# *Part III*
# *Fatigue*

# 10

# INTRODUCTION

## FAILURE DUE TO REPEATED LOADING

Tensile breaks of single fibres with the forms shown in Part II are not representative of the damage which commonly occurs in textile materials in real-life wear. Failure then is most often due to repeated loading over a long period of time, and the forms of break found, as illustrated by the case studies in Parts VI and VII, are usually different. This leads to the need to study fibre 'fatigue' in the laboratory.

*Fatigue* may be defined as the failure of material after repeated stressing at a level less than that needed to cause failure in a single application of stress.* This was a problem which caused troubles for the railway engineers of the last century and the aircraft engineers of this century. They designed with what seemed to be adequate margins of strength, but then got unexpected catastrophic failures after months or years of use.

Owing to these problems, metal fatigue has been widely investigated. Fatigue cracks occur during repeated deformation within the elastic region of a brittle or, more commonly, an elastic-plastic material as shown in Fig. 10.1. The fatigue may be either tension–tension (T–T), compression–compression (C–C), or tension–compression (T–C), but is always a result of recoverable elastic deformation, except very close to the tip of a fatigue crack.

## FIBRE FATIGUE

In fibres, the conditions for fatigue testing are less easily arranged. Firstly, the material cannot be put into axial compression because the fibre buckles. Secondly, in the general-purpose textile fibres, which are semi-crystalline polymers, there is no well-defined elastic region followed by plastic yielding: there is a viscoelastic response, which gives a stress-strain curve

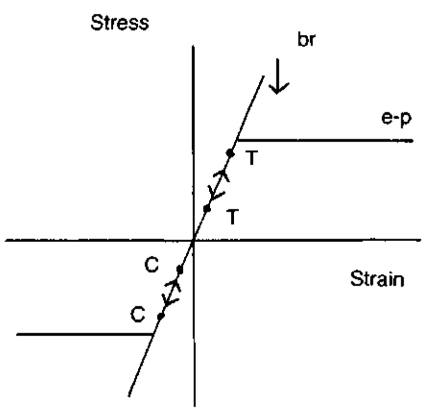



Fig. 10.1 — Cyclic deformation between different levels, T and C, will cause fatigue in elastic–plastic (e–p) or brittle (br) materials.

*The term *static fatigue* is sometimes used to denote failure after the single application of constant load for a long period of time, but our preference is to term this *creep failure*, and reserve the word *fatigue* for cyclic application of stress.

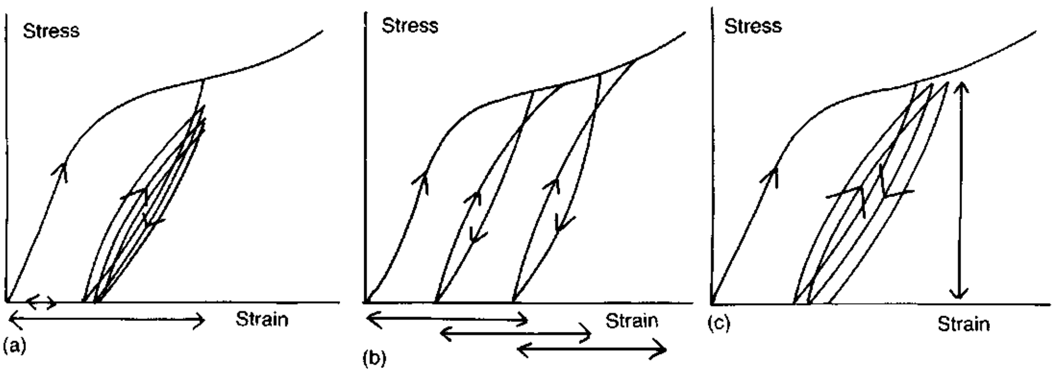



Fig. 10.2 — Typical fibre stress–strain responses. (a) Simple extension cycling. (b) Cumulative extension cycling. (c) Load cycling.

typically of the form shown in Fig. 10.2. Thirdly, there is the anisotropy of fibres which means that the directions of the cyclic stress will have a major effect on the fatigue.

The easiest experimental arrangement gives simple extension cycling, Fig. 10.2(a), in which the fibre is repeatedly stretched between its initial length and a fixed elongation. However, the imperfect recovery means that the specimen is slack for much of the time, and furthermore stress relaxation means that the maximum load steadily decreases. Experience has shown that simple extension cycling does not lead to failure unless the imposed extension is close to the normal breaking extension.

In order to overcome this problem, cumulative extension cycling was adopted. In this method, the slack is removed after each cycle, by unclamping and reclamping a rod attached to the lower jaw holding the fibre, and the selected elongation is imposed on the new straight length, as in Fig. 10.2(b). There are two main responses in this type of test: (i) the fibre may climb steadily up the load–elongation curve until failure occurs at the normal breaking extension, so that the test is no more than a rather complicated tensile test sequence; (ii) the fibre may settle down to an oscillation between two levels, with the recovered extension equalling the imposed extension, and does not break, at least in any practical time. A large amount of work carried out with this method did not yield very interesting results, although it did appear that there was a very narrow band of imposed extensions in which break was occurring at extensions less than the breaking extension and in a different form, which suggested the influence of fatigue. In rayon the band was from about 2% to 2.5% extension and in a typical nylon from about 10% to 10.5%.

Interesting tensile fatigue results came only when the experimental problems of cycling between given load levels were overcome in a new tensile fatigue tester developed by Bunsell, Hearle and Hunter (1971). The cycling has the form shown in Fig. 10.2(c). This tester also operated at a higher frequency, usually 50 Hz, than the old cumulative extension testers. The results of studies with this tester are described in Chapter 11.

## FLEXING AND TWISTING

Two modes of deformation which fibres commonly suffer in use are bending and twisting, and fatigue due to these causes has to be investigated.

The common method of testing flex fatigue is to pull a fibre, held under a small tension, backwards and forwards over a pin, as shown in Fig. 10.3(a), so that fibre elements alternate between straight and bent forms. If the tension is imposed by a hanging weight, there can be complications due to inertial effects and the fibre can swing round so that different sides go into tension or compression somewhat irregularly. Better control is exerted when the tension is imposed by an elastic string, and one side of the fibre then always goes into tension and the other into compression.

Although this type of test is easy to set up, it does not expose the fibre solely to pure bending moments. There are normal forces and frictional forces at the contact between fibre and pin, which can cause surface wear. Attempts have been made to minimize this wear by mounting the pin so that it is free to rotate. In addition, the abrupt change of curvature from bent to straight means that there are shear stresses, which have their maximum value at the centre of the fibre.

Another method, which we have used to a very small extent, is to buckle the fibre repeatedly, as illustrated in Fig. 10.3(b). In the initial deformation this gives a smoothly varying curvature, which could be calculated from elastic theory. But, owing to the non-linearity of recovery, a sharp kink usually develops, giving an unknown level of high curvature.

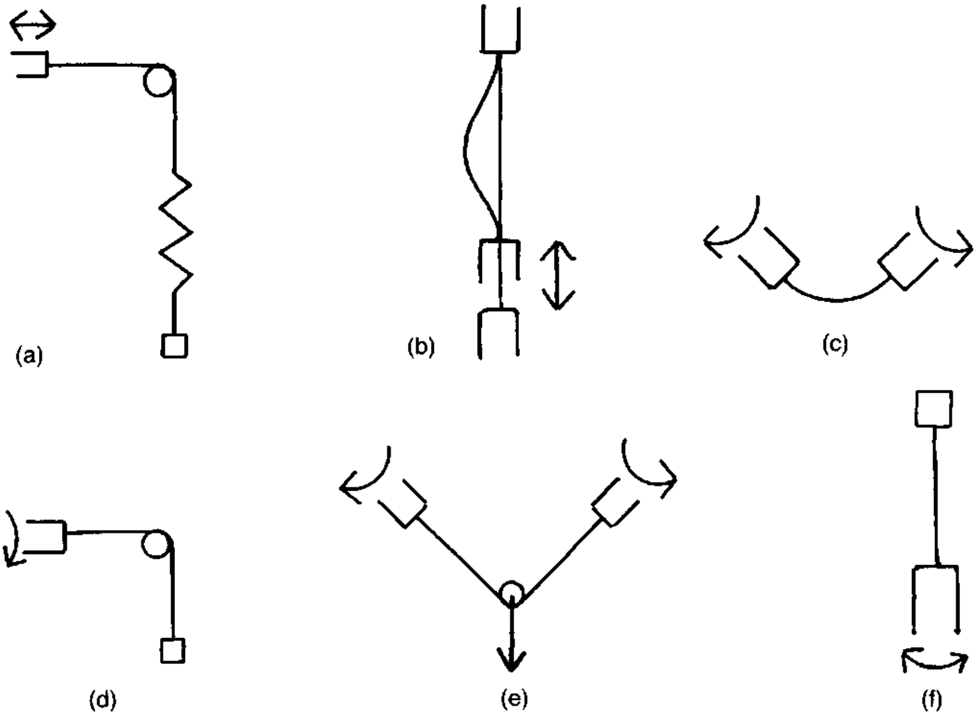



Fig. 10.3 — Bending and twisting fatigue tests. (a) Flex fatigue over a pin. (b) Buckling flex fatigue. (c) Free biaxial rotation. (d) Rotation over a pin. (e) Biaxial rotation over a pin. (f) Torsional fatigue.

Yet another mode of cyclic flexing is biaxial rotation testing. In this technique a bent fibre is rotated so that material on the outside of the fibre goes through a cycle of tension and compression. This is much the same as bending backwards and forwards, except that the extremes are reached by swinging round in a circle instead of by moving in a plane: there is the difference that all positions around the fibre suffer the same cycle of deformation.

Biaxial rotation testing was first used on thick monofilaments, where the specimen can be bent freely between inclined rotating jaws, Fig. 10.3(c). However, for fine fibres, it is not possible to get tight enough curvature unless the bend is concentrated round a pin. The first procedure adopted, Fig. 10.3(d), was to drive the rotation from one end with a weight which was free to rotate hanging from the other end. However, this is not ideal because of the inertial and drag torque from the weight. Various configurations were then adopted in order to drive both ends while maintaining the fibre under a controlled low tension. The best form is shown in Fig. 10.3(e), with the tension imposed by a load on the pin support and appropriate gears driving both ends together from a single motor.

The deformation in this test appears to be solely in bending, as indicated in Fig. 10.4(a), with no torque present except from any frictional drag on the pin. This is true for perfectly elastic materials. But even with the freely bent monofilaments, where there is no friction, twist develops in opposite directions from either end as shown in Fig. 10.4(b). The reason is the hysteresis in the tension-compression relation, shown in Fig. 10.4(d), in contrast to the elastic response of Fig. 10.4(c). Work must be done in each cycle to overcome the energy loss, and this can only come from the torsional drives, which must impose a torque on each end. In terms of force and moments, the explanation is that stress and strain are in phase in an elastic material, but out of phase in a material with hysteresis. Consequently, as seen in Fig. 10.4(e,f), the bending moment shifts in direction and balances a torsional moment on the end of the fibre.

The biaxial rotation test has been very much used in our work, because the forms of failure are similar to those found most commonly in the real wear of textile materials. Both this test, and the flex to and fro on a pin, are easily adapted to be performed in different environments.

Pure twist cycling, Fig. 10.3(f), is easy to formulate in principle, but less easy to put into practice because of the very large number of turns which have to be inserted in each cycle. We have only studied it in one investigation, using a highly geared system, which suffered nearly as much damage as the fibre when driven at high speed.

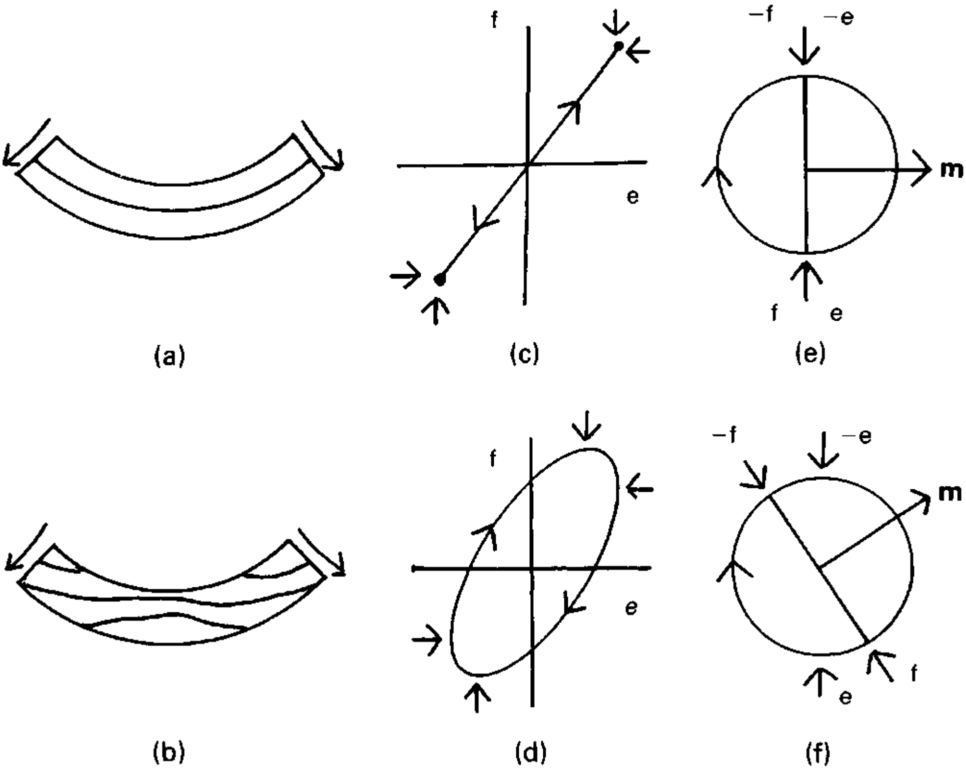



Fig. 10.4 — (a) Simple bending of elastic material, even in rotation. (b) Bending plus false twist in a material with hysteresis. (c) Stress–strain relation of elastic material. (d) Stress–strain relation with hysteresis, showing locations of peak stress and strain. (e) Cross-section of rotating fibre showing peak stress, *f*, and strain, *e*, in phase. (f) Peak stress and strain out of phase which shifts the direction of the bending moment vector, **m**.

## SURFACE ABRASION

Fibres in use can also be subject to surface shear. One way of simulating this is to hang a fibre under tension over a rotating rod or pin as illustrated in Fig. 10.5. We have done a limited number of tests by this method, but more research on it is needed.

Another method is to twist two yarns together, or two parts of the same yarn, and then pull them backwards and forwards, as illustrated in Fig. 10.6. This test has yielded very interesting results, which are dominated by surface shear, although complicated by the presence of many filaments in the yarn. There will be some fibre bending, but this will be of low curvature if the yarn diameter is large. The results from this test are discussed in Part V, Chapter 24, since it is a yarn and not a fibre test. An analogous procedure with single filaments twisted together would give rise to large bending and twisting deformations.

## CONCLUSION

The various test methods described in this chapter do provide useful ways of investigating the forms of fatigue failure of fibres, and illuminate what is found in case studies of wear. However, from the viewpoint of mechanics and basic theory, they have the defect that they all include complicated combined stresses. The subject is still wide open for further research, both experimental and theoretical.

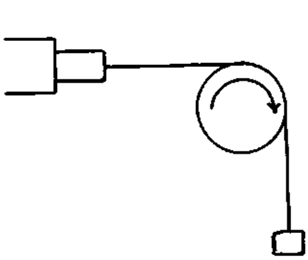


Fig. 10.5 — Surface wear by a rotating pin.

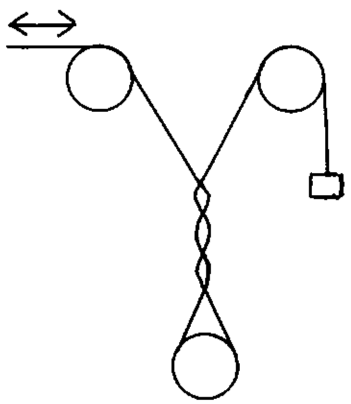


Fig. 10.6 — Yarn-on-yarn abrasion test.

Quantitative studies of fatigue life involve carrying out many tests since there is always considerable statistical variability. The best that can be achieved is usually about a tenfold range between the shortest and the longest life in any set of tests under nominally identical conditions. This does, however, suffice to show up marked differences between different fibres and test conditions.

