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The sequence of damage in biaxial rotation fatigue of fibres

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A multiple splitting mode of failure of fibres, commonly found in textiles in use, can be simulated in the laboratory by a biaxial rotation fatigue test. The paper reports on the development of damage in polyester (PET) and nylon fibres with increasing numbers of cycles, as shown by loss of strength and by crack development observed in SEM or direct observations. Initiation regions, with no loss of strength and crack development regions, with a linear loss of strength, are found. In a coarse polyester fibre, there were two such regions, before final failure, and the damage split into separate zones, both along and across the fibre. In finer fibres, with lower bending strain, there was only one sequence and no observable separation of zones of damage. The effects are discussed in terms of the various stresses imposed on the fibre during the test.

1. Introduction

The commonest mode of fatigue failure of fibres as a result of prolonged use is a multiple splitting, which leads to a break with a bushy end. Failures of this sort have been found in nylon, polyester, acrylic, cotton, wool and other fibre types in a variety of clothing, household and engineering applications [1]. Some single-fibre studies have shown that there is a possibility that such breaks can result from repeated uniaxial bending [2] or twisting [3]; but the laboratory test method which comes closest to simulating many end-use situations consists of a combination of bending and twisting in biaxial rotation fatigue.

In the earliest form of this type of fatigue test, as developed at UMIST [4], the fibre was rotated at one end with the other end hanging over a pin and supporting a weight, which followed the rotation, Fig. 1a; but in later forms, which were constructed with different details of mechanical design, both ends of the fibre were driven with the fibre held under controlled tension over a pin, Fig. 1b [5–7]. Details of the test methods and statistics of fatigue lifetimes for various fibres under various conditions have been reported elsewhere [5, 8–12].

The present paper reports studies of another aspect of the subject, namely the way in which damage develops in a fibre throughout a test as the number of cycles of biaxial rotation increases. In the first set of experiments, fibres were removed from the test after a given number of cycles, and then examined in two ways: tensile testing to determine change of strength and other properties; and observation in a scanning electron microscope. In a second set of experiments, views of the fibre were recorded in visible light during tests.

2. Materials and method

In the first set of experiments, two types of fibre were tested: 0.84 and 4.20 tex§ medium-tenacity polyester (polyethylene terephthalate) monofilament. Both fibres were produced on a pilot spinning unit in the Department of Polymer and Fibre Science, UMIST. They were tested by rotation over a stainless steel pin of 0.254 mm diameter on the tester described by Calil and Hearle [5]. The apparent bending strain, ε, at the outside of the fibre, calculated on the assumption that the neutral plane remains central, is given by $\varepsilon = \pm d/(d + D)$, where d is the fibre diameter and D is the pin diameter. The values were thus ±10.9% for the 0.84 tex filament and ±19.6% for the 4.20 tex filament. In reality, because of the easier yield in compression, the neutral plane will move out, the tensile strain will be reduced and the compressive strain will be increased. The fibre over the pin was immersed in distilled water to minimize heating due to friction. The temperature was between 17 and 20° C, the frequency of rotation was 15 Hz, and the tension on the filament was 70 mN.

As a preliminary experiment, 25 tests on each type of fibre were continued until the specimen broke. The main experiments were then carried on for selected numbers of cycles, increasing in successive tests at intervals of approximately 100 cycles, after which the test was stopped and the specimen removed. The tensile stress–strain curve was then determined on an Instron

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§Tex = g km^{-1}, is the ISO-accepted unit of linear density of fibres.

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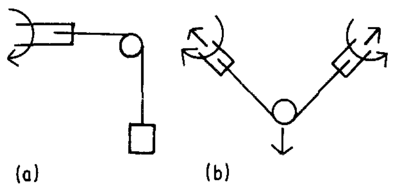


Figure 1 (a) Fatigue test by rotation over a pin, driven from one end. (b) Biaxial rotation fatigue test, as used in these experiments.

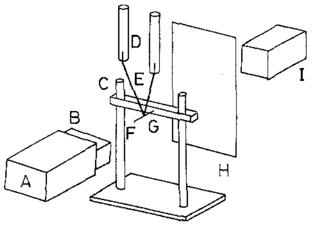


Figure 2 Schematic view of arrangement for TV recording during a test, showing fibre, E, rotated by shafts, D, and passing over pin, F, mounted on beam, G, which slides on rods, C. Fibre is viewed by TV camera, A, through macrophotography unit, B, and illuminated by lamp, I, through diffusing screen, H.

tensile tester with a 5 cm test length and a cross-head speed of 5 cm min^{-1} in a standard atmosphere of 20° C, 65% r.h. The procedure was then repeated, for approximately the same numbers of cycles, but with the fibre removed for examination in the scanning electron microscope (SEM).

For the second set of experiments, 1.7 tex polyester and 1.7 tex nylon 6 filaments were used. The tester was the prototype single-station tester described by Clark and Hearle [6], with the beam holding the pin modified to have only one end of the pin supported, so that the fibre could be viewed from the other end. These tests were carried out in air at 20° C, 65% r.h. Preliminary trials with a high-speed cine-camera did not give good quality pictures and the method was prone to vibration and expensive to run. The procedure adopted was to use a TV camera, which viewed the fibre through a macro-photography unit. The fibre was lit by means of fibre optic light guides, and the picture was recorded on a video-recorder. The arrangement is shown schematically in Fig. 2. In addition, some still photographs were taken at intervals throughout tests in the 35 mm camera attached to the macro-photography systems.

3. Results

The fatigue life statistics for the first set of tests are given in Table I.

Fig. 3 shows the stress–strain curves of fibres which have not been fatigued, together with the breaking points of fibres fatigued for the indicated numbers of cycles. Because these are individual test values, they are subject to scatter. Fig. 4 shows how the residual strength varies with number of cycles. The scanning electron micrographs after increasing numbers of cycles, and for fibres which had broken, are presented in Fig. 5.

The results of the observations with visible light in the second series of tests are best presented by verbal accounts of particular tests, as seen on the TV monitor or the still photographs.

On the 1.7 tex polyester filament at zero cycles, before rotation starts, there were indications of kink-band formation where the fibre passes over the pin. These could be seen as fine lines, approximately perpendicular to the fibre axis, and extending from the centre of the fibre to the surface next to the pin. At 1232 cycles, no further damage could be seen; but, at 1850 cycles, a small region of two or three parallel cracks, about 60 μm long and 15 μm apart, had appeared in the fibre directly below the centre of the pin. The region of cracking quickly spread and at 2202 cycles the crack length had tripled to approximately 200 μm, which may be compared with a length of approximately 370 μm in contact with the pin and a fibre diameter of 28 μm. At 2598 cycles, the crack length had not changed, but the number of cracks had almost doubled. The cracks were still parallel, about 8 μm apart, but the helical path, in opposite senses on either side of the centre point of contact with the pin, was apparent. For the rest of the test no further cracking appeared to occur, but parts of the fibre started to protrude from the fibre surface. The fibre deteriorated rapidly in the final stages of the test, aided by the irregular movement of the damaged fibre over the pin, and at 2950 cycles damage could be seen over most of the fibre in contact with the pin. Failure in this test occurred at 3126 cycles, and the break showed the characteristic multiple splitting failure, Fig. 6a.

