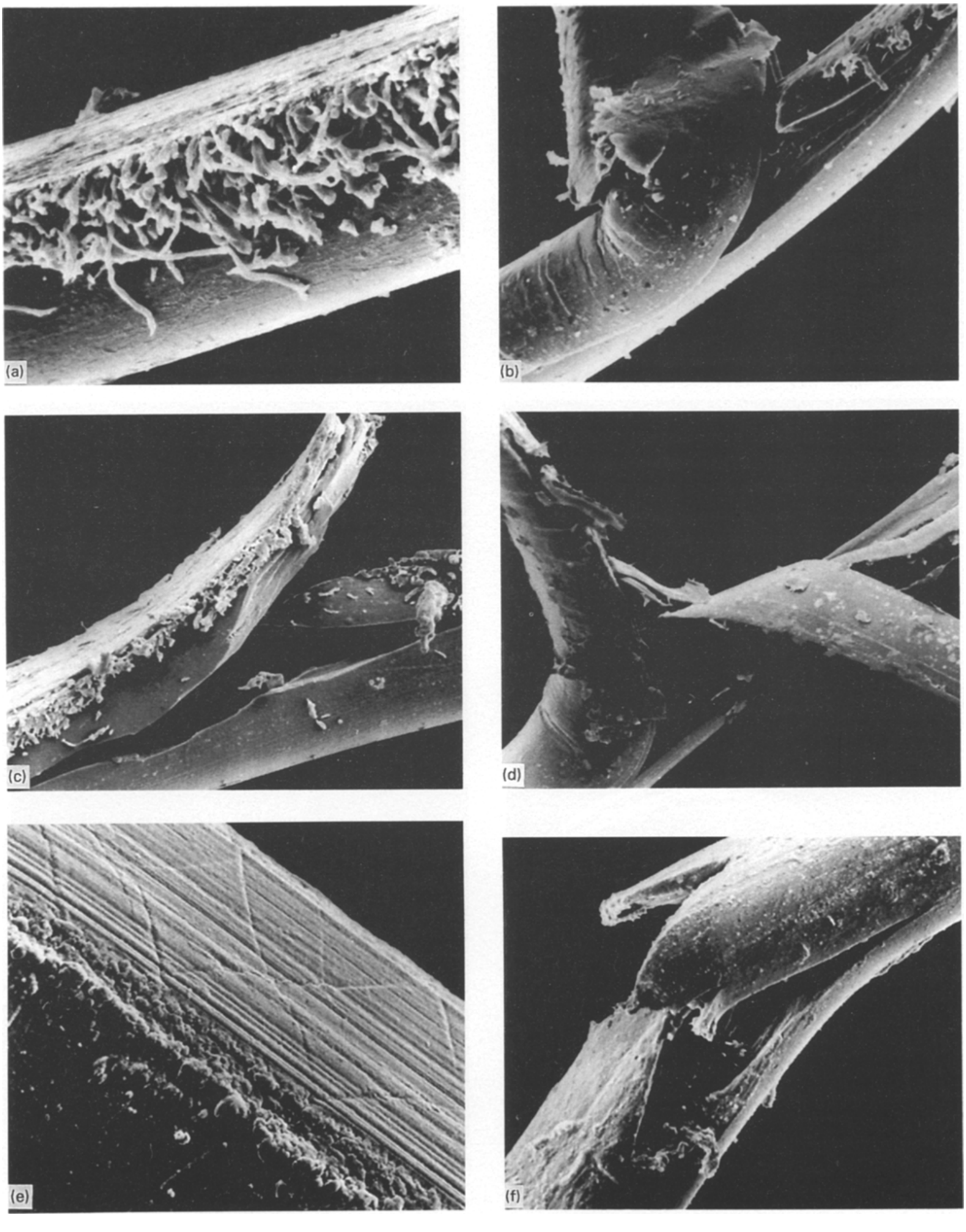


Figure 2 SEM views of fibres after testing under various conditions of bending strain (%) and tension (gf): (a) nylon 6, 19.4%, 10 gf, 21 000 cycles; (b) nylon 6, 16.1%, 12 gf, 19 250 cycles; (c) nylon 6.6, 12.2%, 12 gf, 52 750 cycles; (d) nylon 6.6, 13.5%, 10 gf, 53 100 cycles; (e) polyester, 15.5%, 9 gf, 81 250 cycles; (f) polyester, 12.4%, 10 gf, 83 750 cycles.

carefully removed. Four fibres from each set were examined under the scanning electron microscope and the other four were tested on an Instron tester to determine their stress–strain curve and residual strength. The broken ends of these specimens were also saved for scanning electron microscopic examination. Where necessary, further tests were carried out for intermediate periods, and some tests were allowed to run for as long as 40 min.

3.2. SEM observation of gradual fatigue

Figs 5 and 6 show the appearance of nylon fibres after increasing amounts of flexing. There are no great differences between the behaviour of nylon 6 and nylon 6.6.