The general experience is that increasingly rapid breakdown is observed as one goes from tension–tension cycling, to tension–compression in flex testing, to tension–compression plus torque in biaxial rotation testing. Any cyclic shear stresses lead to breakdown by axial splitting.

## DEVELOPMENT IN FATIGUE TESTING

There has been a significant advance in fatigue testing since 1989. Figure 10.3(b) shows a buckling test, which had been used for a few tests on single fibres at UMIST. This has now been adapted by TTI (Tension Technology International Ltd) as a yarn buckling test for the evaluation of axial compression fatigue in yarns used in ropes, as described in the report on FIBRE TETHERS 2000 (1994,1995), and has also been used on wool yarns intended for use in carpets. In the unrestrained test method, a length of yarn is clamped between jaws a short distance apart, and then subject to cycling between the zero tension position, as mounted, and a reduced spacing. The yarn buckles and, after a number of cycles, the bend concentrates into a sharp kink. Yarns are removed after given numbers of cycles and their residual strength is measured.

A closer simulation of the yarn kinking which occurs in ropes, with lateral restraint from neighbouring yarns, is obtained by testing a number of yarns within shrink-tubing. After a suitable number of yarns have been inserted into the plastic tube, shrinkage is activated by heat. The tube is then mounted in the tester and cyclic buckling applied. The test distinguishes well between different yarns in their sensitivity to axial compression fatigue. In one set of restrained tests, strength loss was detectable in aramid yarns at 1000 cycles but not until 50 000 cycles in polyester yarns, and became severe at 20 000 and 1 000 000 cycles, respectively.

In the new parts of this edition, examples of breaks of buckled yarns are included in Chapter 12 and similar effects in ropes in Chapter 39 and in carpets in Chapter 33.

# 11

# TENSILE FATIGUE

## Nylon, polyester, Nomex, polypropylene, acrylic, Kevlar

Several different loading patterns which can be obtained on the fibre tensile fatigue tester, referred to in the previous chapter, are illustrated schematically in Fig. 11.1(a). In reality the data would have appreciable variability, which might lead to some overlapping of the failure conditions. In a simple tensile test in which a nylon fibre is extended at a constant rate, the tension will increase along the line OA, and break will occur at a tension $T_0$, with the assumption that the rate of extension has been adjusted so that the time-to-break is 20 seconds. If a somewhat lower tension, $T_1$, is held constant for a long time, creep failure will eventually occur at B: we assume that $T_1$ has been selected so that the time-under-load to cause break is 1 hour. Neither of these are fatigue situations, and the breaks will be typical ductile tensile failures, with a V-notch leading to a catastrophic break as shown in Fig. 11.1(b).

Now suppose that we impose an oscillating load from some intermediate tension up to the same maximum value $T_1$, as indicated by C. Experiment shows that break will occur in about

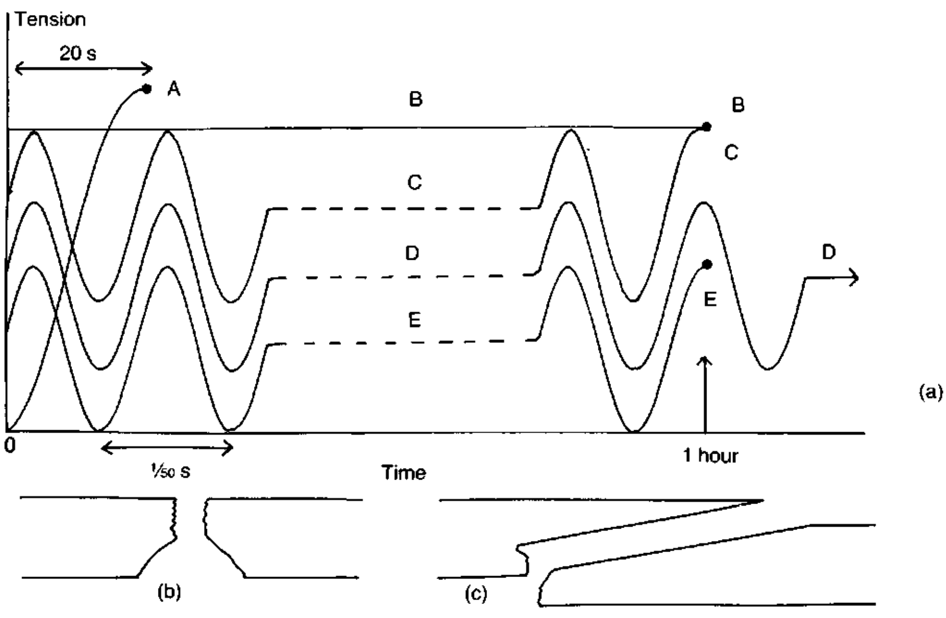



Fig. 11.1 — (a) Loading patterns: note different time scales. A — Constant rate of extension to break in 20 s at tension $T_0$. B — Constant tension $T_1 < T_0$, to break in 1 hour. C — Tension oscillating at 50 Hz between 0.4 $T_1$ and $T_1$. D — Tension oscillating at 50 Hz between 0.2 $T_1$ and 0.8 $T_1$. E — Tension oscillating between 0 and 0.6 $T_1$. (b) Ductile tensile failure with loading patterns A, B, C. (c) Tensile fatigue break in loading pattern E.

the same time as with a constant load. Owing to the inevitable scatter of results it is not possible to say definitely whether the time to failure is nearer to the same value as in creep failure, namely 1 hour in this example, or to the longer time which would give the same area under the load–time curve; but these two are not very different, and certainly there is no hastening of break caused by the oscillation. The form of failure is again the ductile V-notch of Fig. 11.1(b). So this test is just a creep failure under a different loading history — and the behaviour can be predicted with sufficient accuracy from a simple constant-load test.

If the maximum load is lowered slightly below $T_1$, the time to failure will increase. If it is appreciably lowered as in D, break will not occur, at least not within a measured time.

But if the load is lowered still more, as in E, break once again occurs in about the same time, with the precise number of cycles to failure depending on the particular cyclic load. So reducing the severity of loading has unexpectedly led back to a break situation. The criterion which must be satisfied is that the minimum load must be reduced to zero, or, in some fibres, to a critical value close to zero. The form of break is now different, as illustrated in **11A(1),(2)**, and shown schematically in Fig. 11.1(c). A long tail on one end has stripped off the other end. This is a true fatigue situation: failure after cycling between zero and half to three-quarters of the normal breaking load, with break happening between 10 000 and 1 000 000 cycles, with a new characteristic form of fracture.

The sequence of events leading to the tensile fatigue is illustrated in **11A(3)–(6)**, and shown diagrammatically in Fig. 11.2. Fatigue starts with a transverse crack on the fibre surface, **11A(3),(4)** and Fig. 11.2(b). At the tip of such a crack there will be an axial shear stress, and this then becomes the dominant cause of rupture. The crack turns and runs along the fibre at a slight angle to the fibre axis, Fig. 11.2(c), as can just be seen in **11A(4)** and is clearly visible in **11A(5)**. As it proceeds, the crack gets wider and deeper, Fig. 11.2(d), until eventually the tensile stress on the reduced cross-section is large enough to cause a ductile tensile break to become the final stage of fibre failure, Fig. 11.2(e) and **11A(6)**.

The tip of the tail, which is one side of the initial transverse crack, is shown in **11B(1)**. In some tests, a number of separate fatigue cracks develop along the fibre, as shown in **11B(2)**, with one failing first. There are variants in the form of the fatigue. Sometimes, probably owing to surface damage, the initial transverse crack is at an oblique angle, **11B(3)**, and sometimes the shear stresses cause cracks to run in both directions, **11B(4)** and Fig. 11.2(f).

Tensile fatigue in another type of nylon fibre is shown in **11B(5),(6)**. Both types break in a similar way with the axial cracks running across the fibre at an appreciable angle, as indicated in Fig. 11.2(c,d,e), so that the length of the tail is typically about five fibre diameters.

In a polyester fibre, **11C(1)**, the tensile fatigue break looks very different, although the test conditions for failure are similar. The tail of a fatigued polyester fibre is extremely long. This is a consequence of the fact that the axial crack in polyester runs much more closely parallel to the fibre axis, as indicated in Fig. 11.2(g). It must therefore proceed further along the fibre before the cross-section has reduced sufficiently for tensile break to happen. Indeed, as seen in **11C(1)**, the crack has progressed beyond the point at which the final break occurs. This implies that a period of time under load is necessary in order to cause the tensile break to occur, probably at a weak place in the material.

In another set of tests, it was found that the tails sometimes split into two or more parts, **11C(2)**. Details of the fatigue are shown in **11C(3)–(6)**. In this example the final failure started from an internal flaw, which probably weakened the fibre. In other examples the break starts from the surface of the fibre. Particularly interesting are the striations visible on the crack surfaces in **11C(6)**: these may well be steps of growth of the fatigue crack in each cycle.

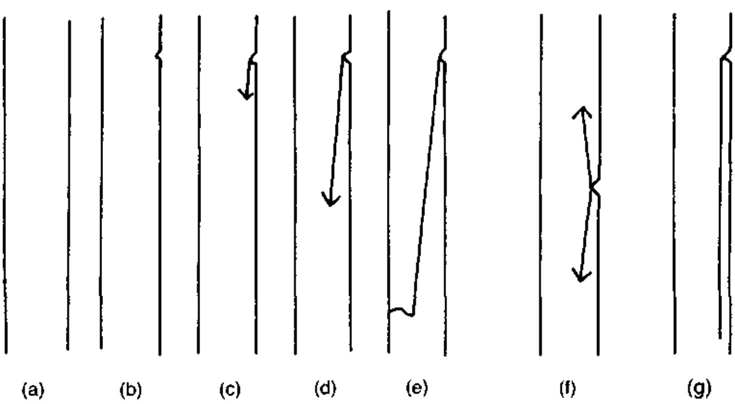



Fig. 11.2 — Sequence of tensile fatigue failure in nylon. (a) Fibre before cyclic loading. (b) After cyclic loading, transverse crack appears. (c) Shear stress at tip of crack causes axial split to start. (d) Axial crack continues getting deeper and wider. (e) Final failure by tensile break over reduced cross-section. (f) Variation with axial cracks running in both directions. (g) In polyester, the axial crack is almost parallel to the fibre axis.

Some other fibres show similar forms of tensile fatigue breaks. The tail of a fatigued Nomex (meta- aramid) fibre is shown in **11D(1)**. However, the detail of initiation in **11D(2),(3)** shows no evidence of a transverse crack: the axial splits seem to shave away directly from the surface. Possibly, surface roughness leads to the necessary shear stresses being present. Polypropylene, shown in **11D(4),(5)**, has a form similar to nylon, although with some distortions.

In the acrylic fibre, Courtelle, the fatigue failure is associated with axial splitting, **11D(6)**, but the criterion that the minimum load must be zero does not apply. An oscillating load causes failure at a reduced maximum load, whatever the value of the minimum load. There may be multiple splitting, **11D(7)**, and a tendency for a sharp separation of a surface skin layer, **11D(8)**.

Experiments on the high-strength para-aramid fibre, Kevlar, have shown no evidence of any appreciable weakening under tensile fatigue conditions. It is necessary to impose a peak load of a value within the range of experimental error for the normal tensile breaking load in order to cause break to occur. However, the form of break does show even more pronounced axial splitting, with breaks extending over very long lengths, **11E(1),(2)**, and showing complicated multiple splitting, **11E(3),(4)**.

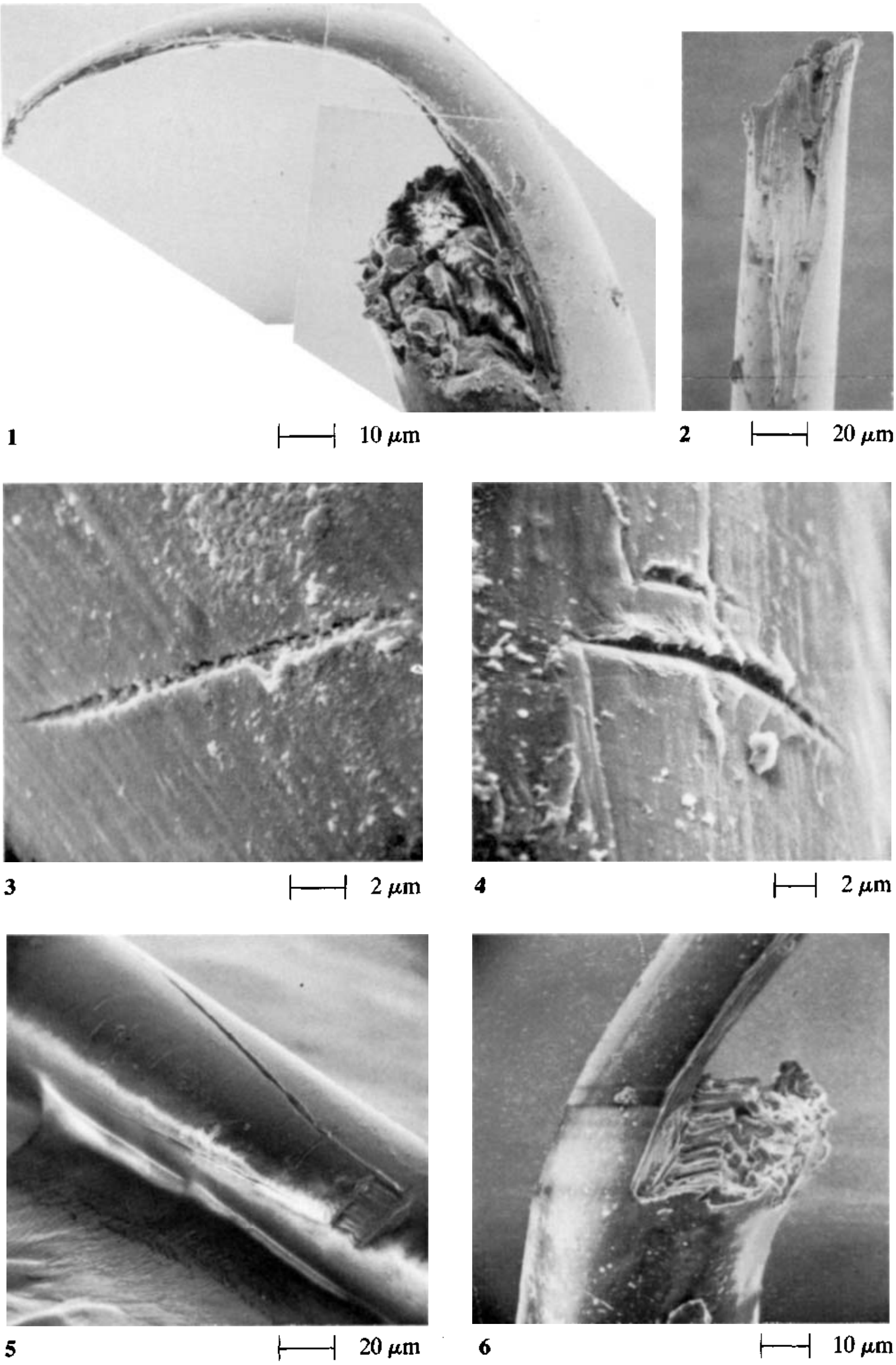



**Plate 11A — Tensile fatigue of medium-tenacity (0.4 N/tex) nylon 66 fibre.**
(1),(2) Opposite ends of break after 62 000 cycles at 50 Hz between zero load and 71% normal breaking load. (3) Initiation of fatigue by a transverse crack. (4) Two transverse cracks with beginning of axial splitting. (5) Well-developed axial split. Note also other transverse cracks on fibre surface. (6) Final failure, with a ductile tensile break over the reduced load-bearing area.