TABLE I Fatigue lives of polyester filaments, 25 tests

	Cycles to failure	
	0.84 tex	4.20 tex
Median	3833	2614
Mean	4019	2422
Standard deviation	1101	469
CV (%)	27.4	19.4

The sequence of events for the 1.7 tex nylon 6 fibre is roughly similar, except that the fatigue life is four times greater and the fatigue cracking less extensive. There was some evidence of kink-band formation at zero cycles. At 2640 cycles, a fine line could be seen perpendicular to the fibre axis, running across the fibre slightly to the left of centre, and this was more pronounced at 5280 cycles. At 6336 cycles there were two lines, approximately 45 μm apart, and at 7392 cycles helical cracking could be seen between these lines. The cracking appeared to stay constant, but fibre material protruding from the surface could be seen at 9680 cycles. Deterioration was then rapid, with damage developing over most of the fibre in contact with the pin. Failure occurred at 13 728 cycles, with a multiple split morphology, Fig. 6b. As reported in other studies, nylon shows fewer and larger splits than polyester and other fibres.

4. Discussion

Because the fibre break points in Fig. 3 lie close to the stress–strain curve of the fibre, as-received, it follows that, as expected, the damage to the fibre is localized and causes a weak place for break to occur, but does not affect the major part of the 5 cm length, which determines the stress–strain response.

In discussing how damage develops, it is convenient

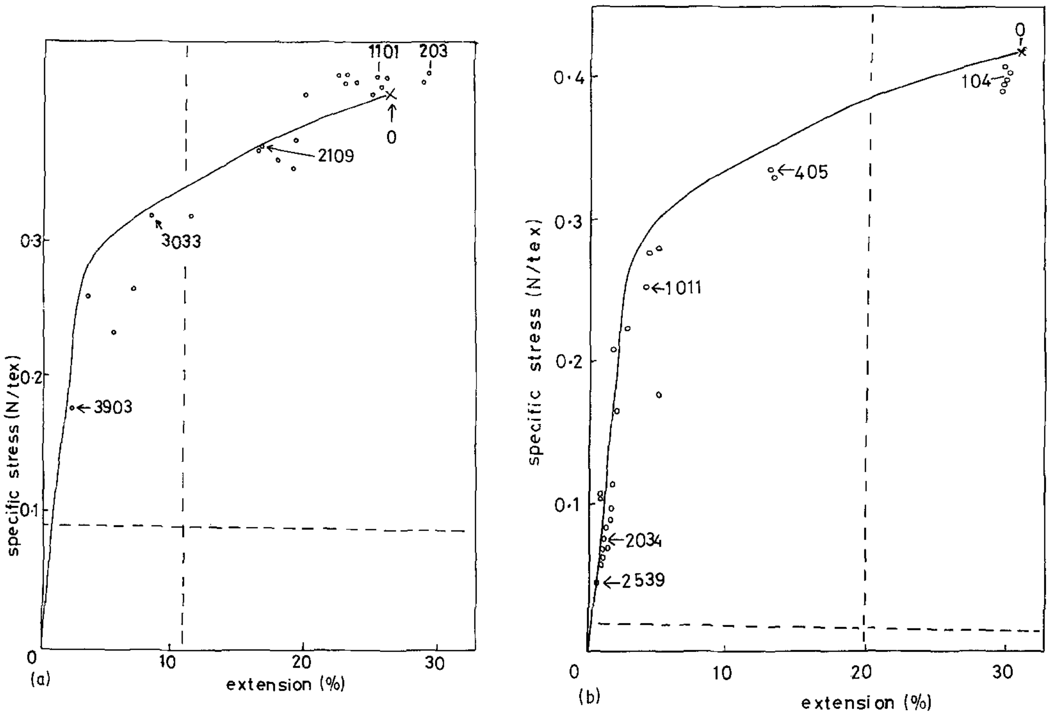


Figure 3 Stress–strain curve of fibre, as-received, plus break points of fibres fatigued for different numbers of cycles, as selectively indicated. The dotted lines indicate the apparent bending strain in the fibre, and the applied tensile stress. (a) 0.84 tex polyester. (b) 4.20 tex polyester.

to deal first with the more complicated sequence of events found with the thicker 4.20 tex polyester filament, fatigued in water. At the start of the test, there is an initiation period, AB in Fig. 4b, lasting for 200 cycles, before the strength starts to reduce. During this period, some development of kink-bands and some surface abrasion can be seen in the scanning electron micrographs, Fig. 5b. The strength then falls linearly with number of cycles, along BC, up to 1500 cycles; and the micrographs show increased development of helical cracks in opposite senses in two zones separated along the fibre. From 1500 to 2300 cycles, along CD, there is what appears to be a second initiation period with no change of strength. During this period, the cracks on the fibre surface in both zones are seen to be fully developed. Away from the centre of the pin, the cracks terminate with a rather smooth transition to the undamaged fibre, but towards the centre, there is an abrupt boundary between cracked and uncracked material; and, in many instances, the material has broken round at least one of these boundaries. After the second initiation period, there is a further short linear fall in strength, along DE, from 2300 to 2600 cycles, before the fibre breaks, at EF, under the tensile stress imposed in the test, namely 17 mN/tex. The damage appears more severe in the last micrographs, with complete rupture and disturbance of outer layers at 2327 and 2538 cycles. A broken fibre, which failed at 2606 cycles, shows the complete rupture across one zone, with the other damage zone separated by a length of apparently undamaged fibre. It can also be seen that there appears to be a division of the break across the fibre into an outer and an inner zone. Surprisingly, the twist direction of cracks in the inner zone is in the opposite sense to that in the outer zone.

The results clearly show that there are two different types of change in the material: initiation periods, with