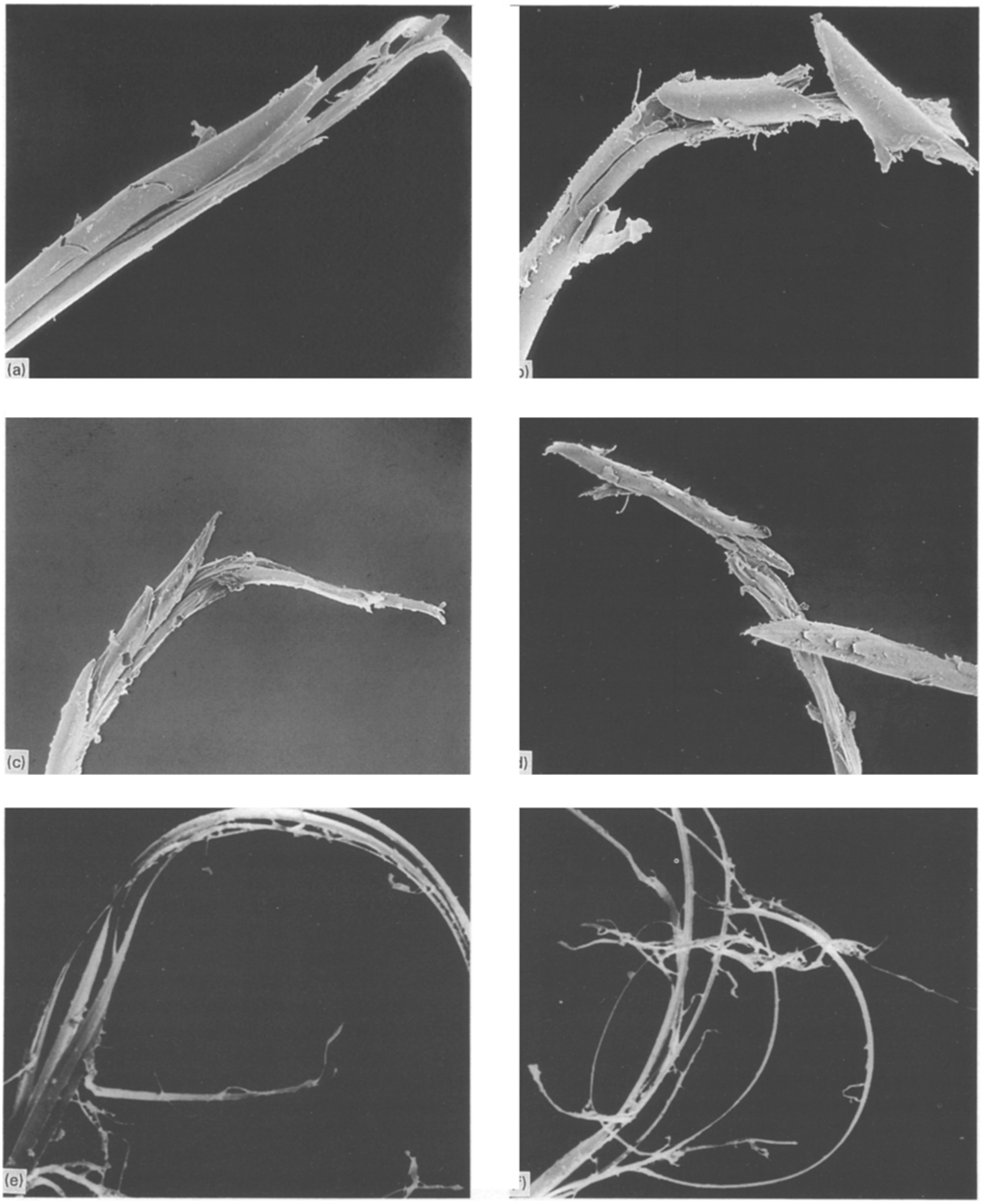


Figure 3 SEM views of fibres broken under standard conditions: (a) nylon 6, 31 000 cycles; (b) nylon 6, 48 250 cycles; (c) nylon 6.6, 114 750 cycles; (d) nylon 6.6, 159 950 cycles; (e) polyester, 102 650 cycles; (f) polyester, 195 150 cycles.

TABLE II Numbers of cycles to failure for fibres tested under standard conditions

	Nylon 6	Nylon 6.6	Polyester
Mean	35 825	104 807	194 616
Median	34 725	98 050	187 825
Standard deviation	11 398	35 387	84 515
Coefficient of variation	31.77%	33.68%	43.65%
Minimum to failure	18 750	49 950	70 000
Maximum to failure	69 900	210 000	360 070

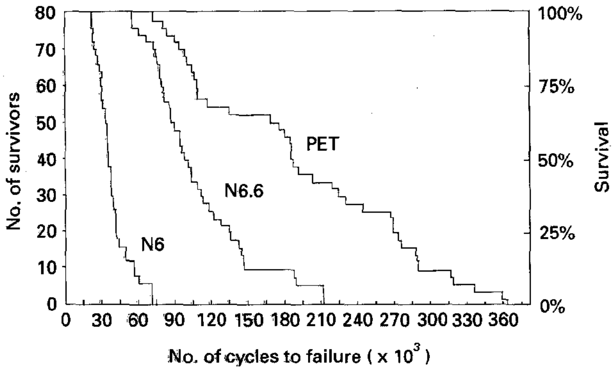


Figure 4 Survivor diagram for 20 tests of each fibre under standard conditions.

Some nylon fibres show a concentration of kink bands on the compression surface after a few hundred cycles of flexing. Once kink-bands appear, their number and location do not seem to increase with increasing period of flexing but they become more pronounced. Generally, as the number of flex cycles increases, abrasion caused by the pin gradually eludes the surface detail of kink-bands. But, once fracture begins from the compression surface, it usually develops at an angle to the fibre axis along a kink-band.

However, after about 30 000 cycles, a long central split is observed along the bending zone. The part on the compression side is then fractured at a kink-band, to leave two tails sticking out from the fibre. The other undamaged half of the fibre is then subject to the full effect of flexing. After further weakening, this half then suffers a typical tensile failure. Because tensile failures initiate from weak points on the surface, the final separation can occur anywhere along this arm.

The polyester fibres are shown in Fig. 7. Kink-bands appear almost instantaneously all along the flexing zone and they remain visible even after layers of the fibre are abraded away. At a later stage, axial splitting appears and, in contrast to nylon develops into multiple splitting. Finally, the separate fibrils break: this is probably a mixture of rupture along kink-bands and tensile breaks, but, as is obvious from Fig. 2f, the situation is too confused to be precise about this.