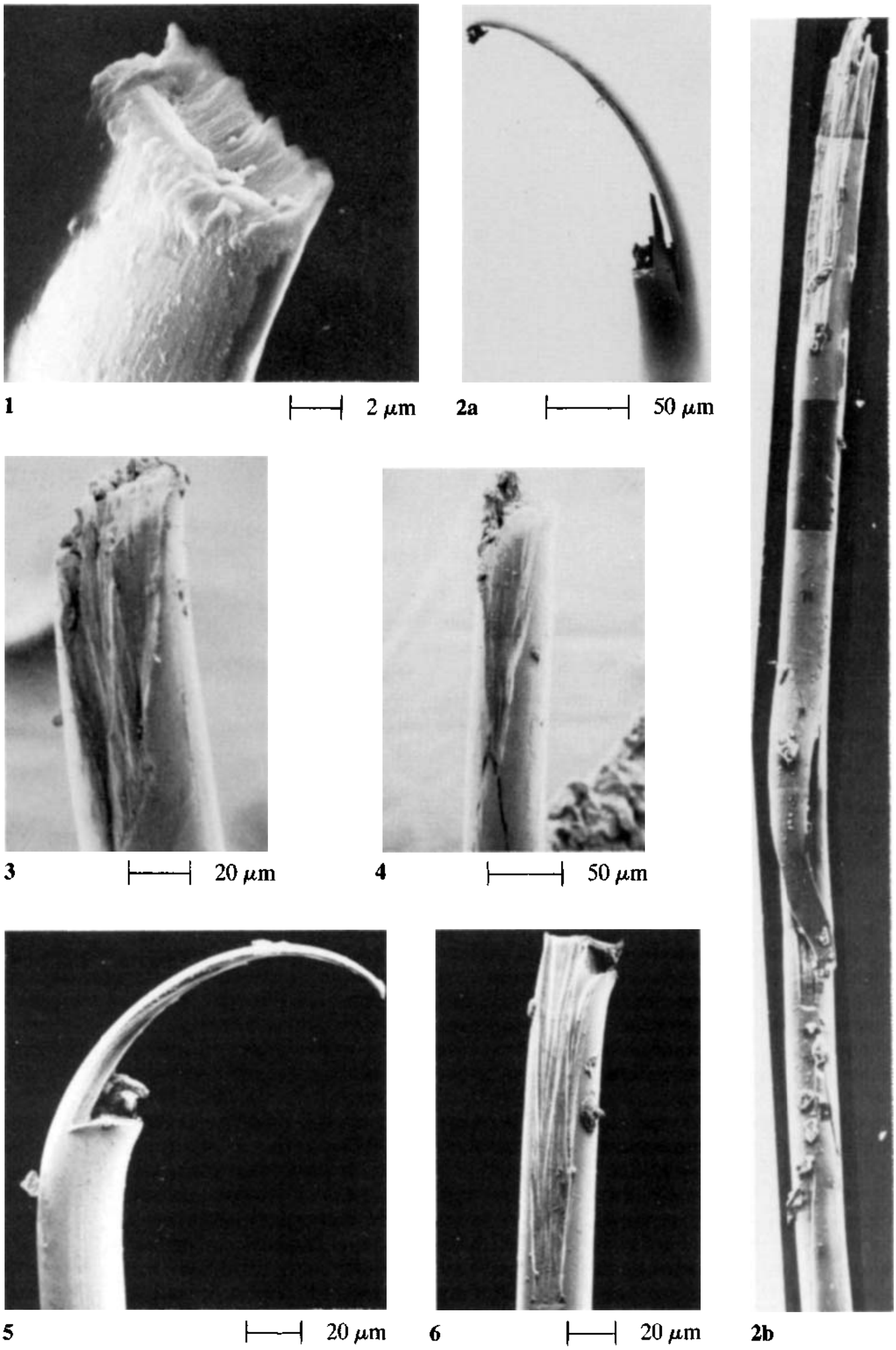
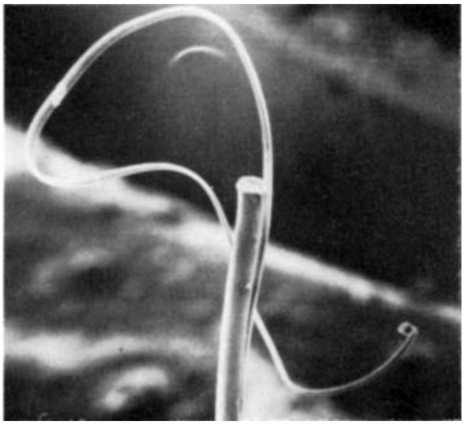
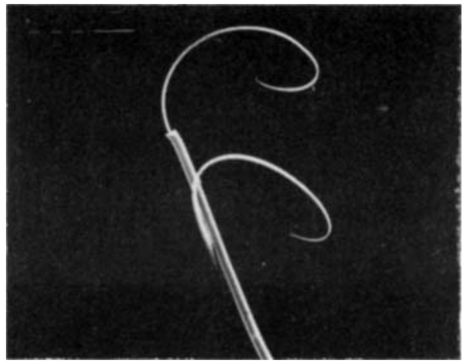


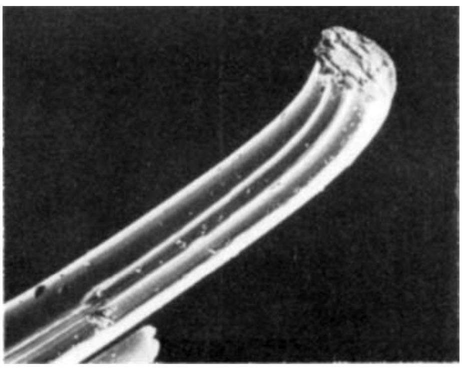

**Plate 11B — Tensile fatigue of medium-tenacity nylon 66 fibre.**
(1) Detail of the tip of the tail, resulting from the original transverse crack. (2a) One end of a break after 65 000 cycles at 50 Hz between zero load and 80% of normal breaking load. (2b) Opposite end of same break. Note the other developing fatigue cracks. (3) Variant form with angled transverse crack. (4) Variant with fatigue cracks running in both directions along fibre from the initial transverse crack.
**High-tenacity (0.6 N/tex) nylon 66 fibre.**
(5),(6) Opposite ends of break after 58 000 cycles at 50 Hz between zero load and 66% of normal breaking load.



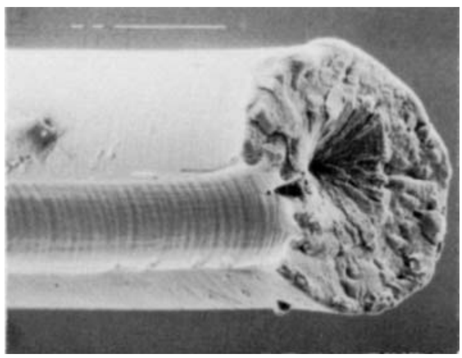
1 50 $\mu m$



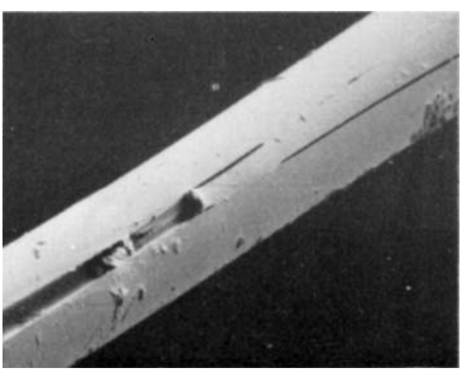
2 100 $\mu m$



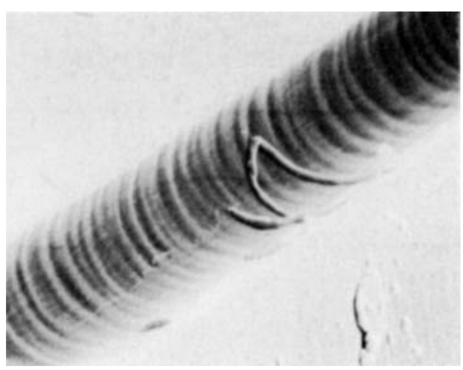
3 10 $\mu m$



4 5 $\mu m$



5 10 $\mu m$



6 2 $\mu m$

**Plate 11C — Tensile fatigue of polyester fibres.**

(1) Break after 83 000 cycles at 50 Hz between zero load and 65% of the normal breaking load.

**Tensile fatigue of another type of polyester fibre.**

(2) With multiple splitting. (3) Detail of failure. (4) Final break, with tensile failure starting from an internal flaw, which is probably a weak place. (5) Detail of crack splitting. (6) Axial crack surface showing striations. Note that this is an enlarged view of the concave cavity in the fibre surface.

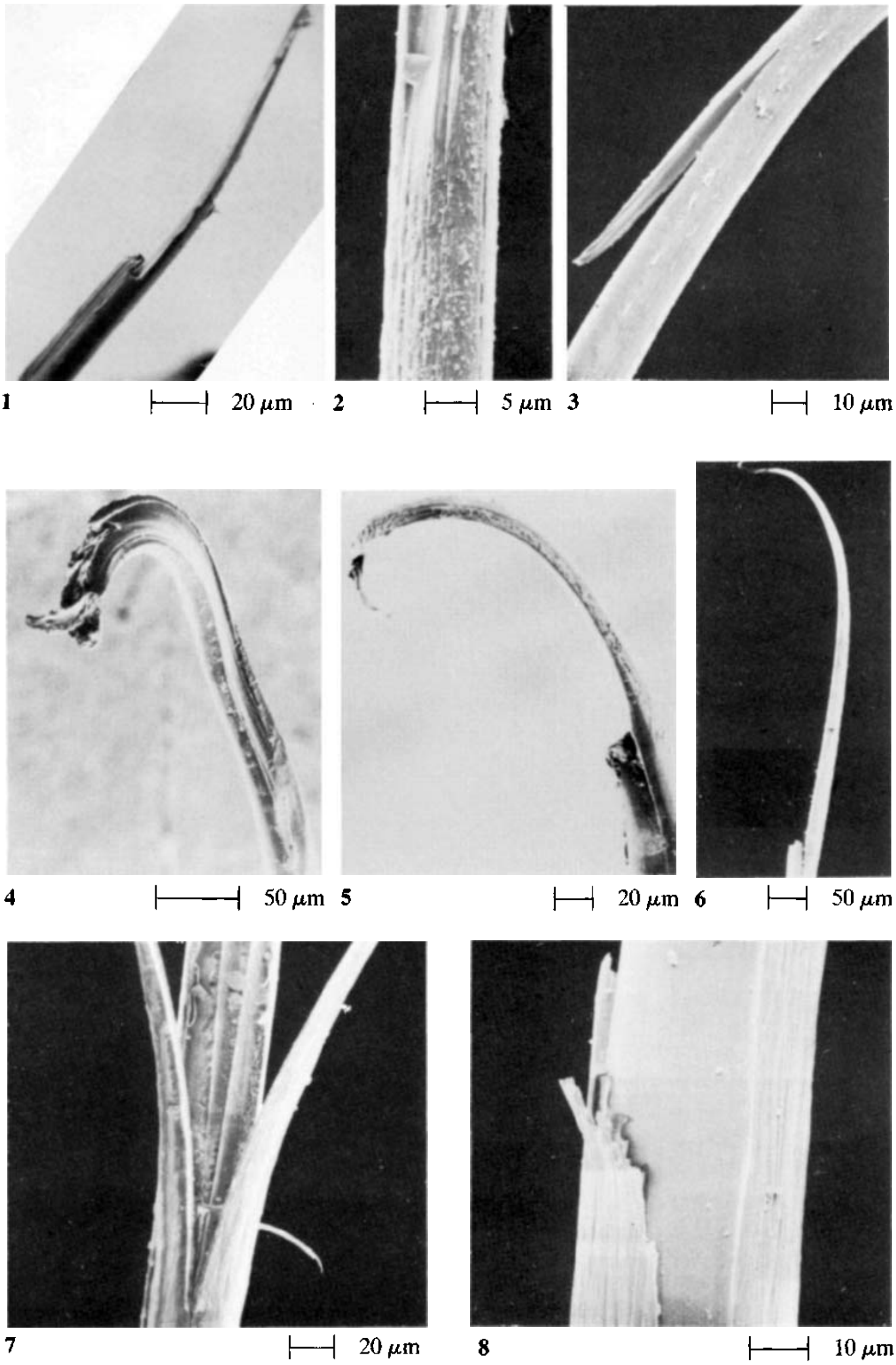



**Plate 11D — Tensile fatigue of Nomex (meta-aramid) fibre.**
(1) Break after 18 000 cycles at 50 Hz between zero load and 60% of the normal breaking load. (2),(3) Initiation regions.

**Tensile fatigue of polypropylene fibre.**
(4),(5) Opposite ends of break after 522 000 cycles at 86% of normal breaking load.

**Tensile fatigue of Courtelle (acrylic) fibre.**
(6) Break after 157 000 cycles at 66% of normal breaking load. (7),(8) Detail of splitting.

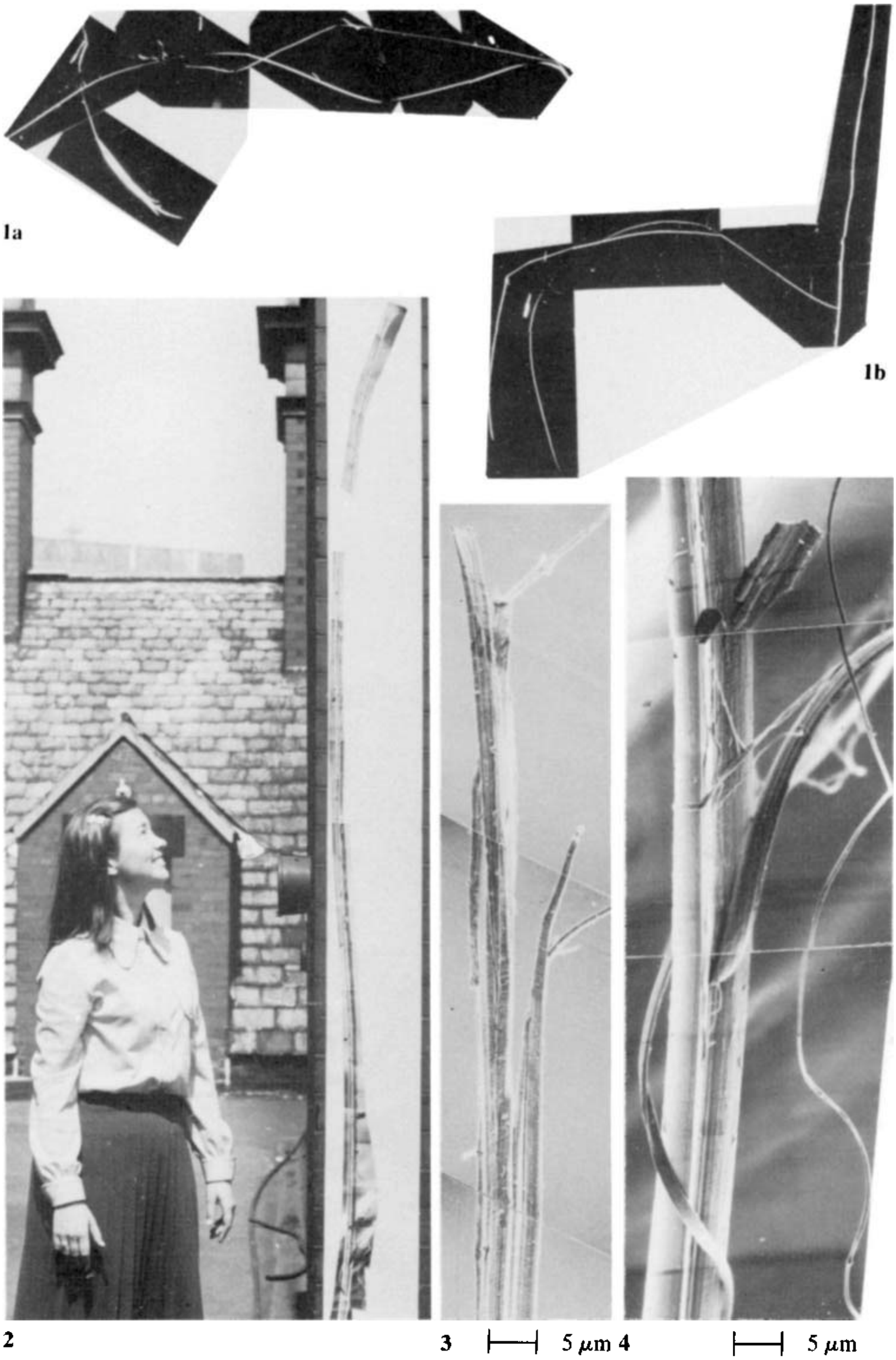



**Plate 11E — Tensile fatigue of Kevlar (para-aramid) fibre.**
(1a,b) Break after 285 000 cycles at over 90% of average normal breaking load. Montage of pictures of both broken ends taken in an optical microscope. (2) Demonstrating the number of SEM pictures, at a reasonable magnification, needed in a montage to show the whole breakage region. (3),(4) Detail of multiple splitting.