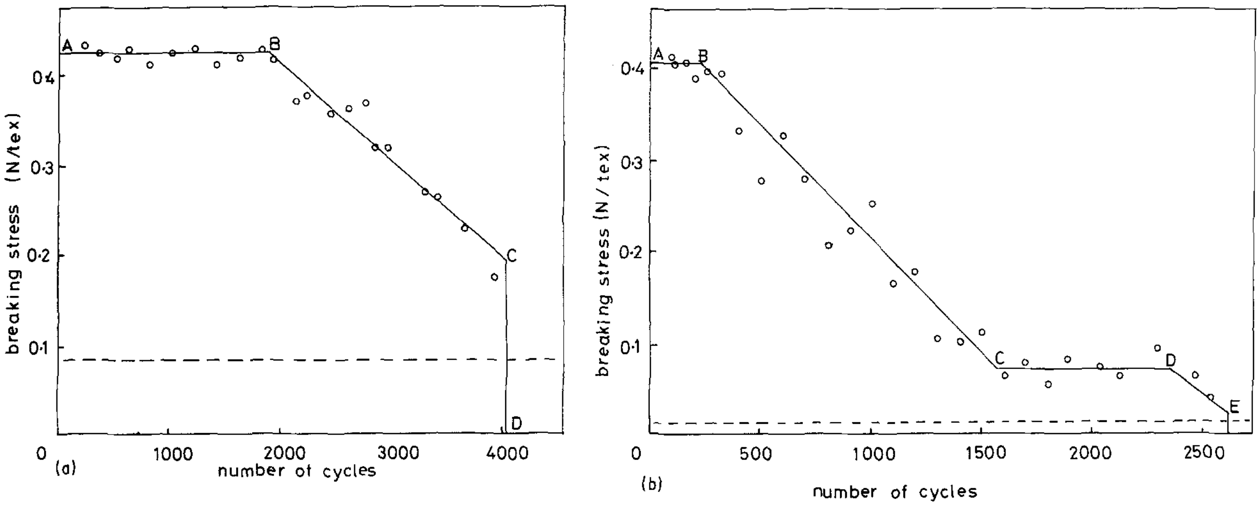


Figure 4 Change of breaking stress (tenacity) with number of imposed cycles. (a) 0.84 tex polyester. (b) 4.20 tex polyester.

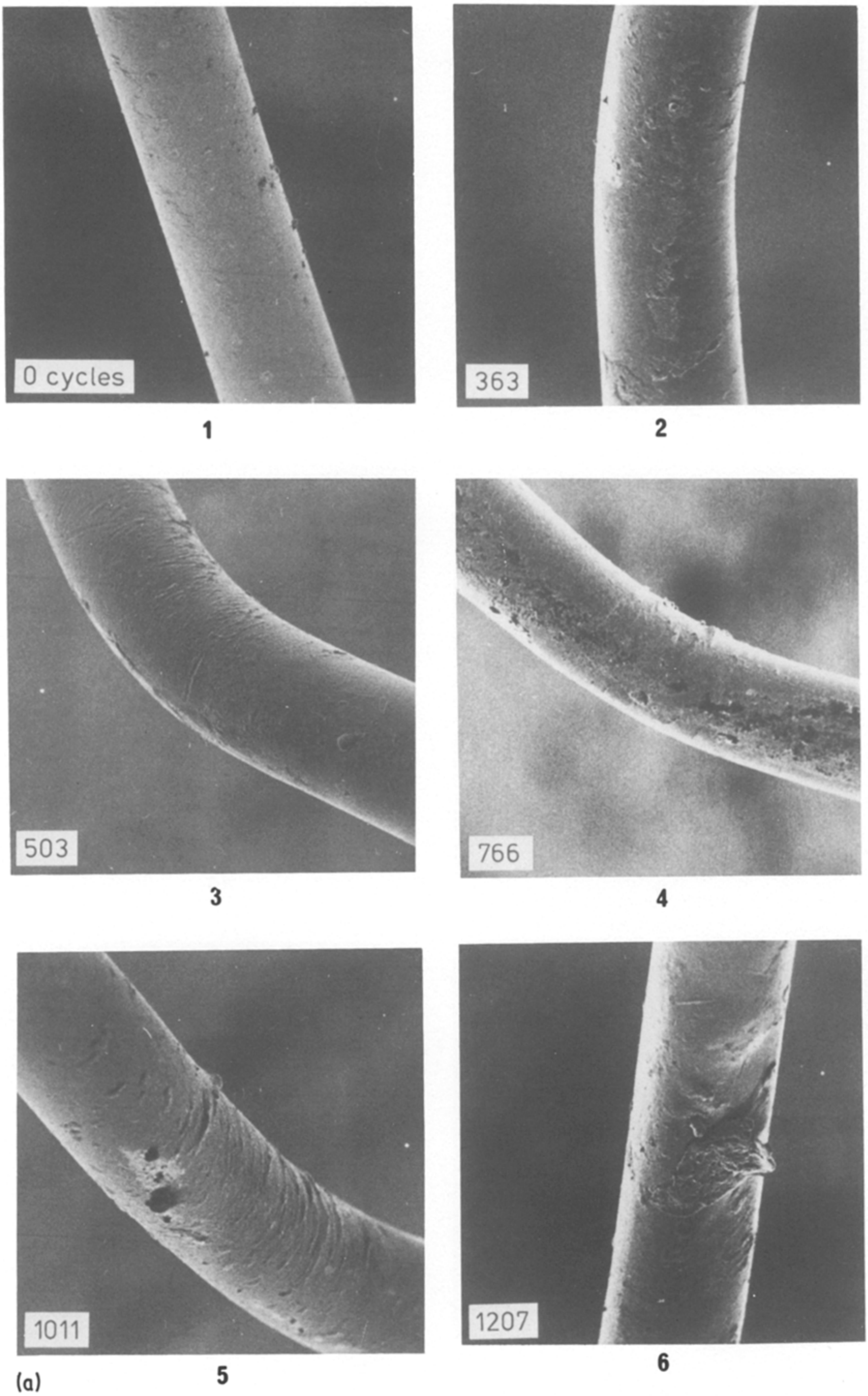
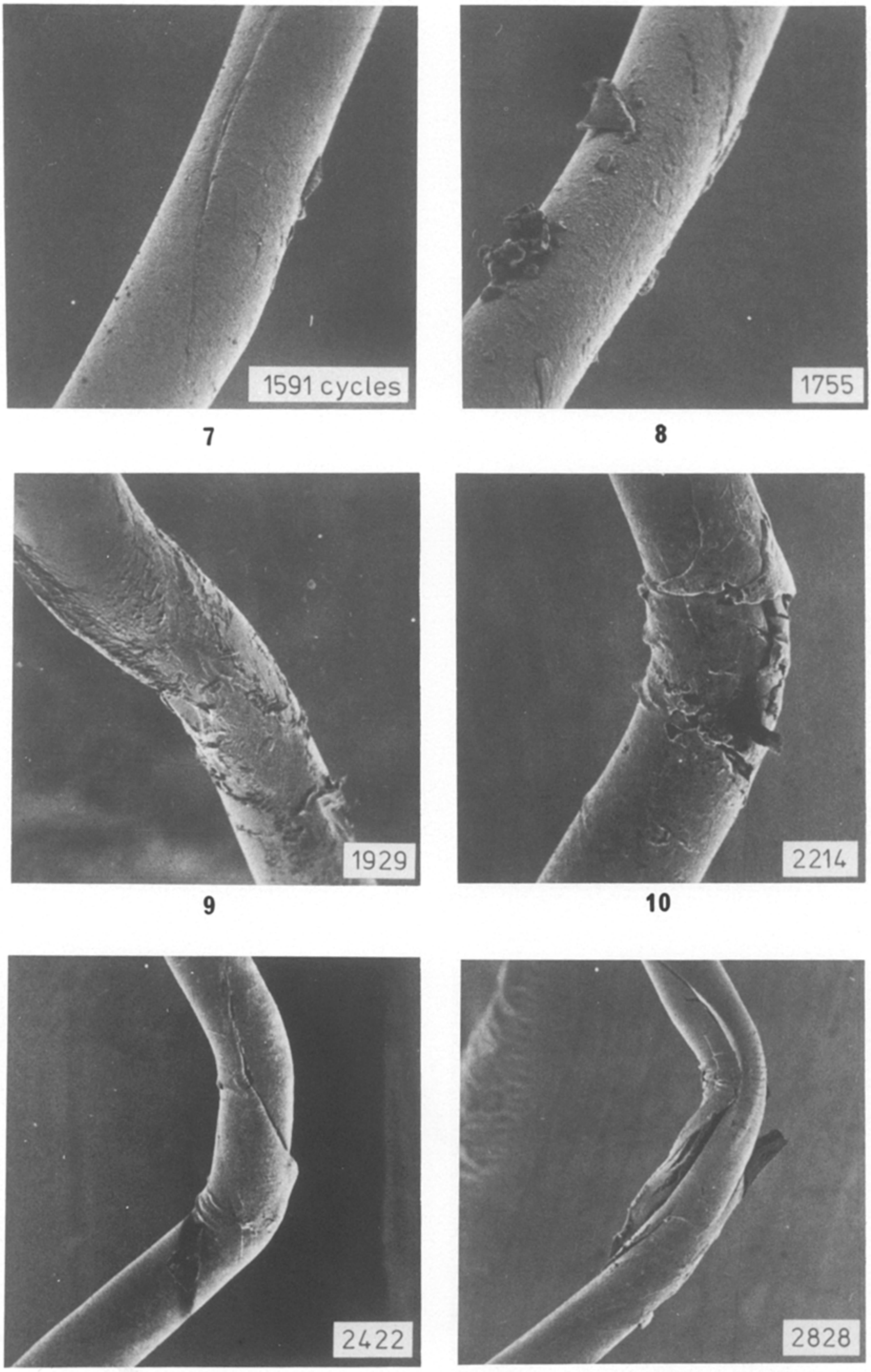