3.3. Deterioration of tensile properties

The stress–strain curves after different periods of cycling, averaged for four specimens, are presented in Figs 8–10. They all indicate a gradual loss in strength

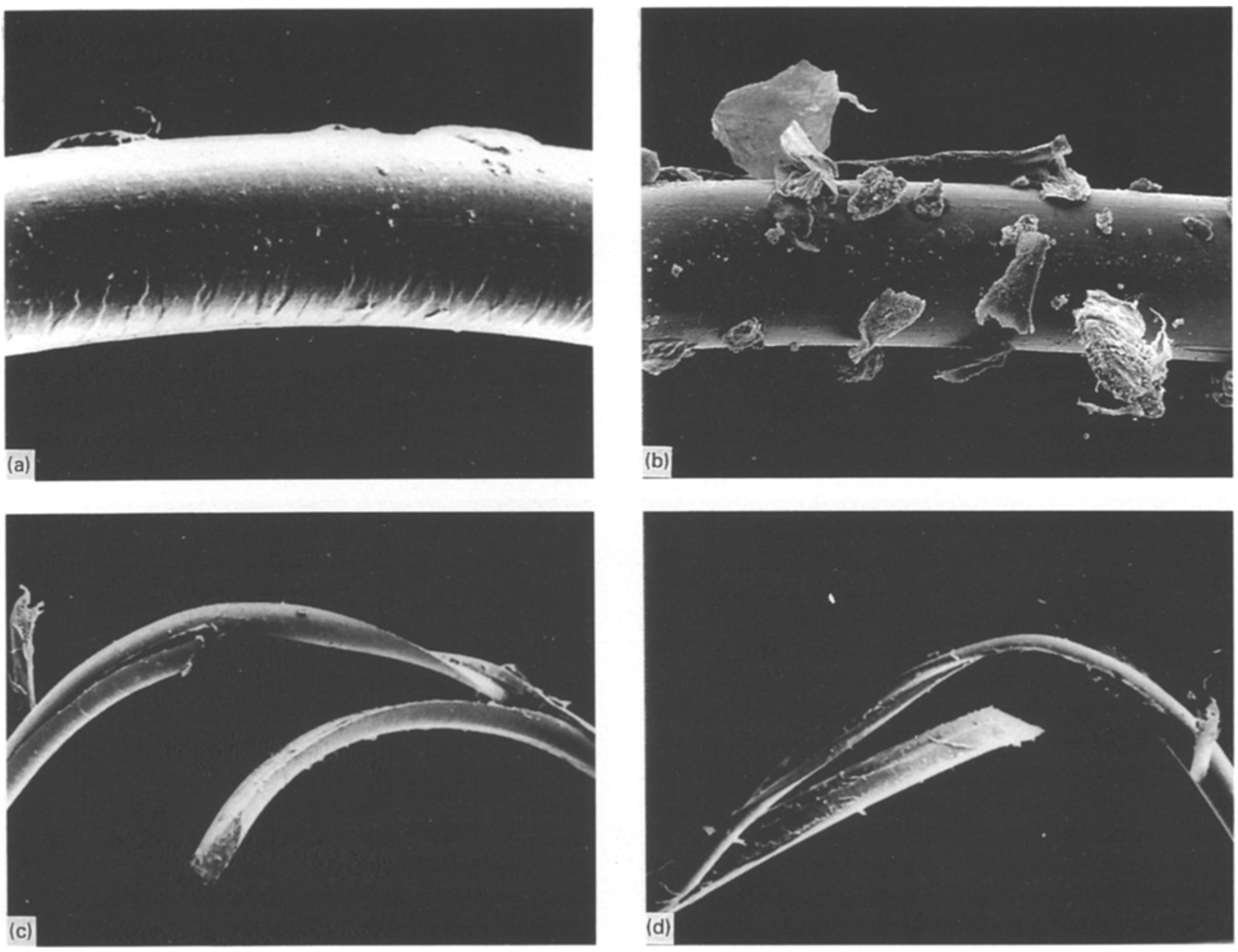


Figure 5 Progressive damage in nylon 6 fibres: (a) 5 min, 15 000 cycles; (b) 10 min, 30 000 cycles; (c) 15 min, 45 000 cycles; (d) 15 min, 45 000 cycles; (e) 15 min, 45 000 cycles; (f) 15 min, 45 000 cycles.

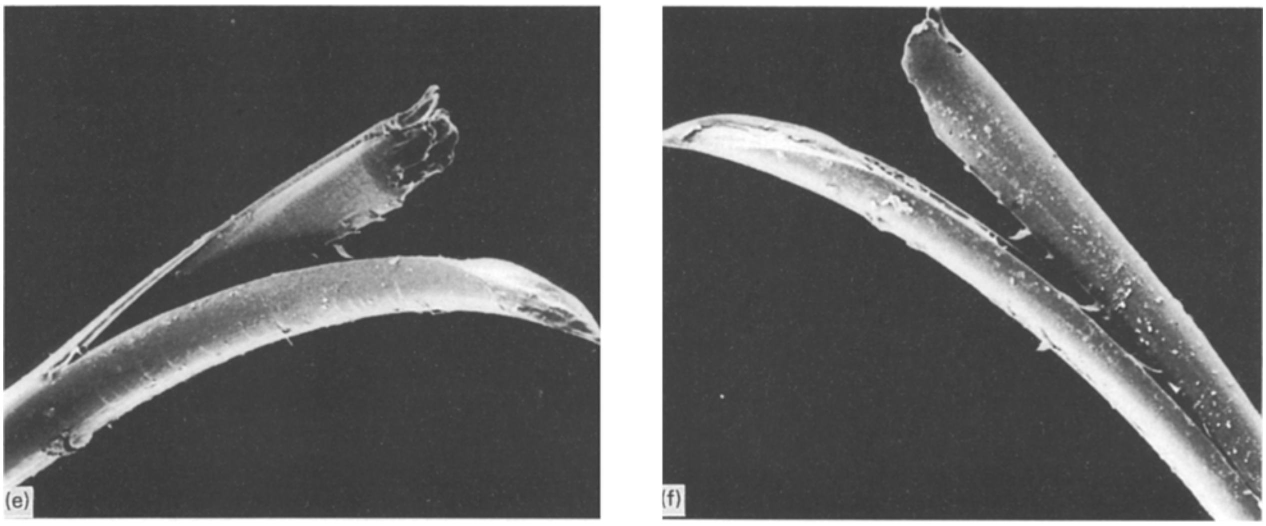


Figure 5 (Continued)

with increasing period of flexing due to weakening of the fibre by the flexing. Some samples, not shown on these graphs, registered no loss in strength after up to 3 min cycling.