# 12

# FLEX FATIGUE

## Polyester, nylon, acrylic, polypropylene, rayon

When fibres are bent, they often develop kinkbands on the inside of the bend. These can be shown up by light microscopy, sometimes with appropriate use of polarized light, **12A(1)**, or in severe examples by SEM, **12A(2)**. Whether or not visible kinkbands appear depends on the fibre and the conditions. Thus polyester develops kinkbands in a single bend at 20°C but not at 100°C, whereas nylon 66 shows the reverse combination. The kinkband is a localized buckling of the oriented structure within the fibre, as indicated schematically in Fig. 12.1, and is the mechanism of mechanical yielding under the compression on the inside of the bend. When the kinkbands are not found, even though there is yielding, this implies that microbuckling occurs at many places throughout the fibre, rather than being concentrated in a band. After repeated cycling, the kinkbands appear.

Although the deformation after a single bend, **12A(1),(2)**, looks severe, it is not mechanically damaging. The bands pull out under tension, and there is no loss of strength. But repeated cycling, by pulling a fibre backwards and forwards over a pin, leads to an intensification of the disturbance at the kinkband, with a break-up into fibrillar strands across the band, **12A(3)**. Eventually, the kinkband fails completely and becomes an angular split through the compression zone from the surface of the fibre to the neutral plane, **12A(4),(5)**. An axial split usually develops at the centre of the fibre. The other side of the fibre then suffers damage, and the final break shows characteristic angular faces, **12A(6)**, which are the original kinkband locations. This sequence of events is illustrated schematically in Fig. 12.2.

If the fibre is allowed to rotate as it is pulled across the pin, the kinkbands develop throughout the fibre. An example of a fibre which has broken in this way, before the test equipment was modified to prevent rotation, is shown in **12A(7)**. The light microscope picture shows up the kinkbands, with the final break along the same angle.

As explained in Chapter 10, flexing by pulling a fibre backwards and forwards over a pin under some tension is not simple cyclic bending. There are normal and frictional forces at the pin surface and shear stresses, which are present at places where the bending curvature is changing. More detailed investigations have shown that the form of failure depends on the type of fibre and the test environment.

The examples of nylon 6 and 66, **12B(1)–(6)**, all show a strong effect of kinkbands combined with varying degrees of axial splitting. An axial split must result from shear stress, but this can

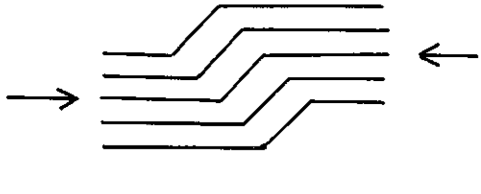
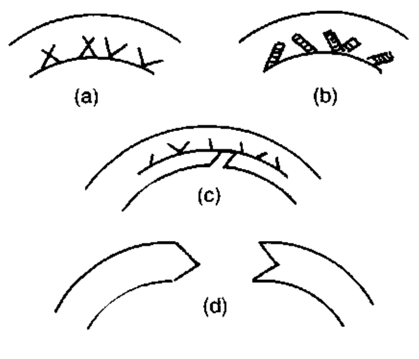


Fig. 12.1 — Schematic view of kinkband formation, due to compression of an oriented structure.

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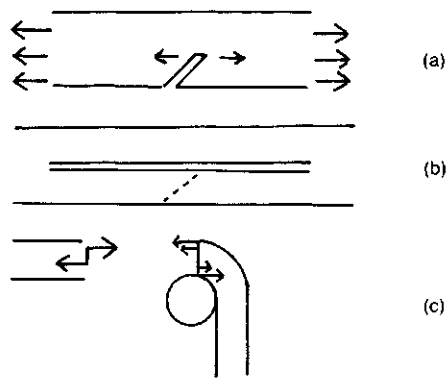


12.3

Fig. 12.2 — Sequence of events in flex failure by kinkband mode. (a) Kinkbands develop on bending. (b) They become more disturbed on cycling. (c) A kinkband fails, axial split is present, and the failure mechanism starts to operate in the other side of the fibre. (d) Final break shows angular faces.

Fig. 12.3 — (a) Shear stress at the tip of a kinkband crack. (b) Axial split occurring first, followed by break at a kinkband. (c) Shear stress in straight part balancing bending moment in bent part.

develop in two different ways. Following the rupture at a kinkband, there will be a shear stress at the tip of the crack, as shown in Fig. 12.3(a), because the fibre is under tension; and this may lead subsequently to an axial split. The other mechanism is independent of the presence of kinkbands, and could lead to axial splitting occurring first, with the kinkband later breaking through to the split, as in Fig. 12.3(b). At the place where the fibre leaves the pin, the bending moment in the curved part has to be balanced by a shear stress in the straight part, as indicated in Fig. 12.3(c). The shear stress is a maximum at the centre of the fibre. As the fibre moves across the pin, the location of the shear stress will move along the fibre and so can cause a long axial split. In reality, there is not an absolutely sharp change from curved to straight, but a small zone of varying curvature, over which the shear stresses are present.

A split of the type shown in **12B(3)** appears to have been caused by the first mechanism, but the long split in nylon, **12C(1)**, occurring before appreciable kinkband damage, must result from the second mechanism. The shear stresses can lead to multiple splitting, as in the polyester fibre, **12C(2)**. Other examples of multiple splitting, either before or after the fibre has broken, are **12D(1)–(4)**, and detail of an axial split is shown in **12D(5)**. In some situations, the axial splitting proliferates into many fine strands, **12D(6)**, although this may be an action of forces of surface wear. Snap-back after break can cause the splits to retract into spiral coils, **12E(1)**.

Further evidence for the early development of an axial split is found in studies of flexing for a certain number of cycles followed by tensile testing to break the fibre. The break can develop in two places, since the two halves of the fibre, which are separated by the axial split, act independently, **12E(2)**, or the break may show very clear axial splits, **12E(3)**. Another phenomenon observed on tensile testing of a flexed fibre is the occurrence of many micro-cracks along the fibre, **12E(4)**.

All the results reported so far in this chapter are from tests in which the combination of tension and curvature (pin diameter) were selected so as to minimize wear on the fibre surface, and cause failure to result from kinkbands and splits within the body of the fibre, as a consequence of flexing. However, if some other conditions are used, wearing away of the surface can become the dominant mechanism, **12E(5),(6)**. This tends to occur when the curvature is too high, and the tension too low. It is interesting to observe the pattern of the kinkbands showing in the worn surface in **12E(6)**. As shown in Chapter 14, surface wear becomes the dominant form of damage when flexing to and fro over a pin is applied to some other fibre types, such as aramid (Kevlar), wool and hair.

A limited study of flexural fatigue on acrylic fibre has shown that splitting and peeling can occur, **12F(1),(2)**, but there are also indications of breakage along a kinkband under compression, **12F(3)**, and of partial granular failure similar to tension breaks, **12F(4)**. Another limited study of polypropylene showed evidence of splitting and surface wear, **12F(5),(6)**.

When a standard viscose rayon fibre is repeatedly flexed, there is none of the long axial splitting or fracture along kinkbands found in other fibres. The break runs perpendicularly across the fibre, **12G(1)**, but in a very rough and uneven manner. There are kinkbands on the inside of the bend, **12G(2)**, and it is likely that the cyclic compressive stress disturbs and weakens the structure, and so leads to this unusual form of failure under the tensile load. Close examination of the fracture surface, **12G(3)**, shows bands of parallel striations and some indication of axial cracks. There is also wear of the fibre surface, **12G(4)**, due to rubbing on the pin. The kinkbands can also be seen in **12G(4)**. The flex fatigue failure of high-tenacity rayon, **12G(5),(6)**, is generally similar to that of standard rayon, although the surfaces are not as rough.

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Flex fatigue tests over a pin have been extended to Dyneema HMPE (high modulus polyethylene) fibres, also referred to as HPPE (high performance polyethylene) fibres, by Sengonul and Wilding (1994,1996). At an early stage of flexing over the pin at room temperature, there is some surface abrasion and particles are shed from the surfaces. Below the surface layer, longitudinal striations appear. As shown in **12H(1),(2)** these become more pronounced and then lead to axial splits. The splitting will be due to the shear stresses associated with variable curvature bending, probably intensified by the disturbance of the structure at kink bands caused by axial compression, as seen in **12H(3),(4)**. Abrasion leads to a progressive thinning of the fibre and the final failure appears as in **12H(5),(6)**.

Another series of tests were carried out at elevated temperatures. The appearance of failures at temperatures from 40°C to 100°C are shown in **12I(1)–(6)**. The fibres show major splitting, but fine fibrillation becomes less at higher temperatures and wider ribbons are split off.

The other new observations of flex fatigue come from the yarn buckling test described in the addition to Chapter 10. The overall appearance of a wool carpet yarn after a period of cyclic buckling is shown in **12J(1)**. Localised sharp kinks can be seen in the centre of the picture, and, in places, these have led to fibre breaks. A major form of damage consists of the development of cracks at kink-bands on the inside of bends, as seen in **12J(2)**. These open up, become more pronounced, and lead to rupture, as shown in the sequence, **12J(3)–(5)**. Sometimes the break is divided into separate steps as in **12J(6)**.

Wool fibres have a tendency to split at cell boundaries, and this has occurred to some extent in the breaks in **12K(1),(2)**, though these are still predominantly along transverse cracks based on kink-bands. However, variable curvature can lead to substantial axial splitting, as seen in **12K(3),(4)**, which would lead to multiple splitting failures of the form shown in **12K(5),(6)**.

For the examination of yarns from the buckling tests carried out in FIBRE TETHERS 2000 (1994, 1995), optical microscopy was used. In addition to being a way of viewing a large number of fibres fairly rapidly and to correlate with the axial compression failures in ropes, as reported in Chapter 39, this technique was chosen to show the effects along the length of fibres on a large scale and, at a smaller scale, to show up kink bands within fibres in polarised light.

**12L(1)** is a fibre from a Technora (Teijin aramid fibre) yarn subject to 100000 buckling cycles. A kink in the fibre, which would weaken the yarn and would eventually break completely, is clearly seen. This occurs where the buckling develops a sharp kink at the centre of the clamped length. The internal kink-bands have progressed to a crack going about half-way across the fibre.

**12L(2)–(6)** are for a Kevlar 29 aramid fibre, which has been subject to buckling fatigue. Kink-bands can be seen on the inside of the bend in **12L(2)**, and these lead to breakage along angular cracks across the fibre, **12L(3)**, sometimes accompanied by axial splits, **12L(4)**.

The damage induced in a constrained buckling test of Kevlar 129 at 3000 cycles, when the yarn strength loss is about 20%, is shown in **12L(5)–(8)**. In some fibres, kink-bands run right across the fibre, **12L(5)**, presumably due to an overall axial compression without buckling. However the commoner feature is to see kink-bands on the inside of bends, **12L(6)–(8)**, developing into cracks.

Vectran is a high-performance, liquid-crystal, melt-spun, aromatic copolyester fibre from Hoechst-Celanese. The appearances of fibres from yarn buckling tests are shown in **12M(1)** for 30000 cycles and **12M(2)** for 100000 cycles.

The damage caused in buckling fatigue of Dyneema, HMPE fibre from DSM, after 100000 cycles, with about 30% loss in yarn strength, is shown in **12M(3)–(7)**. There are kink-bands, which are shown up both in the dark bands in the interior of the fibre and in kinks projecting from the fibre surface. Some fibres develop axial splits, **12M(5),(6)**, and in others, **12M(7)**, there are sharp kinks in the fibre as a whole.

Polyester fibres are more resistant to buckling fatigue. After 1000000 cycles, when the yarn as a whole has lost about 1/3 of its strength, there are a few kink-bands on the inside of bends, **12M(8)**. However the most noticeable features, **12M(9)**, are transverse lines and suggestions of axial cracks spread over the whole fibre.

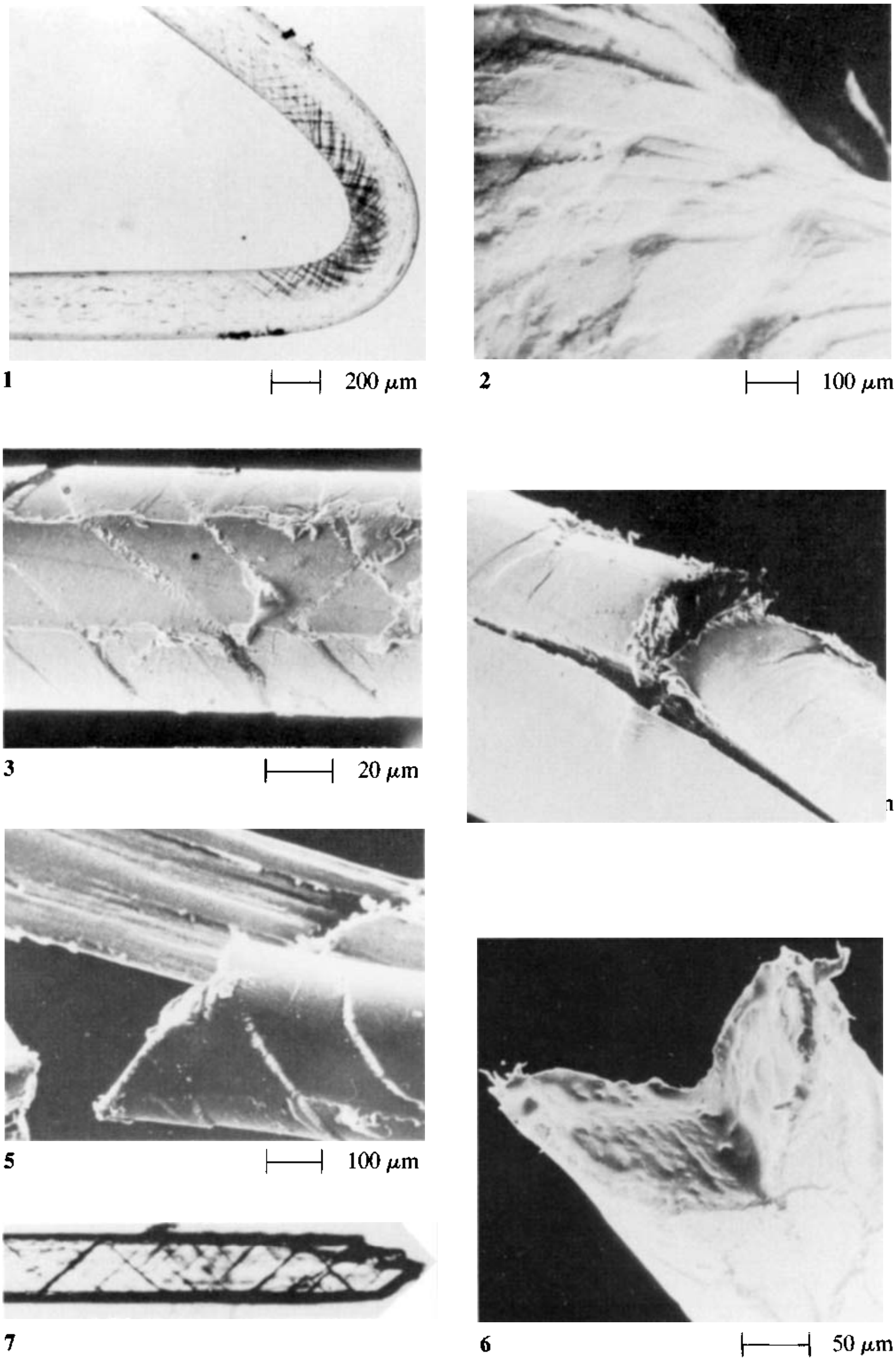
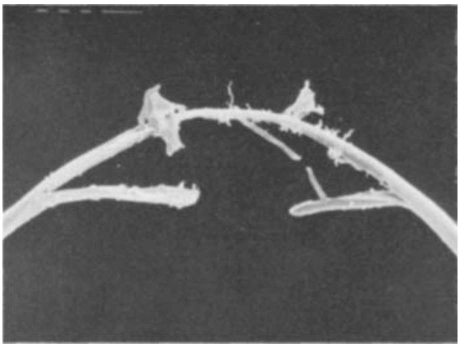



**Plate 12A — Polyester fibre after a single bend.**
(1) Kinkbands shown up in a bent fibre, using polarized light in a light microscope. (2) Kinkbands in a bent fibre in SEM.