Figure 5 Scanning electron micrographs of fibres after increasing numbers of cycles, as indicated, and both ends of a fibre from test continued to break. (a) 0.84 tex polyester. (b) 4.20 tex polyester.

no loss of strength, but with formation of kink-bands; and periods of crack development, accompanied by loss of strength. The indications are that the first sequence of initiation and crack growth, ABC, occurs in an outer zone of the fibre, and the second sequence, CDE, occurs in the central zone.

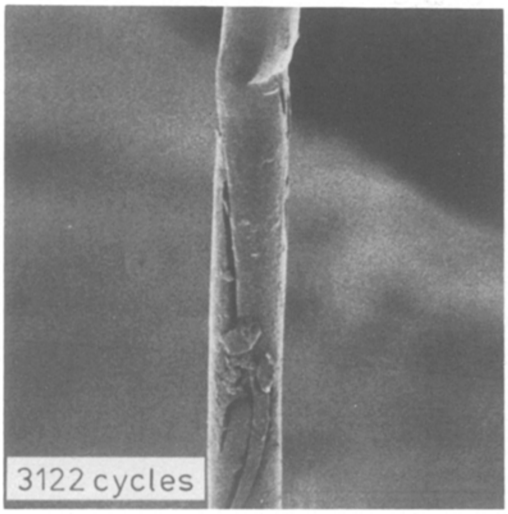
The division into two zones across the fibre can be explained by the nature of bending of oriented linear polymer fibres. It can be expected, and has been confirmed in bending studies by Chapman [13], that the material will yield more easily in compression, so that the stress–strain curve would have the form shown in



7 8 9 10 (a) 11 12

Figure 5 Continued, 0.84 tex polyester

Fig. 7a. If the neutral plane in Fig. 7b remained central, as in the linear elastic (LE) theory of bending, the strain levels on the inside and outside of the bend would be as shown. However, for a material yielding in compression (CY), the deformation energy, which is given by the area between the curve and the strain axis, will be reduced if the neutral plane moves towards the outside, as shown in Fig. 7b, and the strain levels shift, as shown in Fig. 7a. The same point can be proved by analysing the equilibrium of forces. The actual position of the neutral plane and the maximum strain levels in tension and compression can only be



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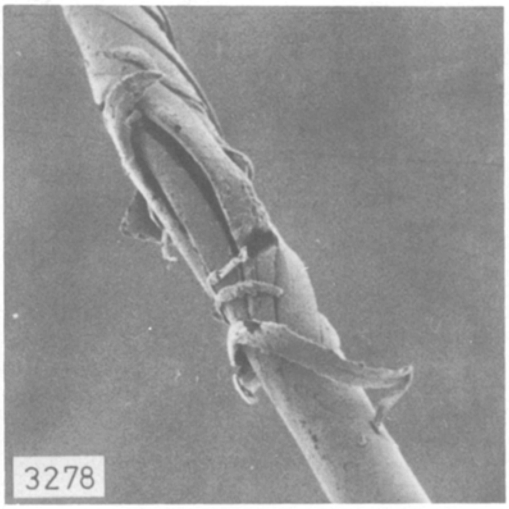

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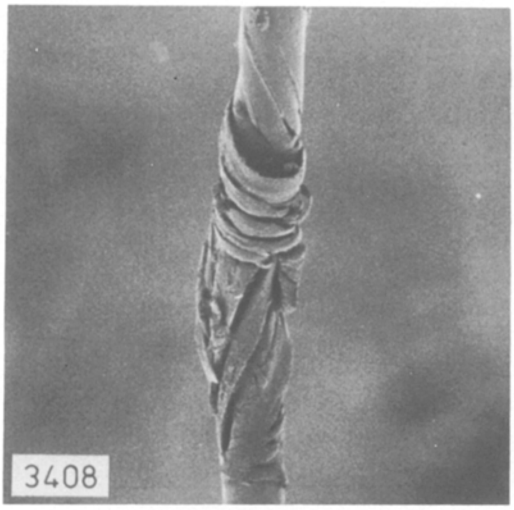

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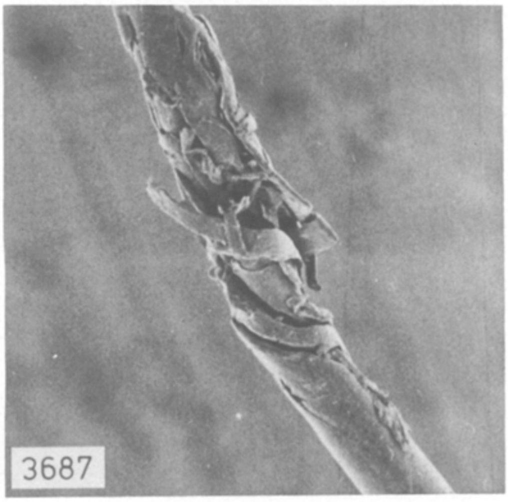