It must be remembered that only 2.5 mm of the fibre length tested in the Instron has been subject to flex fatigue on the pin. Consequently, the load–elongation properties will be dominated by the undamaged portions, and it is therefore not surprising that the same stress–strain curve is followed from the origin. However, the nylon curves do diverge before rupture, indicating a strong additional yield effect after flexing. This is only shown in polyester after the longest period of flexing.

Fig. 11 shows an approximately linear reduction in residual strength with number of cycles.

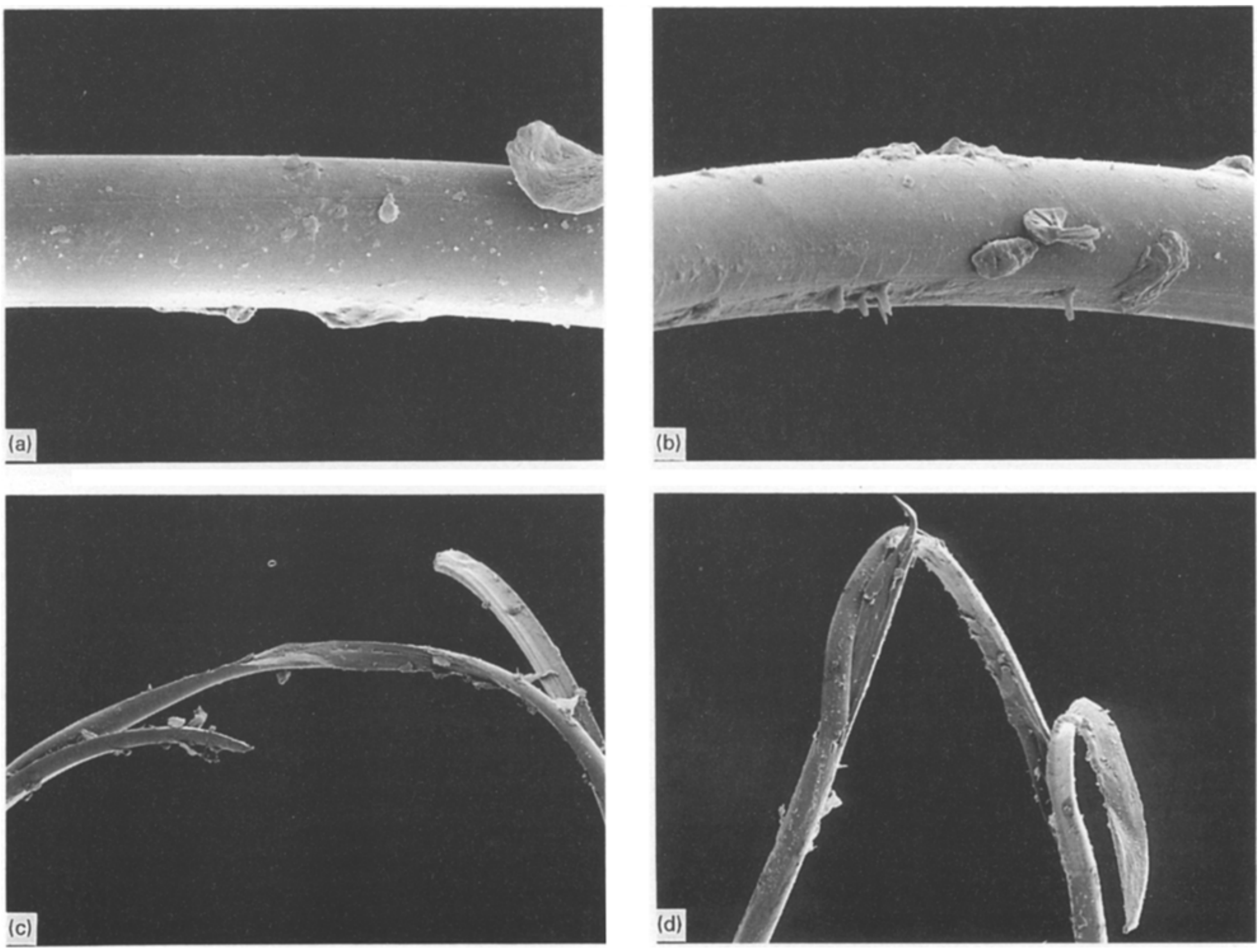
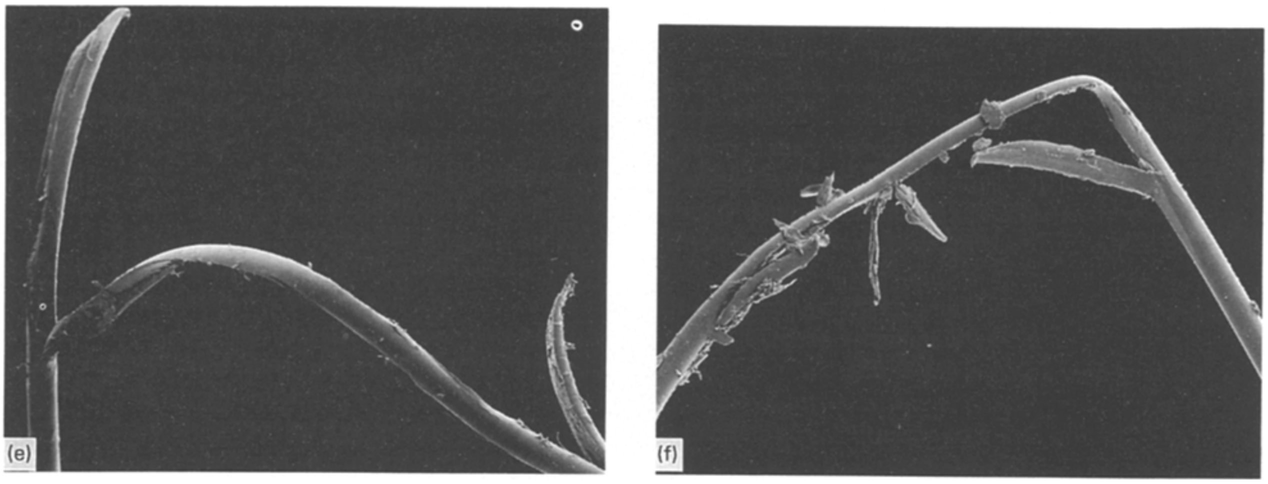