**Polyester fibre in flex fatigue.**
(3) After some flex cycling the kinkbands have become pronounced and broken up. Note the limited wear on the surface in contact with the pin. (4) After more flex cycling a kinkband breaks completely, an axial split is present, and damage starts on the other side of the fibre. (5) Another example of kinkband failure and axial splitting. (6) Broken fibre after flex cycling, with a characteristic angular break along the planes of the kinkbands. (7) Light microscopic view of a fibre which has broken after repeated flexing, in conditions in which the fibre could rotate so that kinkbands developed all over the fibre.



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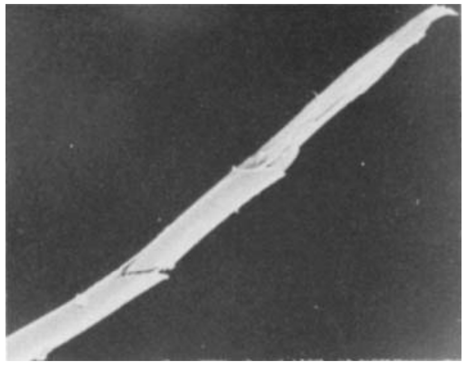
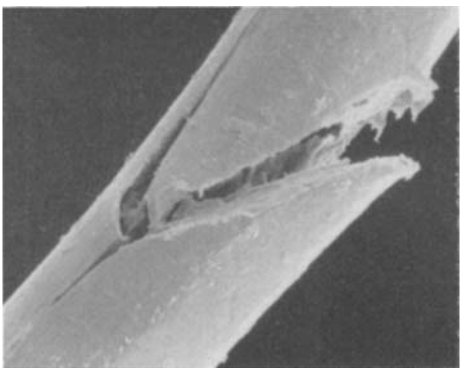
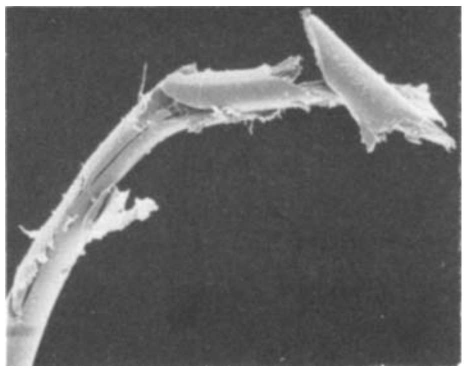


2 100 $\mu$m

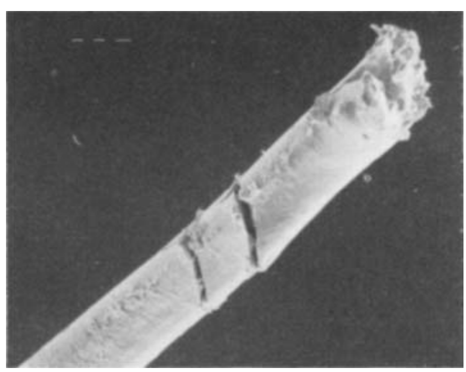


3 20 $\mu$m



4 100 $\mu$m

5 100 $\mu$m



6 50 $\mu$m

**Plate 12B — Flex fatigue of nylon 6 at 20°C, 65% r.h.**

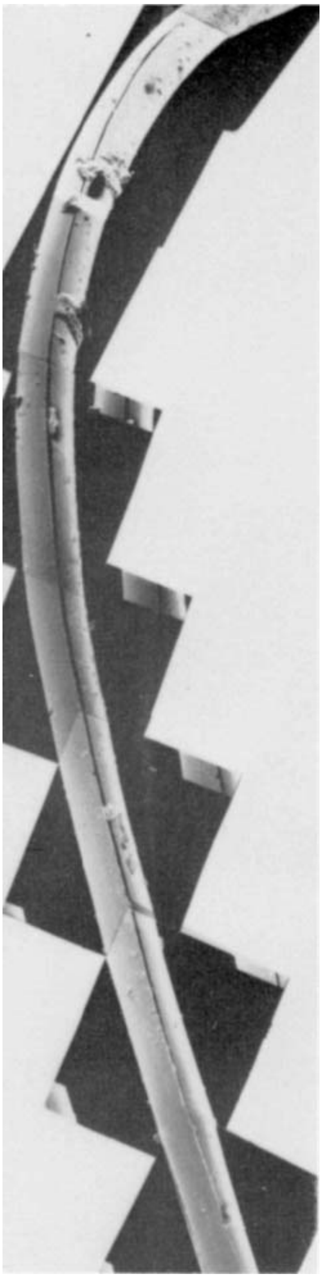
(1)–(4), Examples of kinkband failure and (4) axial splitting.

**Nylon 66 at 20°C, 5% r.h.**

(5) Kinkbands, with more pronounced splitting.

**Nylon 6 at 20°C, 5% r.h.**

(6) Clear kinkband failure.



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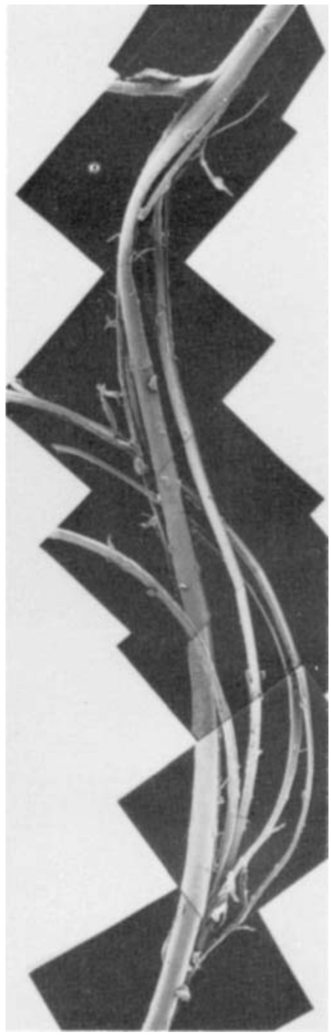

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**Plate 12C — Flex fatigue.**
(1) Nylon 66 at 60°C, 30% r.h. (2) Polyester at 80°C, 5% r.h.

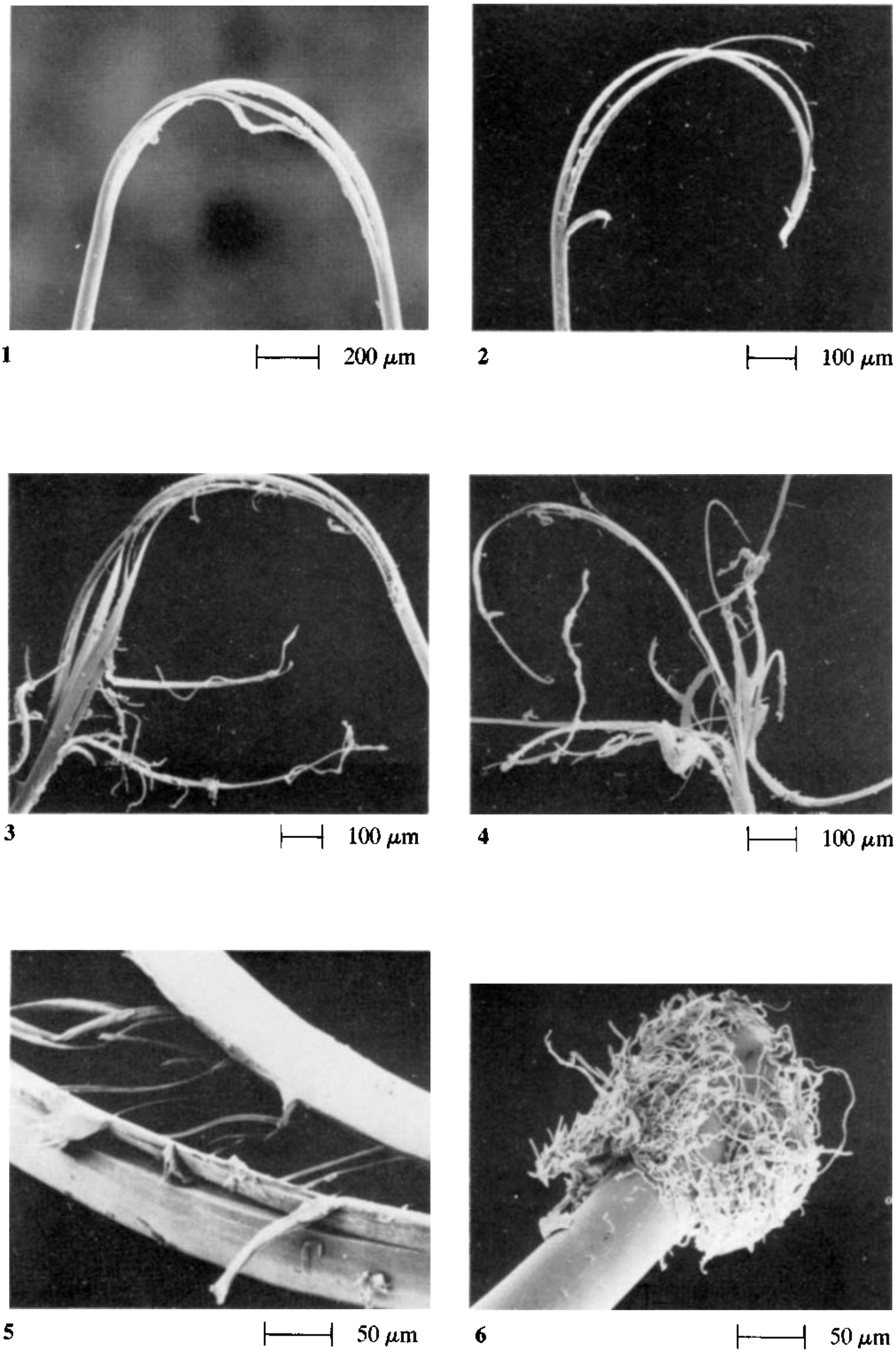



**Plate 12D — Flex fatigue.**
(1) Nylon 6 at 100°C, dry air. (2) Nylon 66 at 100°C, dry air. (3) Polyester at 40°C. (4) Polyester at 20°C, 65% r.h. (5) Polyester at 60°C. (6) Nylon 6 at 20°C, 95% r.h.

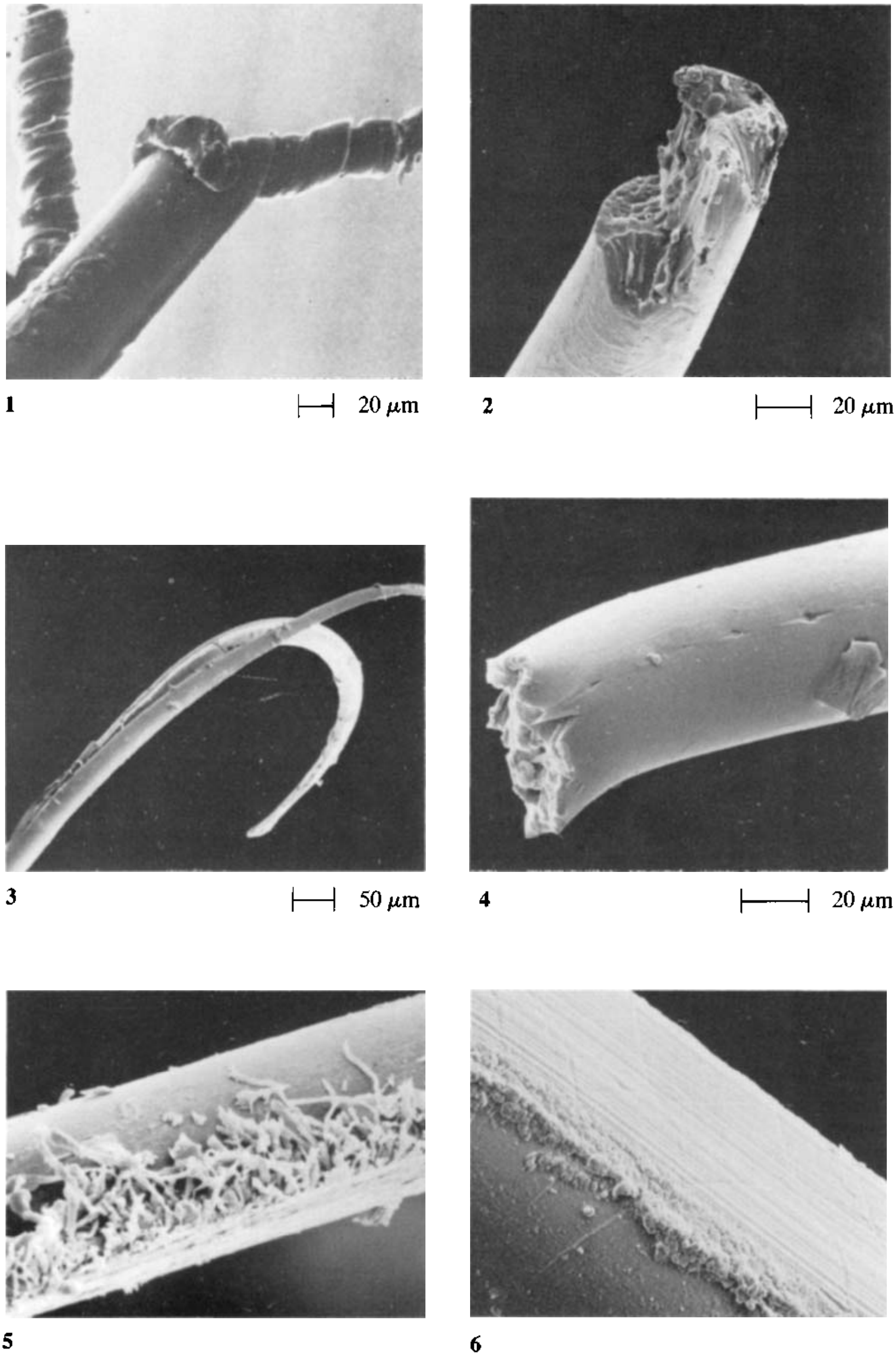



**Plate 12E — Flex fatigue.**
(1) Nylon 6 at 120°C, dry air: effect of snap-back after break.
**Partial flexing at 20°C, 65% r.h. followed by tensile testing.**
(2) Nylon 6. (3) Polyester. (4) Nylon 6.
**Flexing over a pin, under conditions of surface wear.**
(5) Nylon 6. (6) Polyester.