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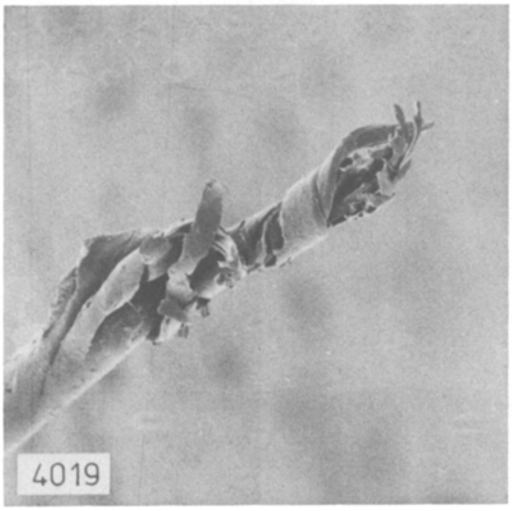

(a) 17

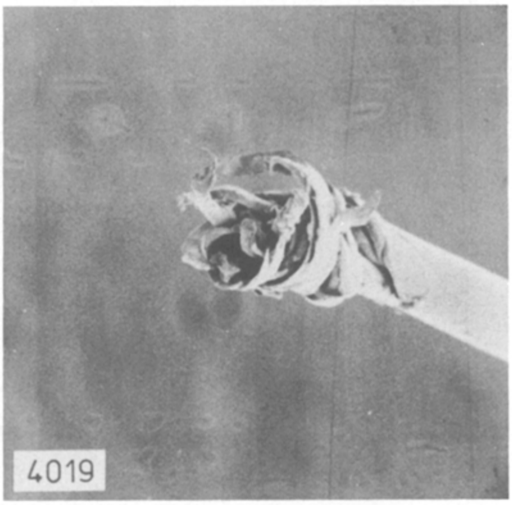

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Figure 5 Continued, 0.84 tex polyester

calculated if the compressive quadrant of the stress–strain curve is known. The positions located in Figs 7a and b are only indicative of the trend.

When the fibre rotates, the displaced neutral plane will define a circle, N, within the fibre. The range of strain variation across the fibre is then shown in Fig. 7c. Outside the circle N the strain oscillates between tension and compression, as it does throughout a linear elastic fibre when the circle shrinks to a point. Inside the circle N, the material is always under compression. It seems likely that the two zones observed in the broken fibre correspond, at least approximately, to the division by the circle N. Disruption of the material is likely to be greatest when there

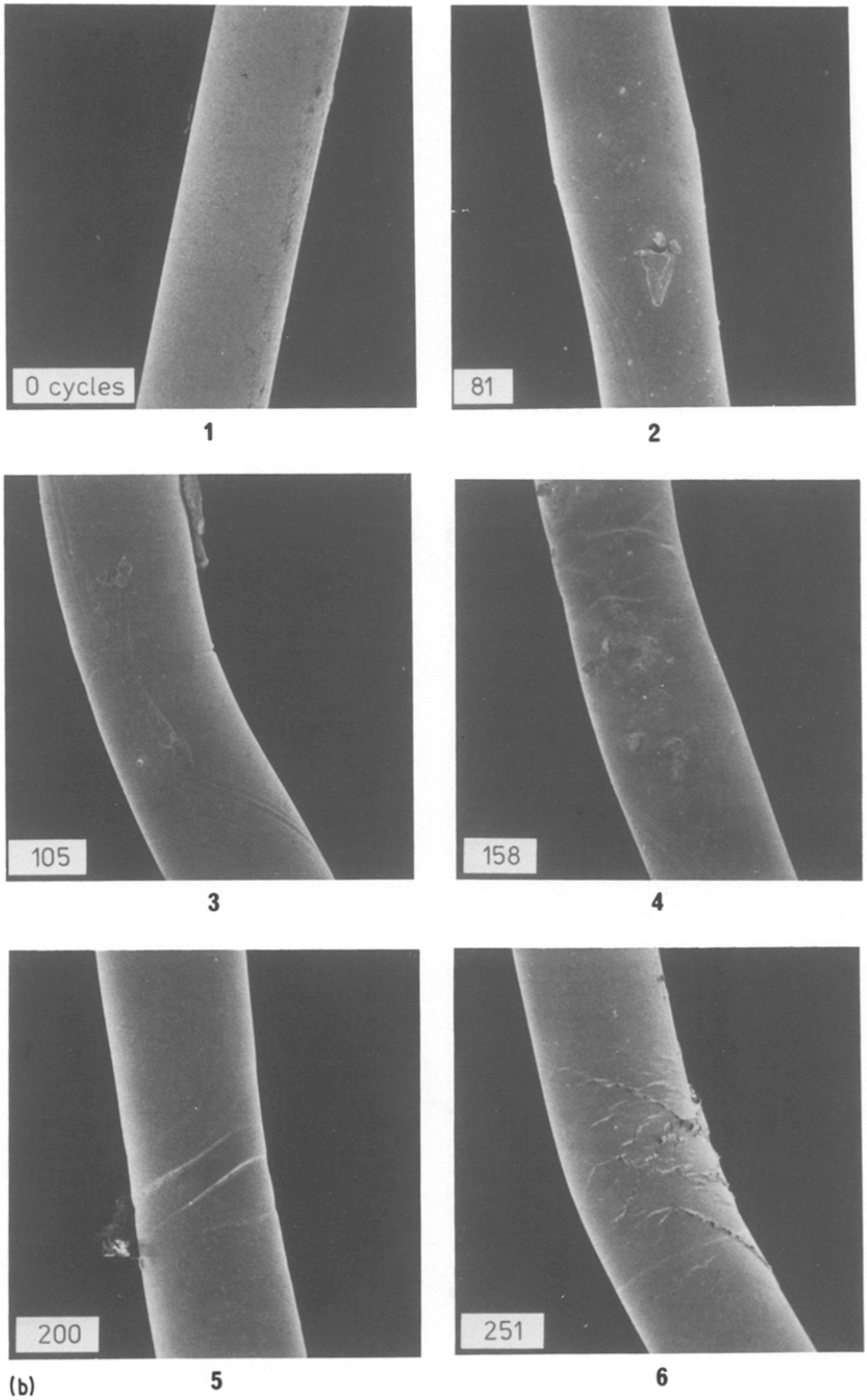
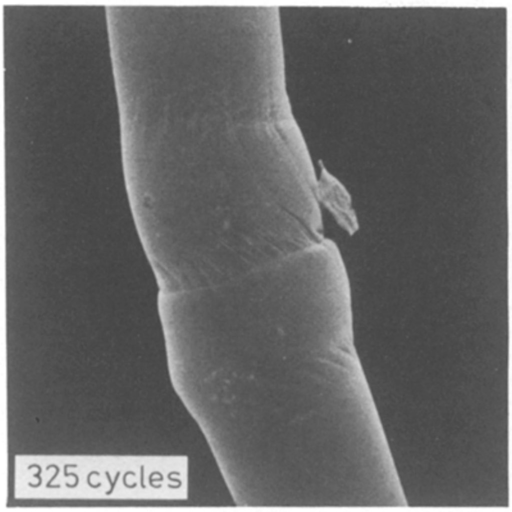


Figure 5 Continued, 4.20 tex polyester

is an oscillation between tension and compression, so that the first stage of initiation and crack development occurs in the zone outside N. When this material has broken down to the extent that it cannot support stress, the neutral plane will move in and a second stage of initiation and crack development will occur in the inner zone. The greater number of cycles in the second initiation period can be explained by the lower levels of strain; but the rate of loss of strength due to crack growth seems to be unchanged.