Figure 6 Progressive damage in nylon 6.6 fibres: (a) 5 min, 15 000 cycles; (b) 10 min, 30 000 cycles; (c) 20 min, 60 000 cycles; (d) 20 min, 60 000 cycles; (e) 30 min, 90 000 cycles; (f) 40 min, 120 000 cycles.



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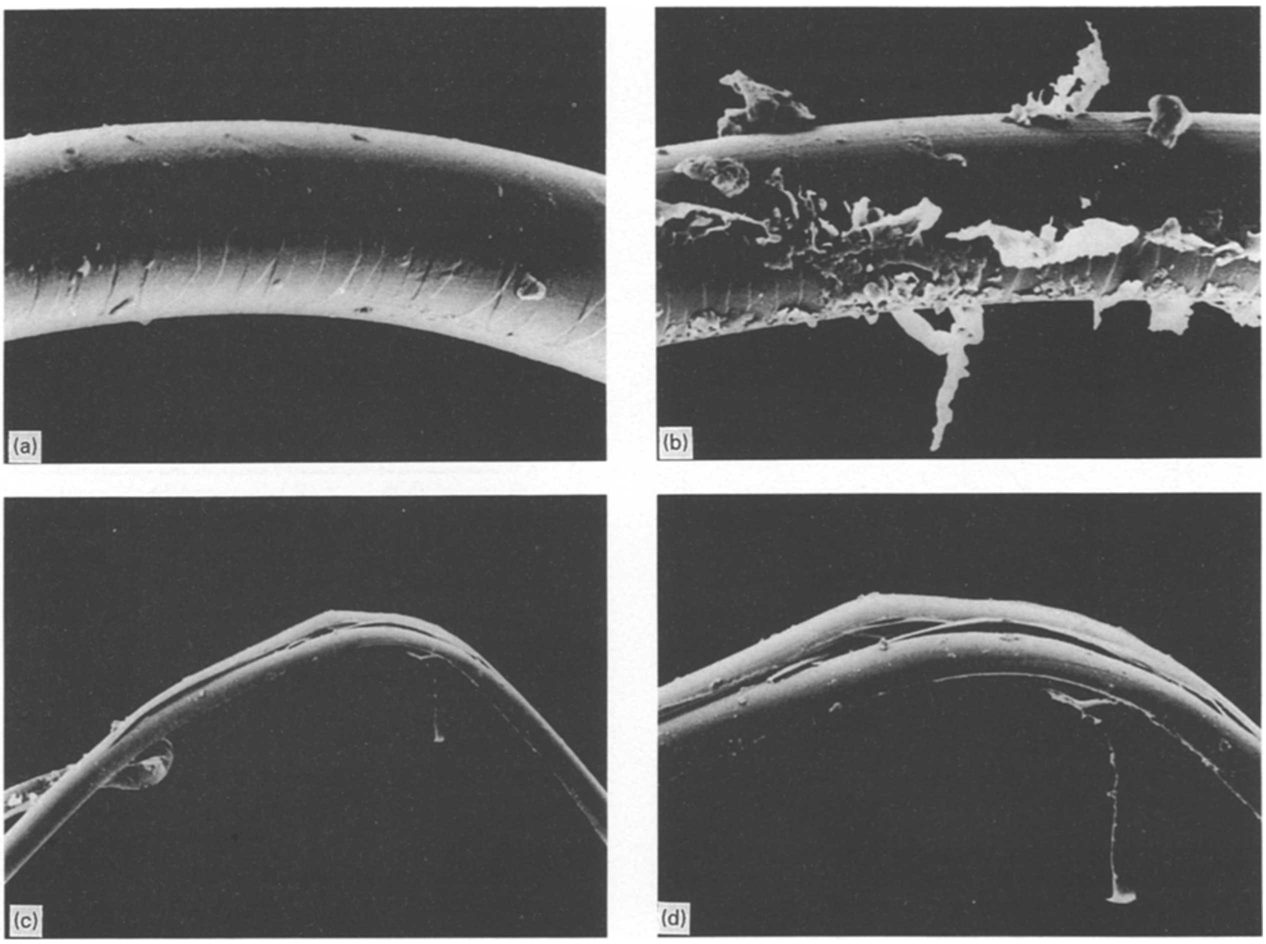


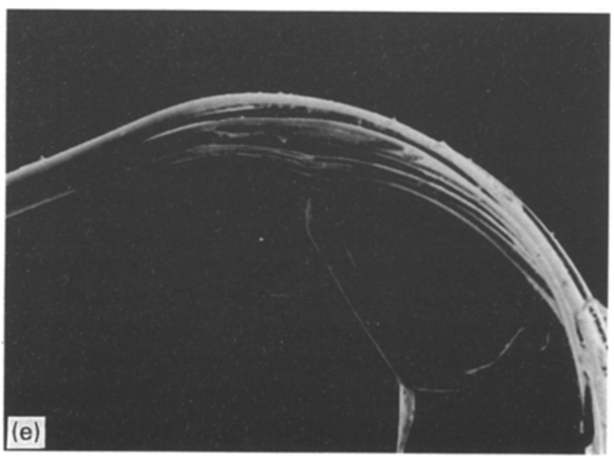


Figure 7 Progressive damage in polyester fibres: (a) 10 min, 30 000 cycles; (b) 20 min, 60 000 cycles; (c) 30 min, 90 000 cycles; (d) 30 min, 90 000 cycles; (e) 35 min, 105 000 cycles.