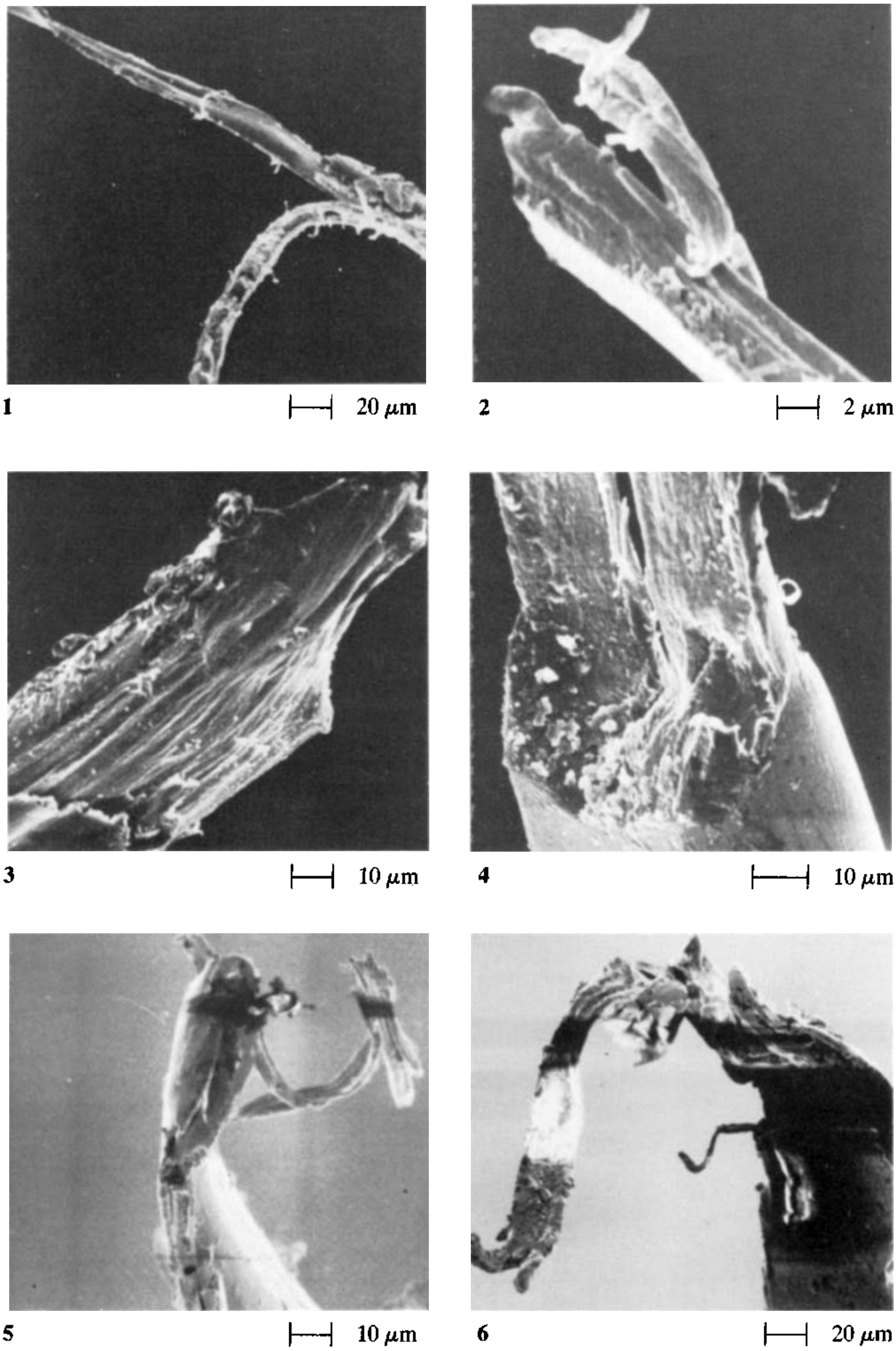
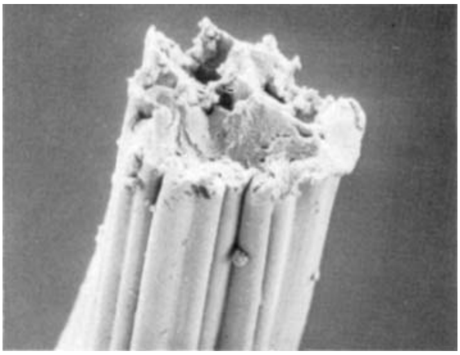
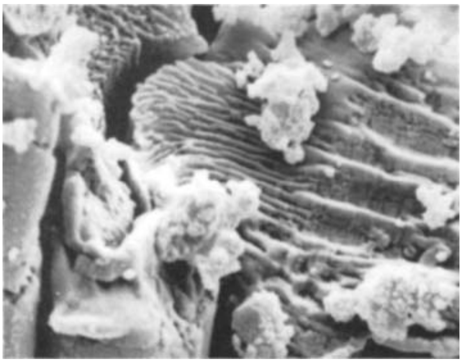



**Plate 12F — Flexing over a pin: Acrilan acrylic fibre at 6.2% bending strain.**
(1),(2) Tip of fibre which broke at 33 000 cycles. (3) Fibre which broke at 99 250 cycles. (4) Fibre which broke at 125 500 cycles.
**Flexing over a pin: polypropylene at 3.8% bending strain.**
(5) Fibre which broke at 251 250 cycles. (6) Fibre which broke at 684 000 cycles.

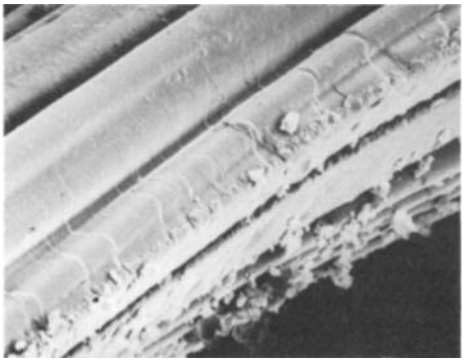


1 10 μm

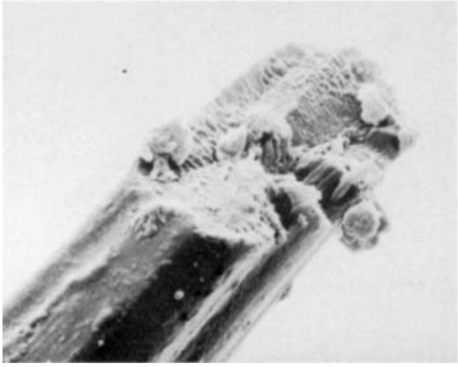
2 5 μm



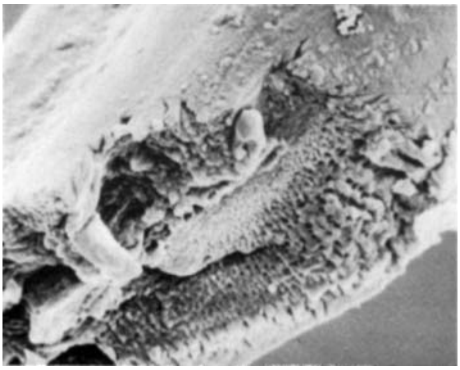
3 2 μm



4 5 μm



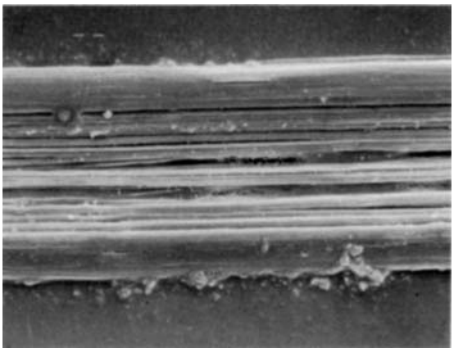
5 5 μm



6 2 μm

**Plate 12G — Flexing over a pin: viscose rayon.**

(1) Break of standard rayon. (2) Inside of bend showing kinkbands. (3) Detail of break. (4) Surface wear, due to rubbing on pin. (5),(6) Break of high-tenacity rayon.



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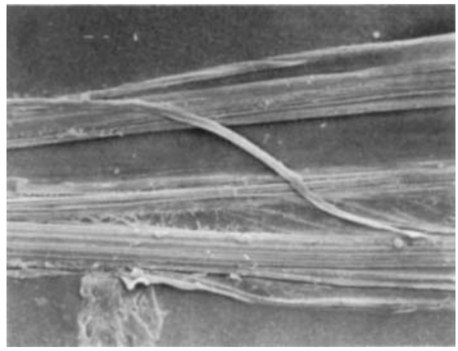

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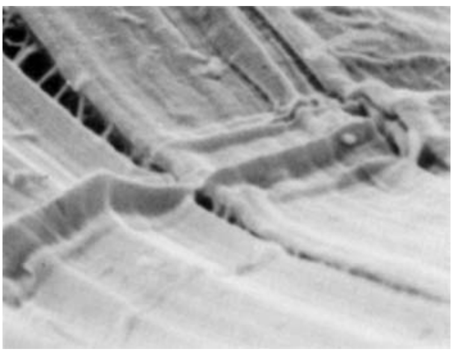

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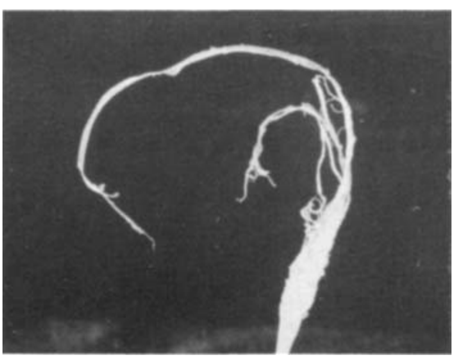

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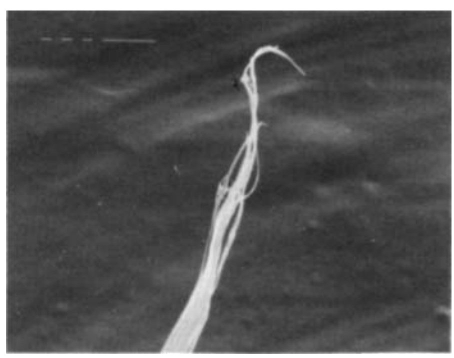

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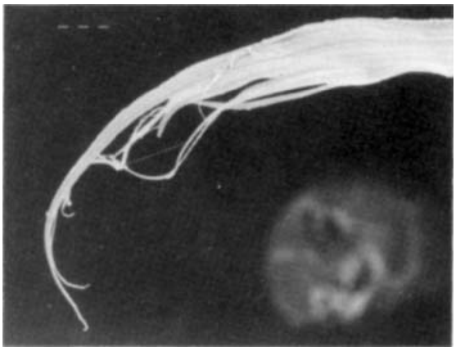
**Plate 12H — Flex fatigue of Dyneema HMPE fibres at room temperature.**
(1) After 20 minutes at selected test condition. (2) After 30 minutes. (3),(4) Detail of kink-bands and splitting. (5),(6) Failure after about 60 minutes.



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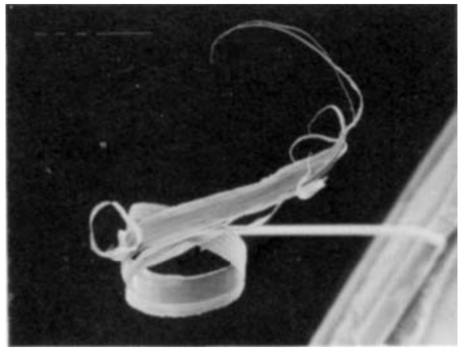

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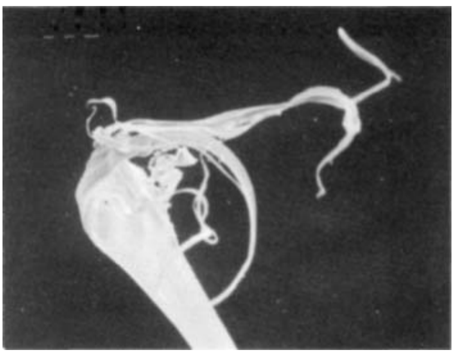

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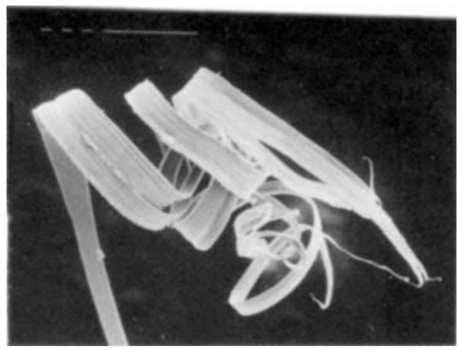

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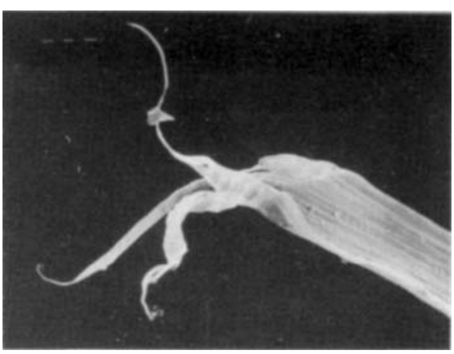

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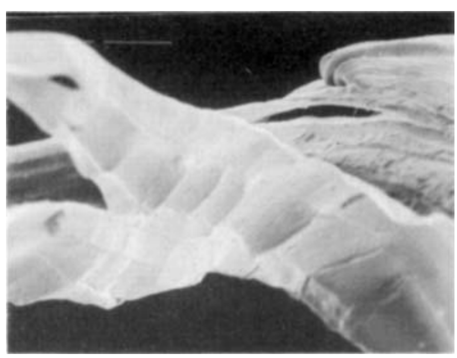

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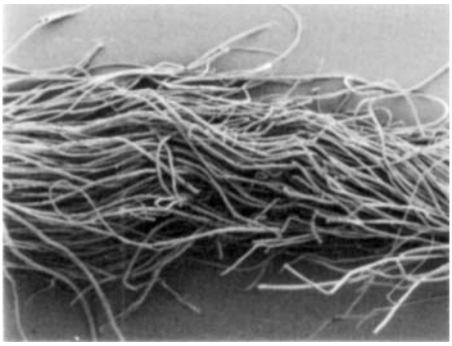
**Plate 12I — Dyneema HMPE fibres failed in flex fatigue at elevated temperatures.**
(1) At 40°C. (2) At 60°C. (3) At 80°C. (4)–(6) At 100°C.



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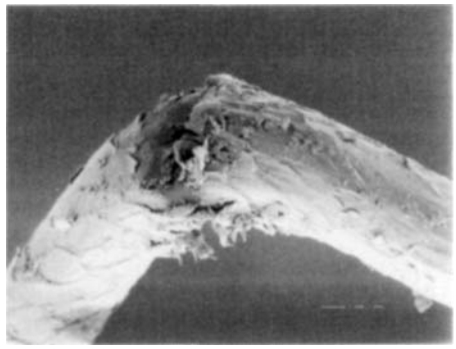

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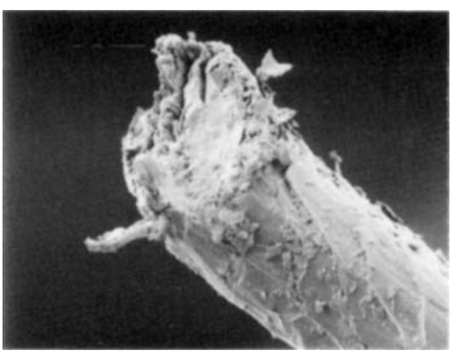

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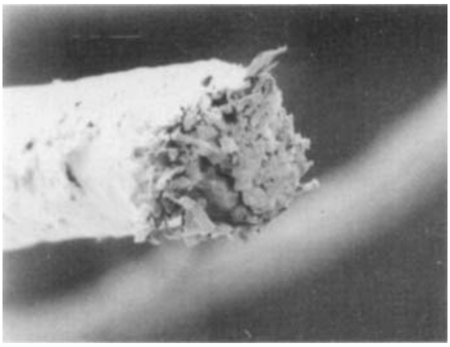
**Plate 12J — Buckling fatigue of a wool carpet yarn.**
(1) Overall view of failure region. (2)–(5) Progressive cracking at kink-bands leading to a sharp transverse break. (6) Break divided into two transverse cracks.



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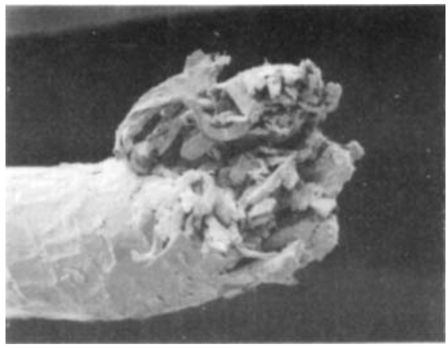

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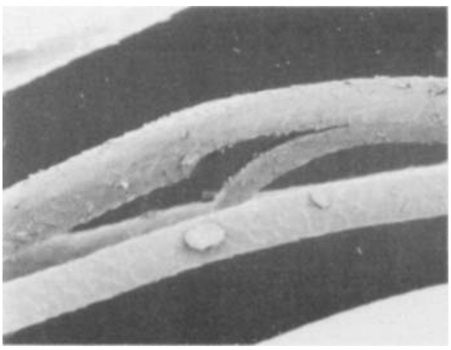

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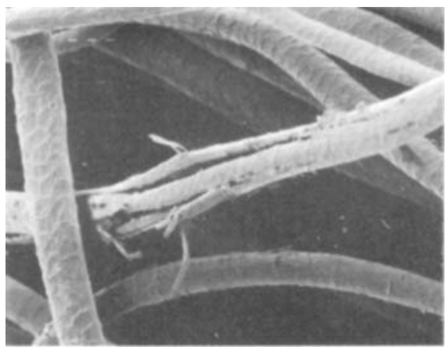

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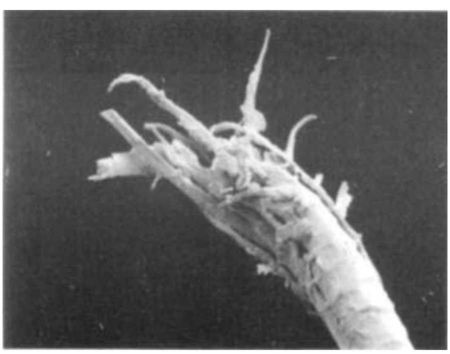

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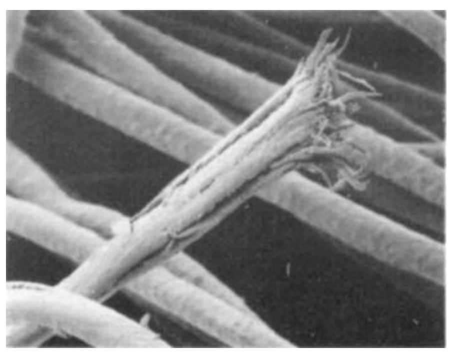

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**Plate 12K — Buckling fatigue of a wool carpet yarn (continued).**
(1),(2) Breaks at transverse cracks with some axial splitting. (3),(4) Development of axial cracks along fibres. (5),(6) Breaks with multiple splitting.