The separation of damage zones along the fibre can be explained by the force distribution along the fibre, shown schematically in Fig. 8. First, there is a small constant tension, Fig. 8b. Second, there is a bending



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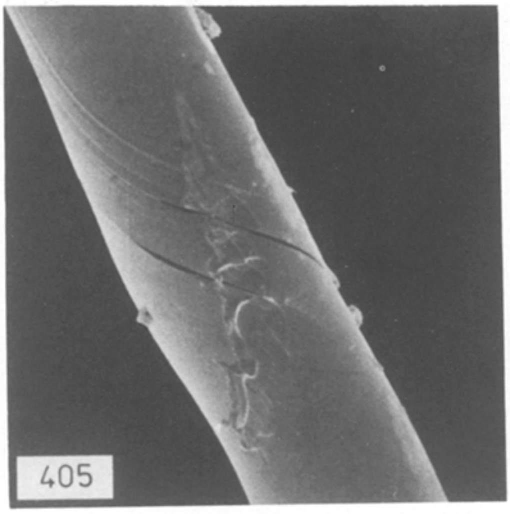

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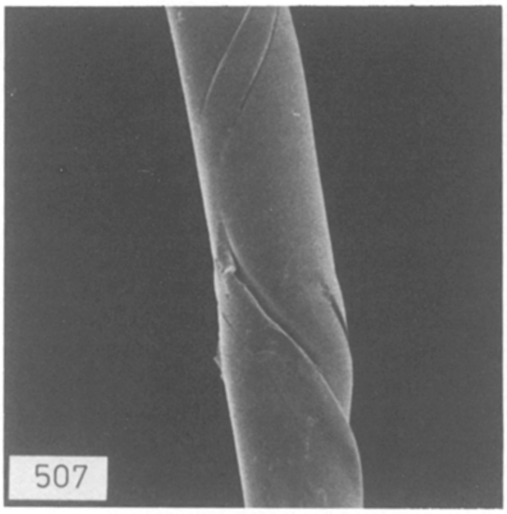

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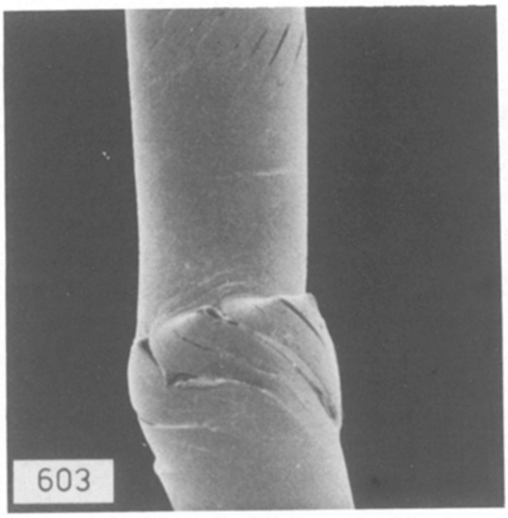

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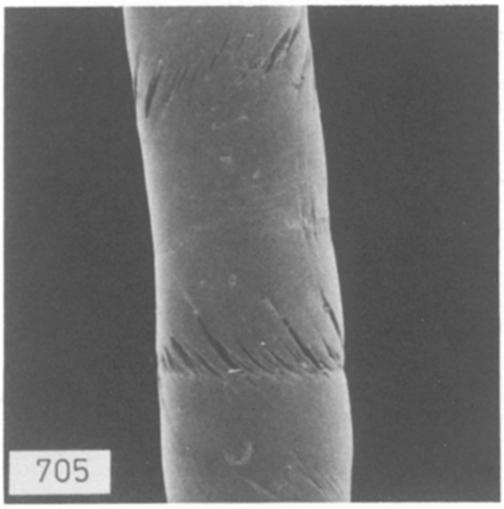