3.4. SEM observations of flexed fibres after tensile testing

In order to explain effectively the observations of fibres broken in a tensile test after flexing, a typical tensile failure micrograph of nylon 6 is given in Fig. 12. Here, as documented in the literature [2], failure clearly initiates from a weak spot on the surface of the fibre and spreads characteristically in a V-notch fashion towards the centre of the fibre. About a third

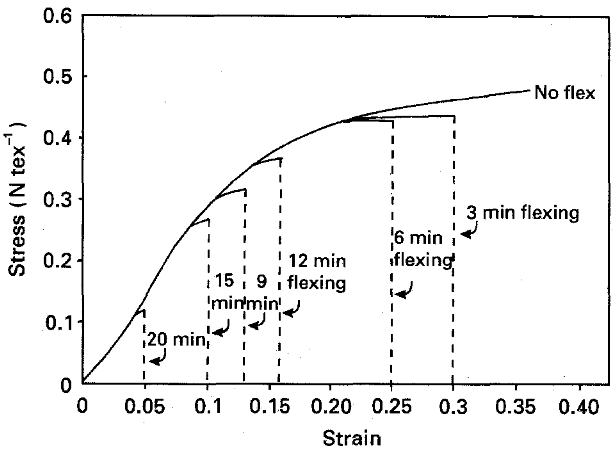


Figure 8 Stress–strain curves of nylon 6 fibres.

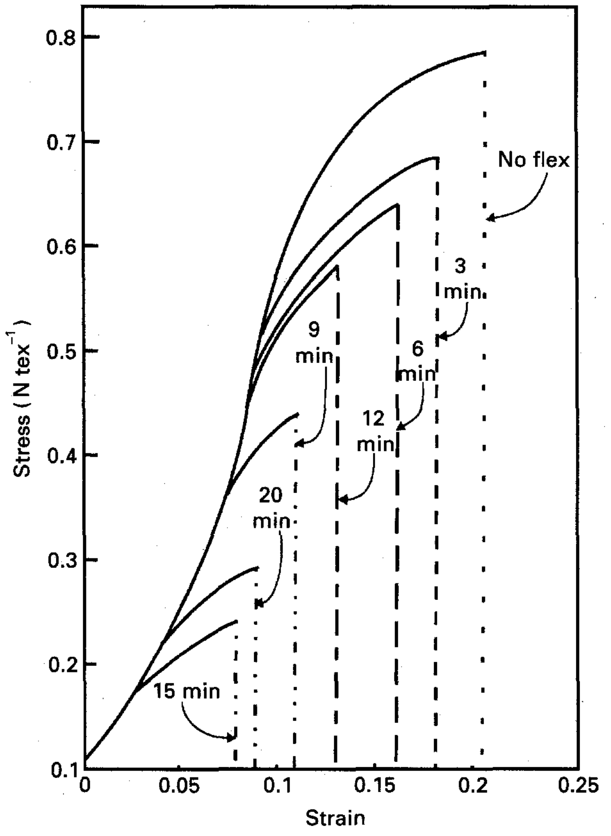


Figure 9 Stress–strain curves of nylon 6.6 fibres.

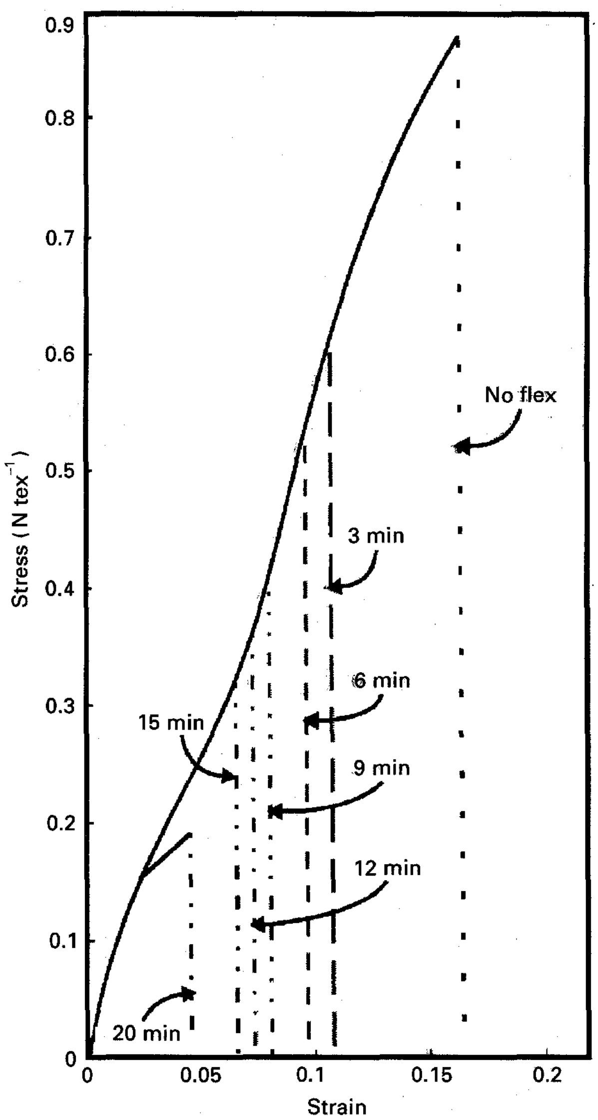


Figure 10 Stress–strain curves of polyester fibres.