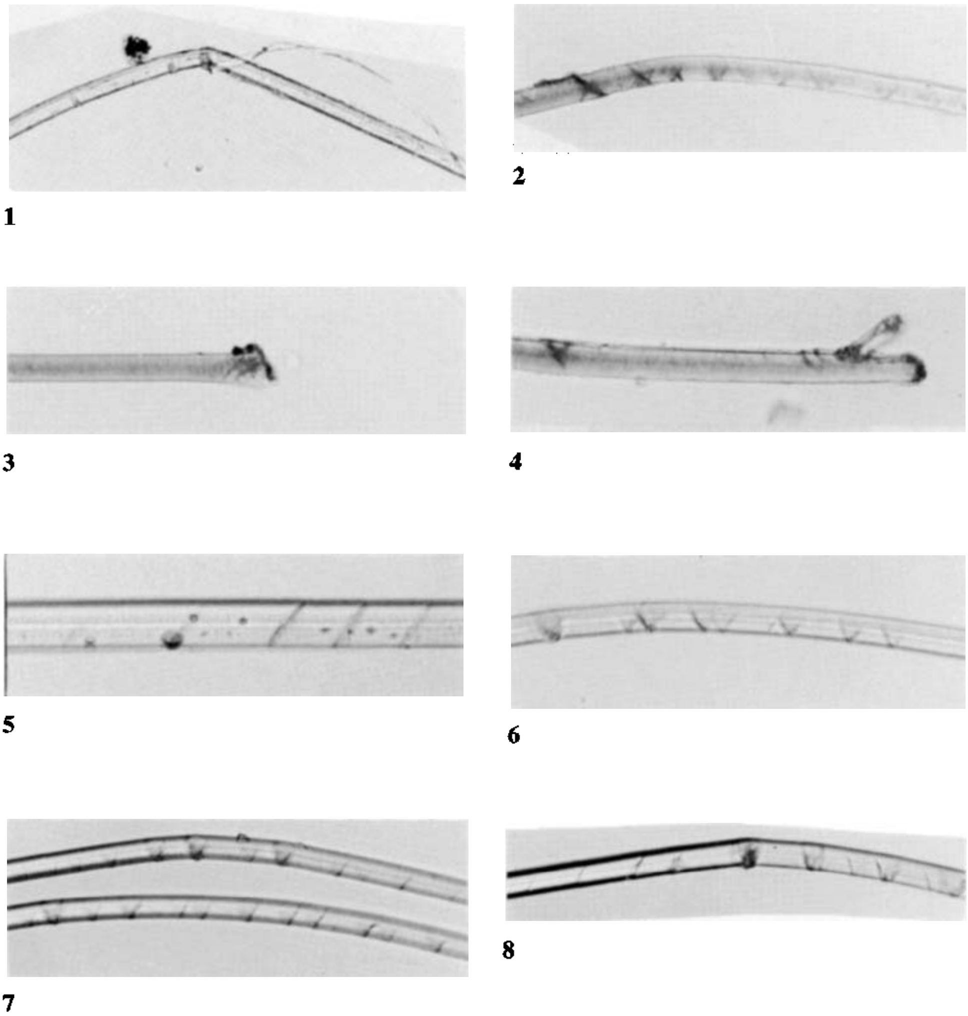


**Plate 12L — Buckling fatigue of aramid yarns.**
(1) Technora after 100000 cycles. (2)–(4) Kevlar 29. (5)–(8) Kevlar 129 after 3000 cycles.

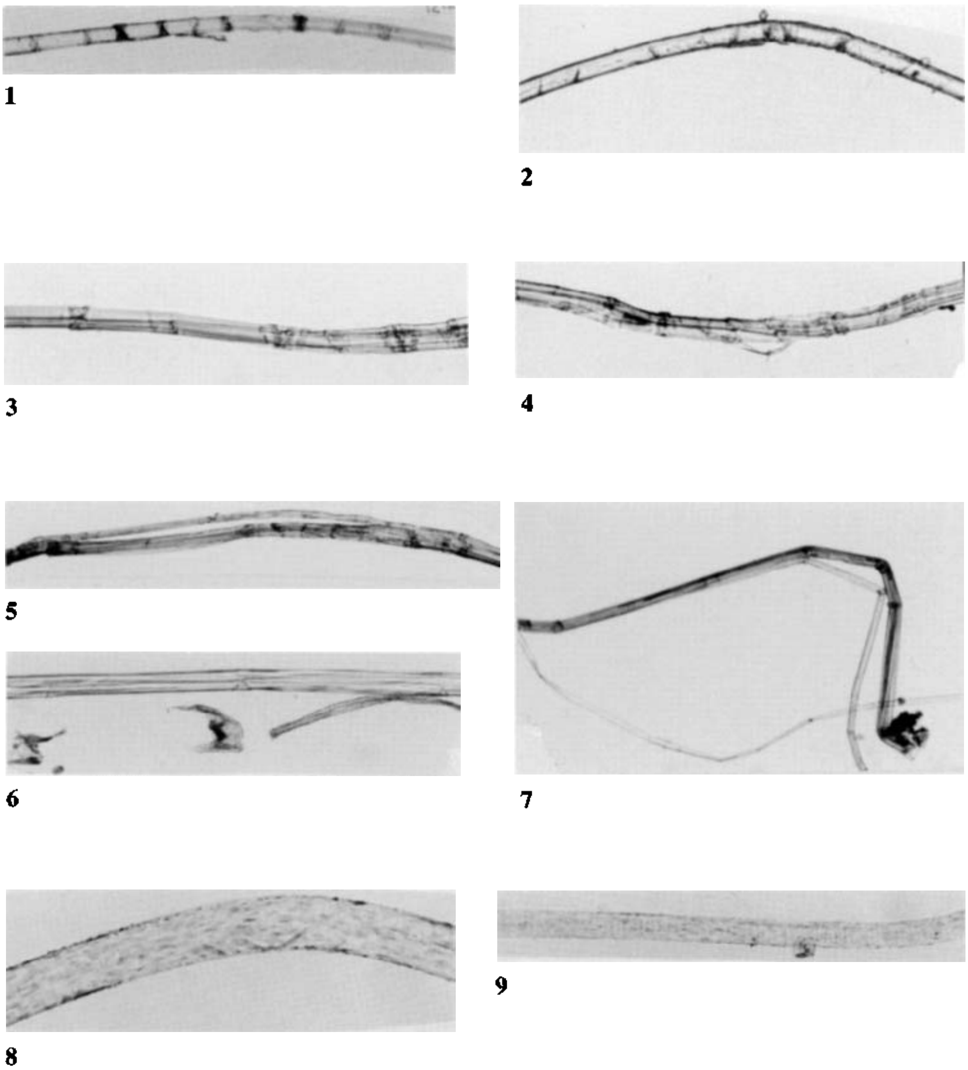


**Plate 12M — Buckling fatigue.**
(1) Vectran after 30000 cycles. (2) Vectran after 100000 cycles. (3)–(7) Dyneema SK60 after 100000 cycles. (8),(9) Polyester after 1000000 cycles.

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# 13

# BIAXIAL ROTATION FATIGUE

## Many fibre types

When a thick nylon monofilament is bent through about 90° and then rotated, it starts to crack axially as shown in **13A(1)**, and finally breaks to give an end with multiple splits, **13A(2)**. The principle of the test method was illustrated in Fig. 10.3(c). Note that the monofilament in **13A(1)** is twisting in opposite senses on either side of the centre point: S on the left and Z on the right.* This shows that the centre has been held back by a torsional drag, and so inserted false twist. As explained in Chapter 10, the torque results from the need to overcome the hysteresis ('internal friction') in bending.

Another example, in which a nylon monofil is just starting the final stage of break, is shown in **13A(3)**. In polyester there tend to be more splits closer together, **13A(4)**. When the bend is concentrated by holding the monofil under tension over a pin while it is rotated, the splits are usually fewer and larger, **13A(5),(6)**.

For fine textile fibres, it is essential to use a pin to get the required high curvature. When using the technique illustrated in Fig. 10.3(d), with drive from one end, the damage in nylon and polypropylene fibres shows the typical multiple splitting form, **13B(1)–(4)**. In this test method the twist is all in the same direction, since it is the free, weighted end which lags in rotation.

With a synchronous drive from both ends, as indicated in Fig. 10.3(e), there is torque on each side, and the twist develops in opposite senses in the two broken ends, as seen in the polyester fibre, **13B(5),(6)**. This test was carried out in water, but the form of break is similar to that with dry fibres.

Progressive damage to a fibre during biaxial rotation fatigue is shown in **13C**. There was a period of initiation before the first signs of damage appear at about 150 cycles, **13C(1)**. By 250 cycles, **13C(2)**, cracks are clearly apparent, and become steadily more severe, **13C(3),(4)**. Measurement of the residual strength shows that there are five stages in the test: the initiation period, when there is no loss in strength; a period when strength decreases linearly with number of cycles; another initiation period, when strength remains constant; a second period when strength falls; and final breakage. The fibre appearance during the second initiation period is shown in **13C(5)**, and indicates major damage in the outer visible part of the fibre. Shortly before final breakage, **13C(6)**, the individual splits are beginning to break. The final failure shows the typical multiple splitting, **13C(7),(8)**.

In **13C(3)–(7)**, it can be seen that the splitting divides into two regions along the fibre, and in **13C(8)** that it divides into two concentric regions in the fibre cross-section.

The reason for the axial division is that, as indicated in Fig. 13.1, the torque, which arises from friction on the pin or hysteresis, must be zero at the centre point on the pin; but the torque then builds up in opposite senses along the bent fibre to reach a maximum at the point where the fibre leaves the pin, and the torque from the drive shafts is applied through the straight fibre. So the most severe stress conditions occur where the fibre loses contact with the pin, and it as at these two places that the splitting occurs. The stresses near here will be further accentuated by the shear stresses, resulting from the change from a curved to a straight path.

* The terminology S and Z is used to indicate left-handed and right-handed twist respectively in textile yarns, and is adopted here to denote twist in a fibre. The definition relates to the direction of orientation on the surface of a twisted cylinder. A balanced combination of S and Z twist, so that there is no 'real twist' resulting from a rotation of one end relative to the other, is known as false twist.

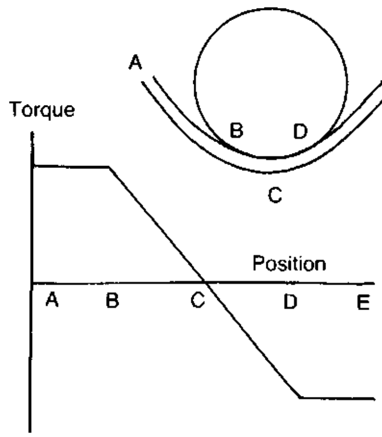



Fig. 13.1 — (a) Fibre passing over pin, bent along BCD, but straight along AB and DE. (b) Variation of torque along fibre.

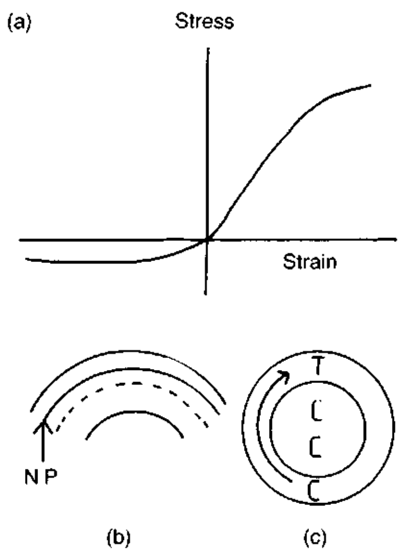


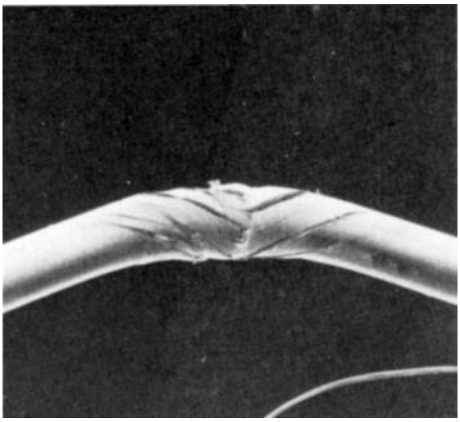

Fig. 13.2 — (a) Typical fibre stress–strain curve showing yield at a low stress in compression. (b) Location of neutral plane, NP. The dotted line is the central plane, which would be the neutral plane in an ideal Hookean material. (c) Cross-section, showing rotation of neutral plane, with outer zone in tension–compression, and inner zone always in compression.

The division across the fibre is probably caused by the fact that in a fibre which yields easily in compression, as indicated in Fig. 13.2(a), the neutral plane moves out towards the tension side, as in Fig. 13.2(b). Only the part outside this position will suffer the more severe effect of tension–compression cycling, as indicated in Fig. 13.2(c). This outer part will break up during the first stage, leaving the central zone to break up separately in the second stage.

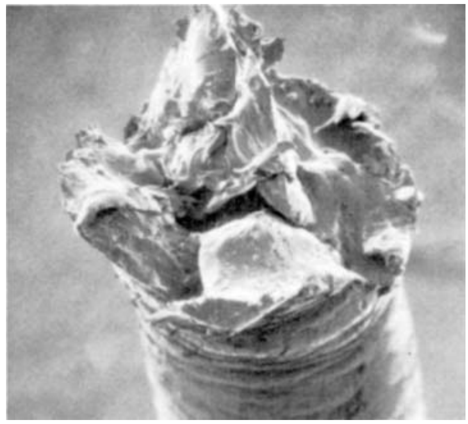
The polyester fibre, shown in **13C(1)–(8)**, with a linear density of 4.2 tex, is rather thick for a textile fibre, although still much finer than the monofils of around 100 tex shown in **13A**. Finer polyester fibres, for example the fibre with a linear density of 0.84 tex shown in **13C(9)**, and the broken fibres in **13B(5),(6)** and **13D(1)**, do not exhibit the division of the splitting into separate zones, either axially or transversely. The reason is that the scale of the splitting relative to the fibre diameter is too coarse for separation to occur. The reduced fibre diameter not only reduces the size of the fibre cross-section, which leads to a merging of the cross-sectional zones, but also makes a smaller pin necessary to maintain the same bending strain and therefore reduces the length of fibre in contact with the pin, which causes the axial zones to merge.

Biaxial rotation fatigue with failure by multiple splitting for various types of man-made fibre is illustrated in **13D(2)–(6)**. The breaks are generally similar in character, except that the nylons show fewer and larger split portions than the other types of fibre. The same form also occurs in the natural fibres cotton, wool and hair, as shown in Chapters 18 and 19.

Multiple splitting of the form found in laboratory biaxial rotation fatigue tests is the commonest form found in the use of fibres in textiles, and many examples are included in the case studies in Parts VI and VII.



1 100 μm



2 50 μm

3 100 μm

4 50 μm

5 50 μm

6 50 μm

**Plate 13A — Biaxial rotation fatigue of thick monofils, without a pin.**
(1), (2) Nylon 66, 67 tex. (3) Nylon 66, 111 tex. (4) Polyester, 67 tex.
**Rotation of thick monofil over a pin.**
(5), (6) Nylon 66, 67 tex: opposite ends of break.