(b) 11

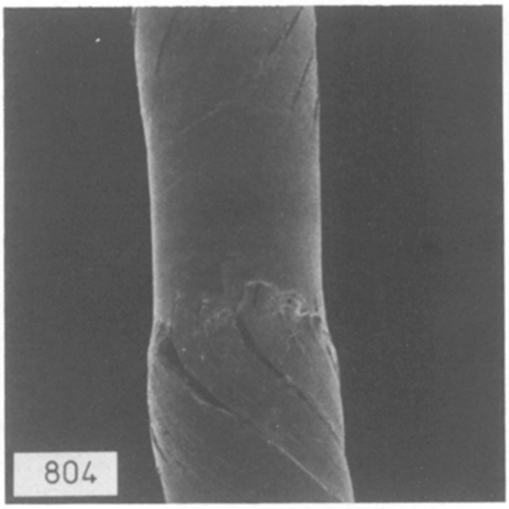

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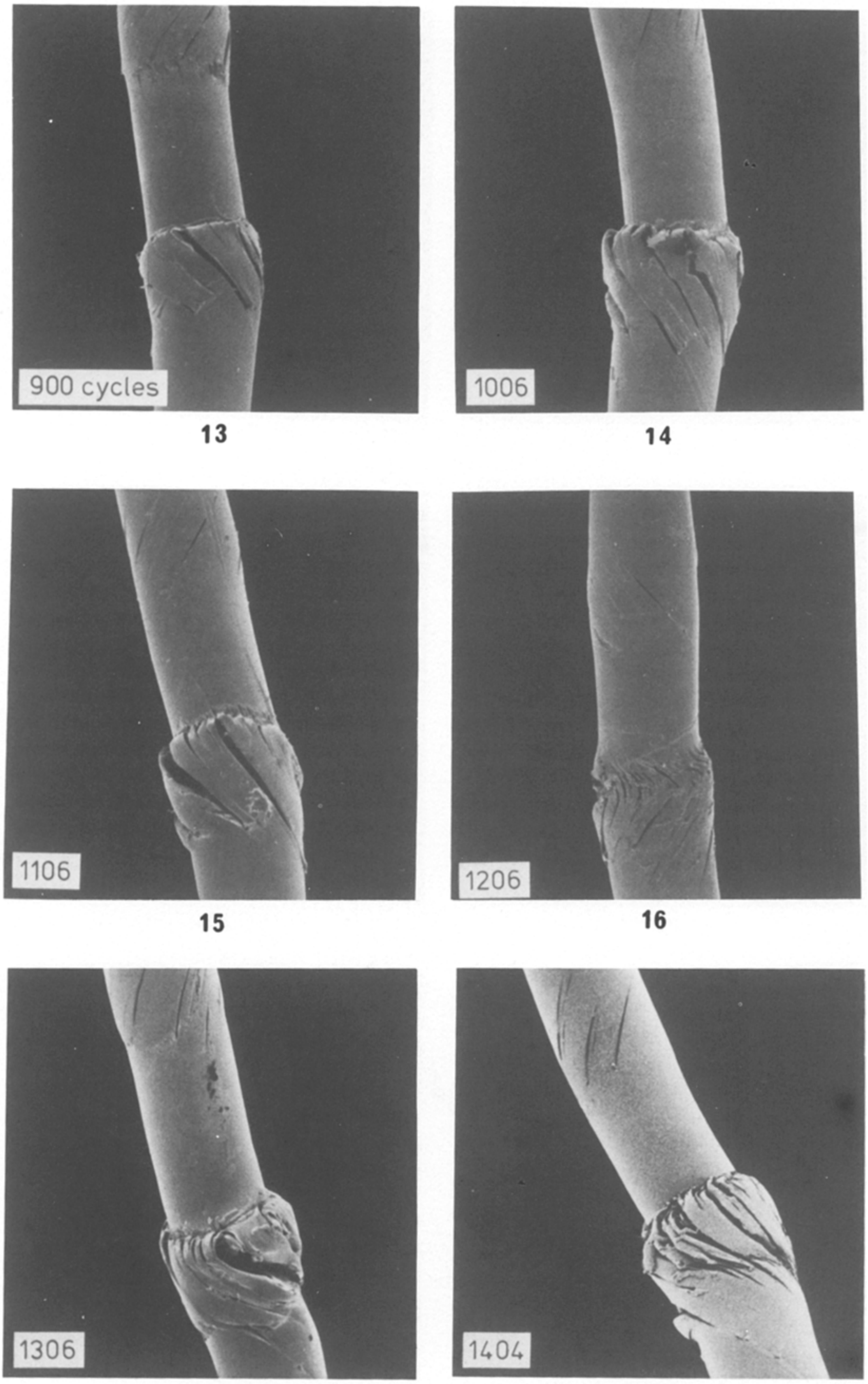
Figure 5 Continued, 4.20 tex polyester

moment due to fibre curvature, Fig. 8c. If the fibre is assumed to follow the shortest path, shown dotted, and go directly from the pin curvature to straight, the bending moment would appear as a step at the contact point. In reality, as discussed in detail by Hearle and Miraftab [2], there must be a transitional zone of varying curvature and bending moment. According to the standard theory of bending of beams [14], equilibrium requires a shear force which depends on rate of change of curvature, and takes the form shown in Fig. 8d. The shear stress increases from zero at the extreme positions to a maximum at the centre of the fibre. If there was zero friction on the pin and the fibre was perfectly elastic, this would complete the list of forces.



13 14 15 16

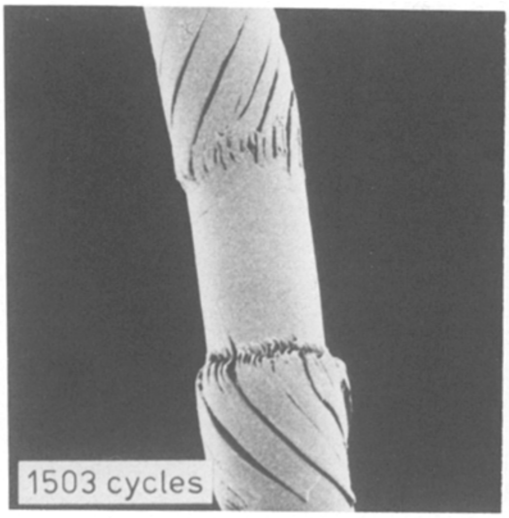
(b) 17 18

Figure 5 Continued, 4.20 tex polyester

But friction or hysteresis impose a drag, as discussed by Calil *et al.* [15], which imposes a torque increasing, in opposite senses, from zero at the centre point of contact to a maximum value where the fibre is straight.

It is clear from Fig. 8 that the most severe stresses, with maximum torque and shear as well as high bending moment, are near the points at which the fibre leaves the pin. This defines the two zones of damage. The sharp cut-off towards the centre may be due to the step down to zero in shear stress.

The total combination of stresses at any point of the fibre will be given by summing the contributions from each of the causes. All except the tensile force give a



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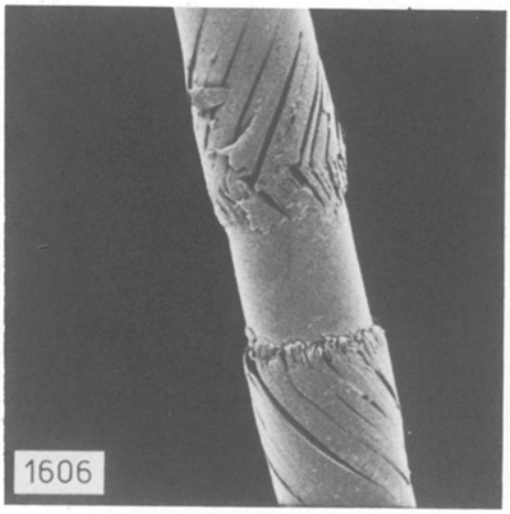

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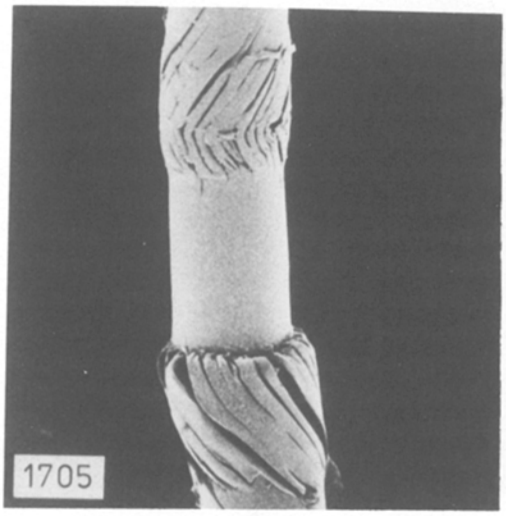

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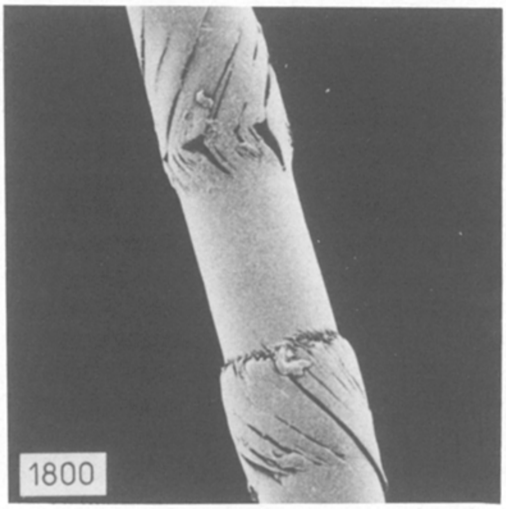

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(b) 23

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Figure 5 Continued, 4.20 tex polyester

variation of stress across the fibre, and the values will change as the fibre rotates. It is therefore difficult to disentangle the various influences. Probably the initiation is associated with rearrangement of the packing and path of the linear polymer molecules or disturbances of the fine structure due to tension–compression with kink-band formation. The crack development will be associated with the shear stresses, as found in uniaxial bending fatigue [2], but will be biased by the torque.