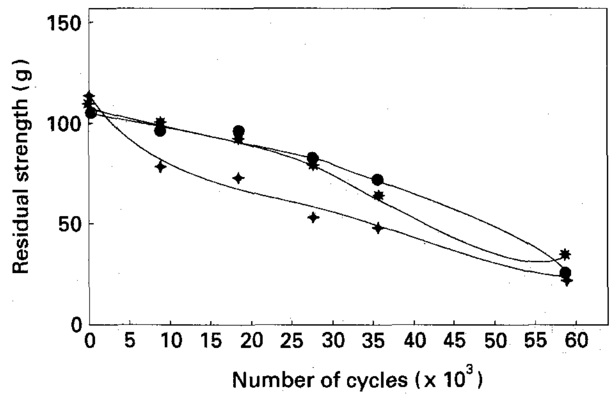


Figure 11 Reduction in residual strength with number of fibres. (+) Polyester, (*) nylon 6.6, (●) nylon 6.

or half of the way across the fibre, the growth of the V raises the tensile stress on the unbroken part to a level at which catastrophic failure occurs perpendicularly across the rest of the fibre.

Tensile testing fibres after a long period of flexing gives little or no information as to how and when fracture begins, mainly because of extensive surface abrasion. However, tensile testing fibres after a relatively short period of flexing is different. As seen in Fig. 13a–d, for nylon fibres, their failure pattern appears to start in a similar way to that of pure tensile testing. But then, rather than completing the course as if it was a genuine tensile failure, the open end of the V meets with an existing axial crack which changes the final course of the failure quite distinctively. Fig. 13a shows two independent V-notch failures developing before meeting with the central crack.

A particularly good representation of the axial splitting in its early stage of development is given in only 3 min flexing, these rather regular central fracture regions, which are not on the abraded region, are about to join up and split the fibre axially.

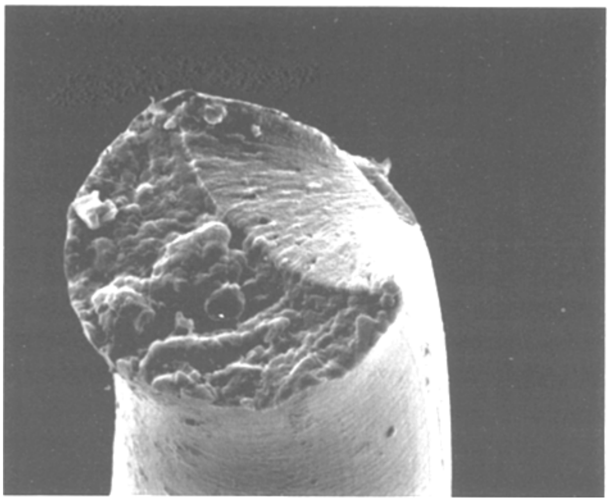


Figure 12 Typical tensile break of nylon 6 fibre. Nylon 6.6 and polyester are similar.

As can be seen from Fig. 14, the flex fatigue process in polyester is somewhat similar, but multiple splitting is much more predominant.

4. Conclusion

Studies of nylon 6, nylon 6.6 and polyester fibres, flex fatigued over a pin, have helped to elucidate the mechanisms leading to failure. In conditions in which severe abrasion is avoided, damage to the fibre structure results from the effects of compression on the inside of the bend and of shear stresses in the variable curvature region where the fibre leaves the pin. Under the conditions of the present tests, axial splitting is always a major factor, although the weakening of the material as the kink-bands develop into cracks leads to the final rupture. In nylon, where single central splits occur, the rupture occurs first on one side and later on the other side. In polyester, which shows a longer lifetime, multiple splitting leads to a more confused pattern of failure.

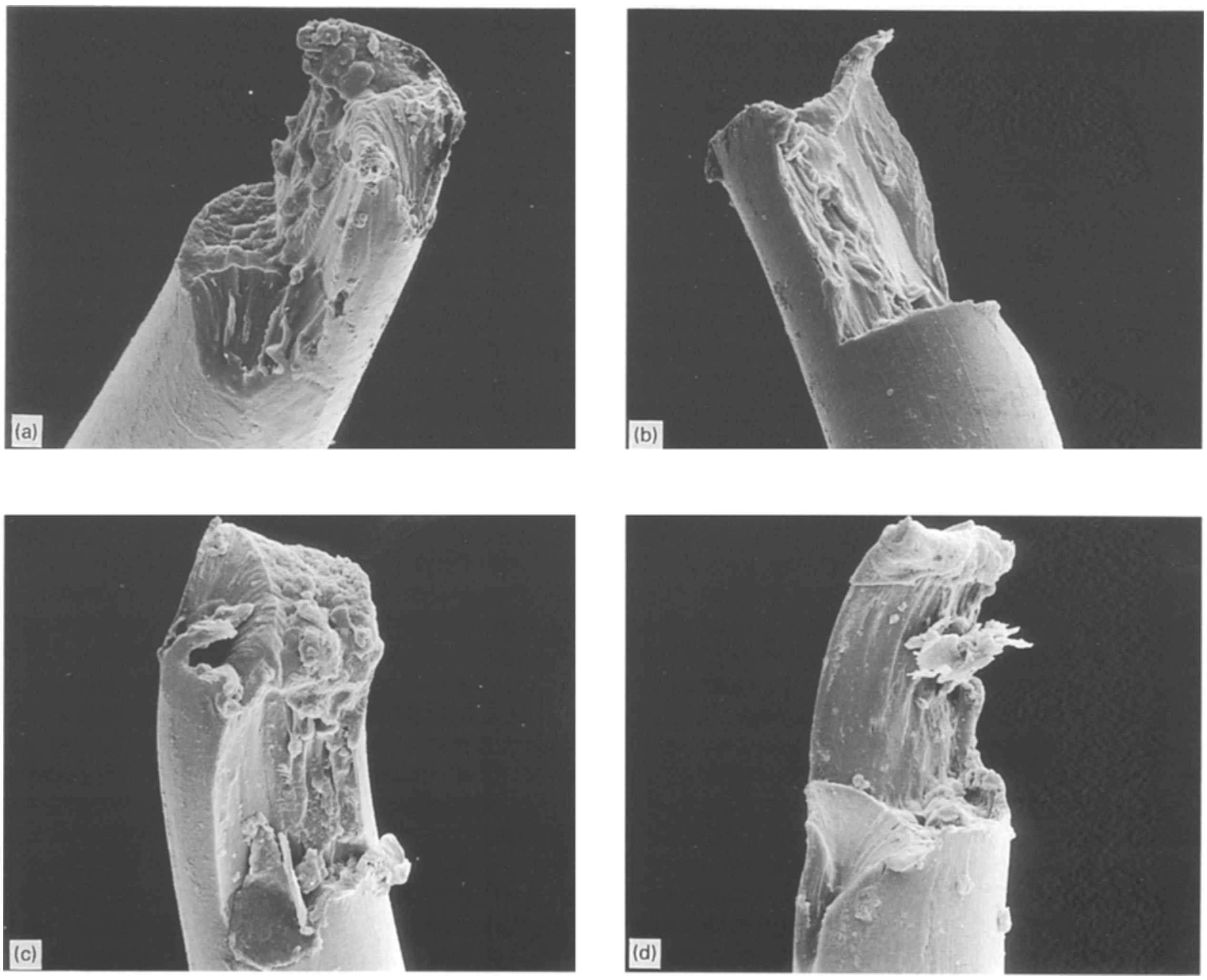
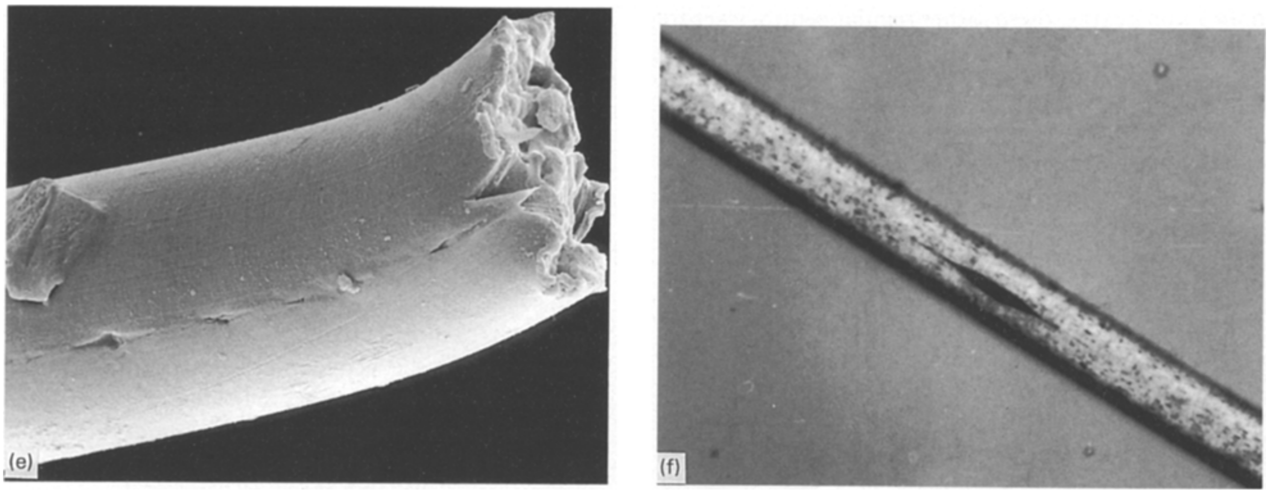


Figure 13 Tensile breaks of nylon fibres after flexing for limited periods: (a) nylon 6, 15 000 cycles; (b) nylon 6, 15 000 cycles; (c) nylon 6.6, 30 000 cycles; (d) nylon 6.6, 30 000 cycles; (e) nylon 6, 9000 cycles; (f) nylon 6, 9000 cycles.



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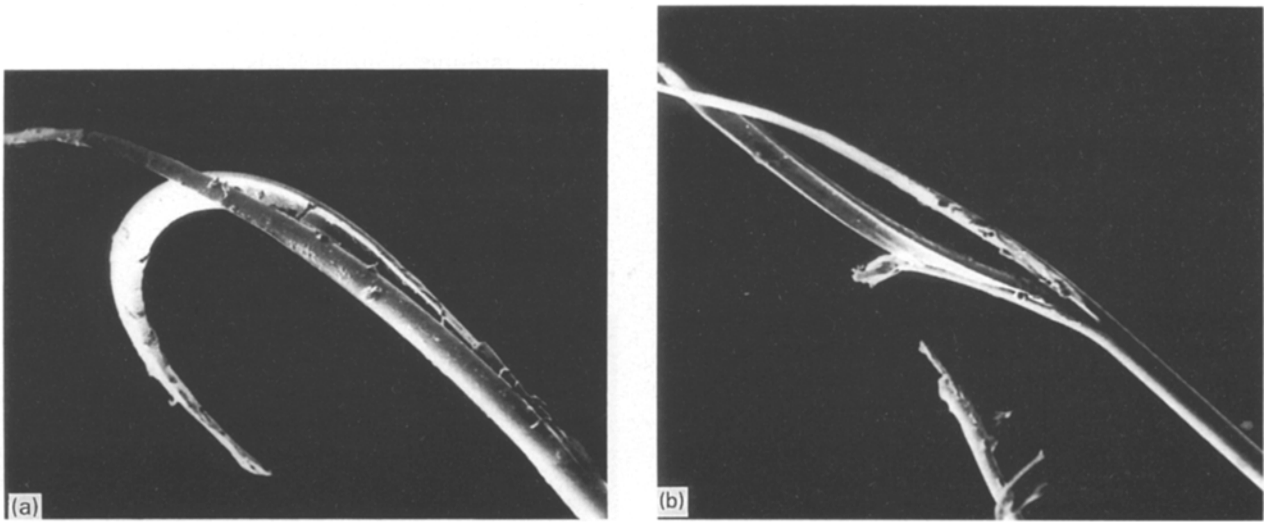

Figure 14 Tensile breaks of polyester fibres after flexing for limited periods: (a) 15 min, 45 000 cycles; (b) 15 min, 45 000 cycles.

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