It is not easy to explain why the twist in the central zone should be in the opposite direction to that in the outer zone, and opposite to the drive from rotation on that side of the test specimen. It may be that the

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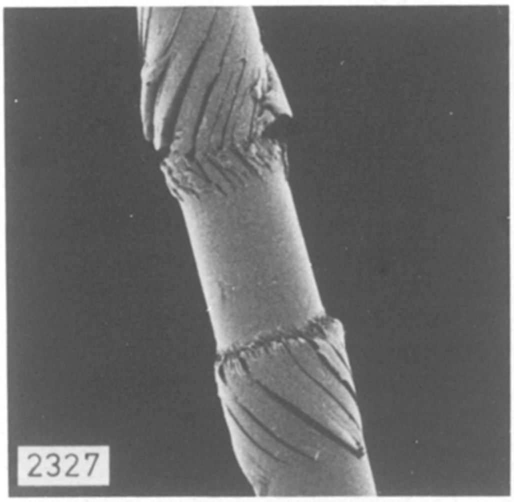

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(b) 29

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Figure 5 Continued, 4.20 tex polyester

asymmetry which occurs when one section is breaking but the other is supporting stress more strongly may cause a redistribution of torque forces, with the zero torque position moving across the weak failing zone. More probably, the appearance might be a consequence of snap-back after break, when there would be a rapid untwisting of the length of fibre between the pin and the jaw as the torque drops to zero at break.

In the finer 0.84 tex polyester monofilament there is only one stage of initiation and crack growth before final failure in the fatigue test. Up to about 2000 cycles, along AB, in Fig. 4a, which is about half-way through a complete test, there is no strength loss and

Figure 6 Scanning electron micrographs of broken fibres, in second set of tests. (a) 1.7 tex polyester. (b) 1.7 tex nylon.

the only visible damage is some kink-band formation and some abrasion, seen in Fig. 5a. The loss of strength between 2000 and 4000 cycles, along BC, which is accompanied by crack development, occurs at about half the rate per cycle of the 4.20 tex filament. Both the longer initiation and the slower crack growth can be attributed to the lower apparent bending strain levels of 10.9% for the 0.84 tex filament, compared to 19.6% for the 4.20 tex filament.

The period of loss of strength ends at about twice the value of the tension on the fibre during the test, indicating a further rapid loss of strength at the end of the test. This is probably also true for the 4.20 tex filament, although the smaller value of the tensile stress makes a precise evaluation difficult.

In the final break of the finer fibre, there is no evidence of two zones across the fibre. This, together with the occurrence of only one sequence of initiation and loss of strength, indicates that the cracking develops right across the fibre in one stage. Two possible explanations can be offered. The first is that the smaller diameter of the fibre, relative to crack spacing, means that a separation into two zones cannot be resolved: the cracks spread over from the outer zone into the inner zone. The second is that because the strain level is less, the neutral plane will not move out so far and the circle N will be smaller. It is also possible that there is a qualitative difference, suggested in Fig. 7a, in that in the 0.84 tex filament the maximum tensile strain may not reach the yield strain, whereas in the 4.20 tex filament it may do so.

There is also no separation of the splitting into two zones along the fibre, although the final break does occur near one end of the split region. It may be that because the cracks run right across the fibre, they propagate more easily and join up in the centre. Alternatively, the difference may be a result of detailed differences in the magnitudes of the stresses, and the way they vary along and across the fibre.

The observations on the 1.7 tex polyester and nylon fibres tested dry seem to follow the same general pattern as the 0.84 tex polyester filament tested wet, and the descriptions of the observations speak for themselves.

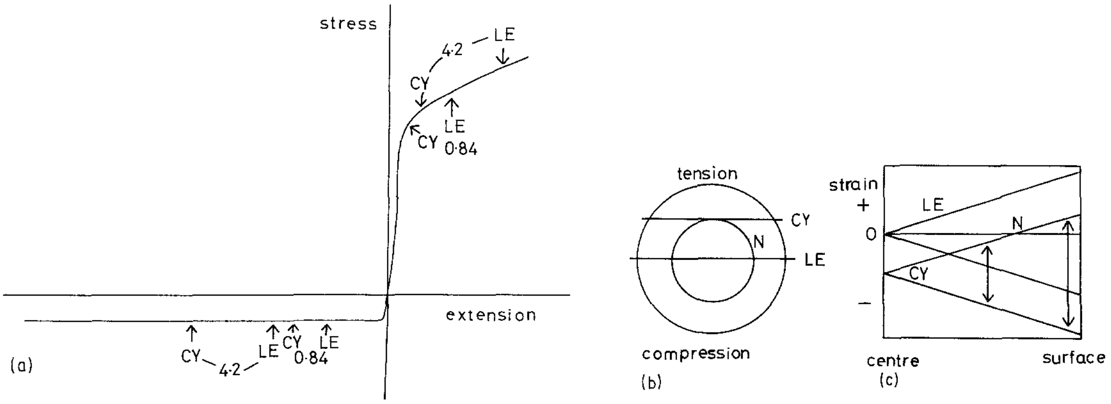

Figure 7 (a) Expected form of fibre stress–strain curve, with levels of strain on the tension and compression side, with the linear elastic assumption of a central neutral plane (LE), and in the actual situation with compressive yielding (CY). The actual locations of the CY values for the 0.84 tex and 4.20 tex filaments are indicative only. (b) Fibre cross-section, showing position of neutral plane in the two cases, and the circle formed by rotation of the plane CY. (c) Strain variation across the fibre during rotation.

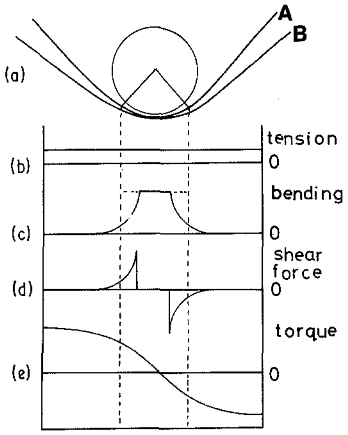

Figure 8 (a) Fibre path over pin: A, line with idealized geometry of contact with pin joining directly to straight line to clamp; B, line for real geometry with a transition zone of variable curvature. (b) to (e) Variation of principal forces along the fibre.

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