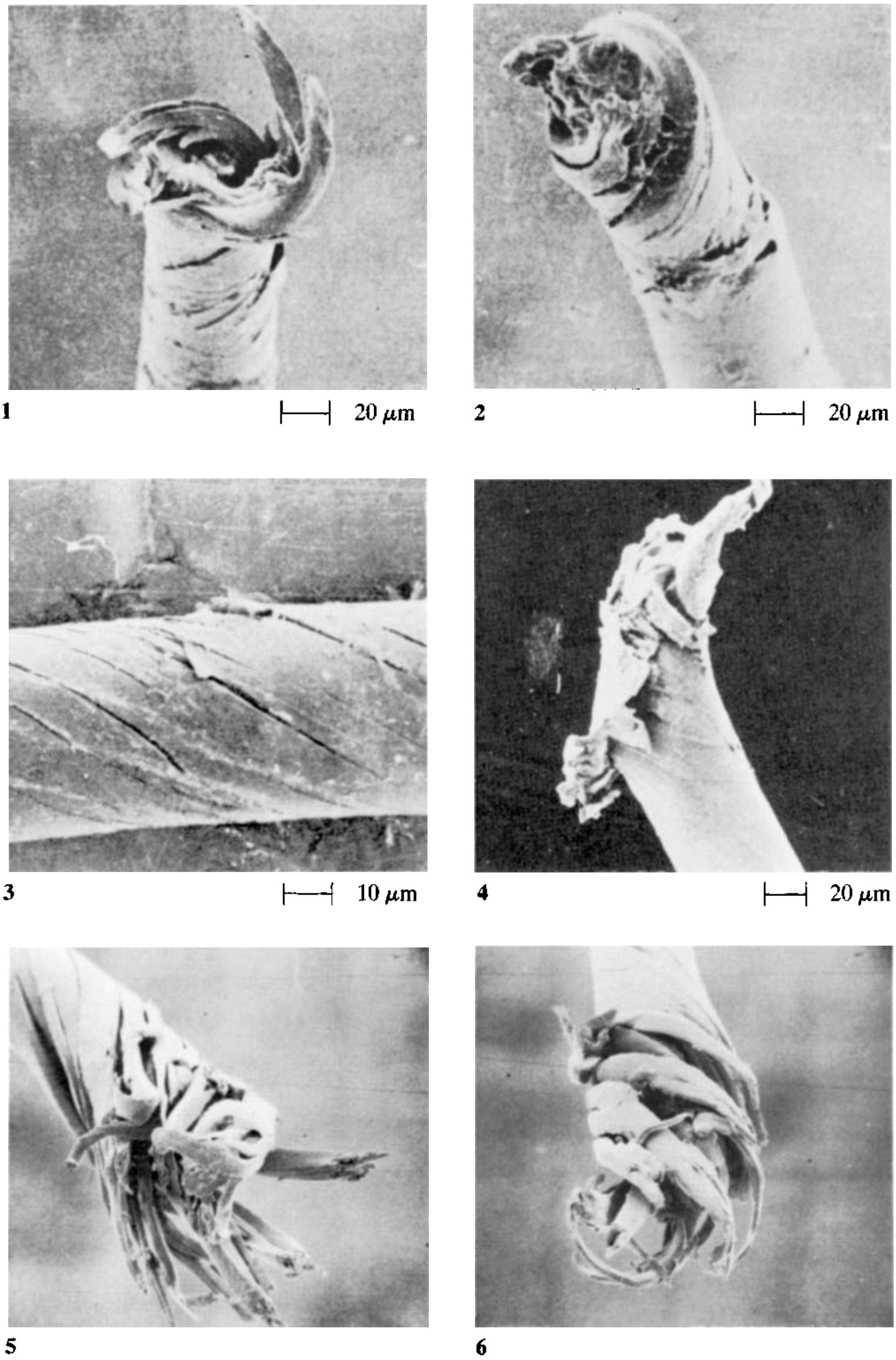
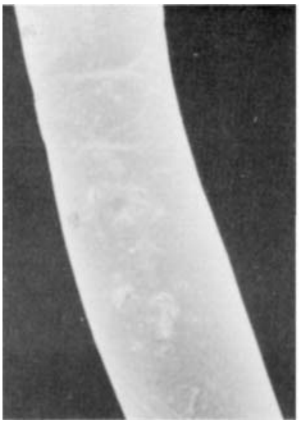
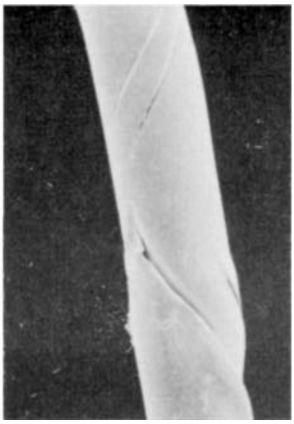



**Plate 13B — Rotation over a pin (with drive from one end).**
(1), (2) Nylon 66, 17 dtex, failed at 3690 cycles, opposite ends. (3) Nylon 66, 17 dtex, unbroken at 5000 cycles. (4) Polypropylene, failed at 3435 cycles.
**Biaxial rotation over a pin.**
(5), (6) Polyester 8.4 dtex, failed after 12 608 cycles in water, opposite ends. Note twist in opposite senses.

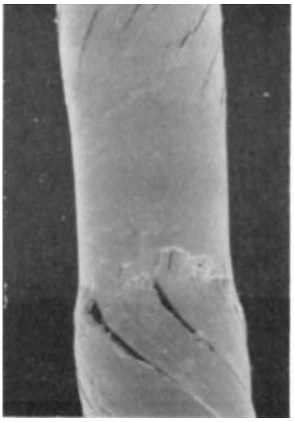


1 158

2 251



3 507



4 804

5 1503

6 2538

7 2606

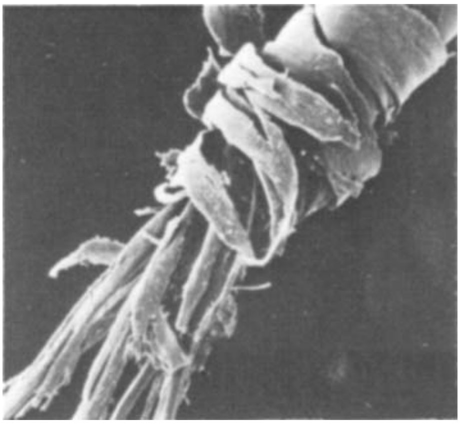
8 2606

9

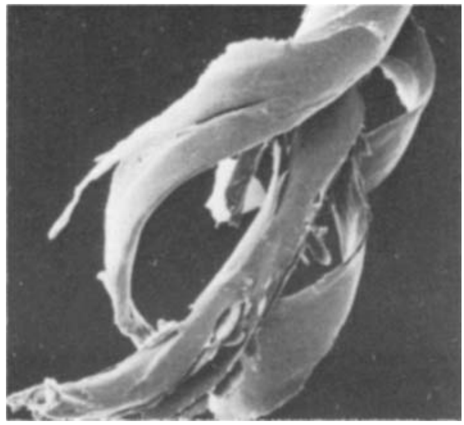
**Plate 13C — Progressive damage in biaxial rotation over a pin. Polyester, 4.2 tex.**
(1)–(6) Unbroken at increasing numbers of cycles. Note that these are different specimens removed from the test after different times: they are not a succession of pictures of the same fibre. The numbers below each picture indicate the number of cycles for the specimen. (7),(8) Opposite ends of failed fibre, after break at 2606 cycles.

**Polyester, 0.84 tex.**

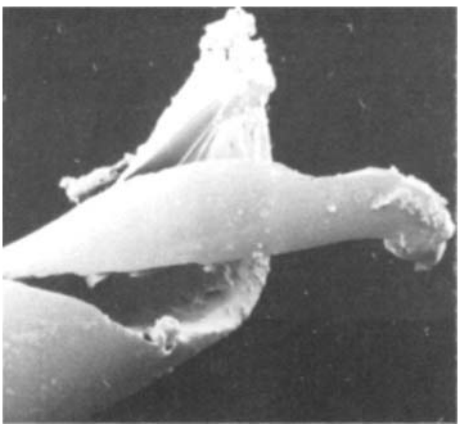
(9) Close to failure, after 3687 cycles.



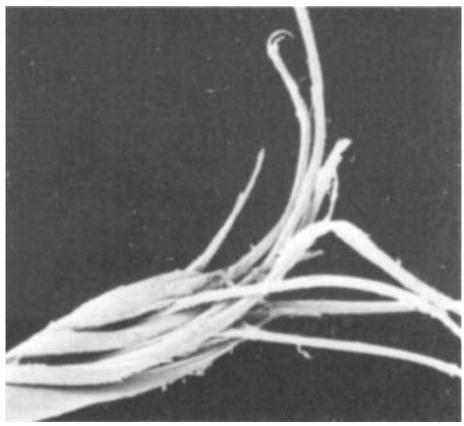
**1**



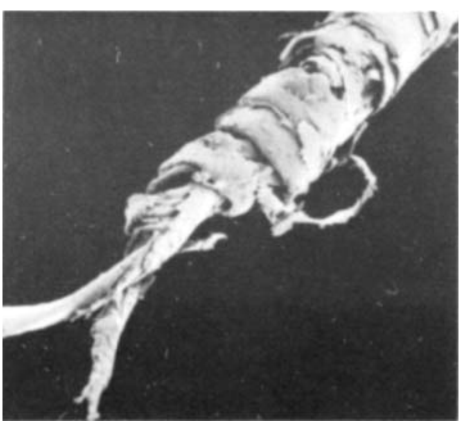
**2**



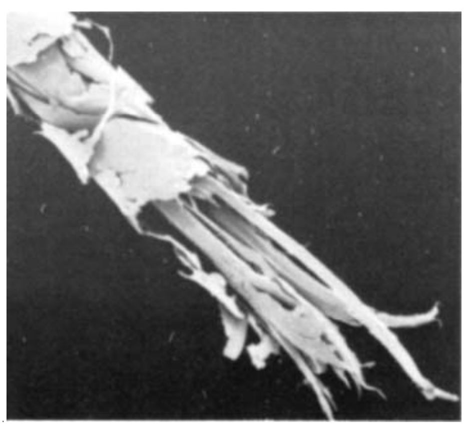
**3** 20 μm



**4** 50 μm



**5** 50 μm



**6** 20 μm

**Plate 13D — Biaxial rotation over a pin.**
(1) Polyester, 17 dtex, failed at 3126 cycles. (2) Nylon 6, 17 dtex, failed at 13 728 cycles. (3) Nylon 66, 17 dtex, failed at 4045 cycles. (4) Acrylic, Courtelle, 17 dtex, failed at 2885 cycles. (5) Modacrylic, Teklan, 18 dtex, failed at 8007 cycles. (6) Polyvinyl alcohol (PVA), 11 dtex, failed at 18 177 cycles.

# 14

# SURFACE SHEAR AND WEAR

## Many fibre types

As shown by the pictures of nylon and polyester fibres in **12E(5),(6)**, the test method of pulling a fibre to and fro over a pin, which is intended to demonstrate flex fatigue, can in some circumstances lead to failure by surface wear. This always happens with the highly oriented para-aramid fibre, Kevlar, and the appearance after a period of flexing over a pin is shown in **14A(1)**. A similar form of surface wear is found if the fibre is not repeatedly flexed, but is held in a fixed bent configuration over a rotating pin as shown in Fig. 10.5. The final failure of the Kevlar fibre, when the tensile stress on the reduced cross-section reaches its limiting value, is by axial splitting, **14A(2),(3)**, although evidence of the surface wear can be seen.

Examples of surface wear in wool, cotton and rayon caused by a rotating pin are shown in **14A(4)–(6)**. The picture of wool, **14A(4)**, shows very clearly how the wearing of the surface eventually reduces the area of cross-section to a size in which tensile rupture takes place. The mechanism is illustrated schematically in Fig. 14.1.

Results from another series of experiments show the detail of how the wear takes place in nylon, **14B(1)–(6)**, and polyester, **14C(1)–(4)**, fibres. In some instances, **14B(1),(2)** and **14C(1)**, fine fibrillar strands are worn away; but in other cases, **14B(3)** and **14C(2)**, ribbon-like strips peel away. Sometimes the final break tapers right across the fibre, **14B(4),(5)**, but, in other examples, **14B(6)** and **14C(4)**, a substantial part breaks transversely.

The influence of surface shear stresses in causing damage to fibres is clearly important, but basic laboratory studies on single fibres have been very limited. Speculation on possible forms of damage resulting from shear stresses on fibre surfaces is illustrated in Fig. 14.2. Other evidence of splitting and peeling under surface shear comes from studies of yarn-on-yarn abrasion (Chapter 24) and from some case studies reported in Chapters 31 (underwear), 39 (ropes) and 40 (some industrial products). In these situations the shear stresses will be cyclic and reverse in direction, which can be more damaging than the unidirectional shear stresses applied by a rotating pin. It must also be remembered that cyclic shear stresses arising indirectly at the tip of a crack in tensile fatigue testing (Chapter 11) and due to change of

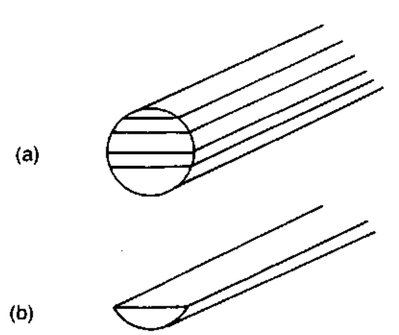



Fig. 14.1 — (a) Successive stages in wearing away of surface, (b) leading to tensile failure of reduced cross-section.

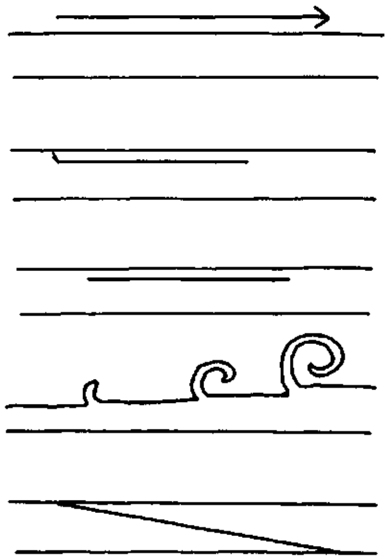



Fig. 14.2 — (a) Shear stress on fibre surface. (b) Crack penetrates into fibre and then runs along fibre. (c) Crack starts below surface. (d) From (b) or (c) multiple layers may peel off surface. (e) Alternatively split may run across fibre.

curvature in flex testing (Chapter 12) have been shown to be important failure modes. The whole subject of the effect of shear in promoting rupture of fibre structure justifies much more experimental and theoretical research.

Finally, we show an example from the more recent series of experiments of the surface wear in Kevlar, **14C(5)**, which leads to a tensile break with multiple splits, **14C(6)**.

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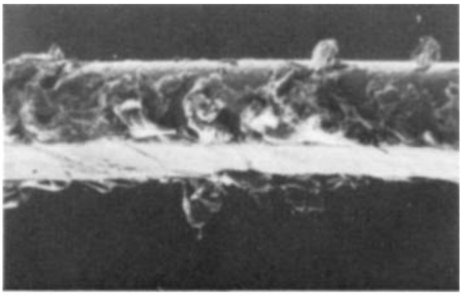
Further studies of fibre-to-metal abrasion by the method of holding a fibre under tension for a 90° arc round a rotating pin have been made by C. Cork and M. A. Wilding at UMIST. In these tests, the geometry was changed from that shown in Fig. 10.5, so that the rotating pin was immersed in a dish of water. The fibre came down at 45° from a clamp into the water, round the pin and up again over a guide to a weighted hanging end. The abraded nylon 66 fibres, shown in **14D(1)–(4)**, were fairly thick (18.7 dtex), comparatively weak, with a tenacity of 3.8 gf/dtex, and high breaking extension (76%). The breaks show an angled wearing away of the fibre surface until there is not enough material left to support the tension and the thinned fibre cross-sections break, sometimes with axial splitting. The nylon 6 fibres, illustrated in **14D(5),(6)**, are similar in properties (16 dtex, 5.1 gf/dtex, 53%); commonly, as shown, one broken end has a simple smooth rupture but the other shows more splitting.

Fibre-to-fibre abrasion, using an arrangement like the yarn-on-yarn test shown in Fig. 10.6, of partially oxidised polyacrylonitrile fibres (PAN) was studied by Zhu. As noted in Chapter 10, the use of this method on single fibres involves appreciable bending and twisting, as well as surface abrasion. The tests of the fibres shown in **14E** were made at 65% r.h. and 20°C under a tension of 0.5 gf, which is about 15% of break load, with 1 turn of twist, a wrap angle of 35°, a stroke of 12 mm, and at a frequency of 120 Hz. The PAN fibres had been removed from various positions in the oven, so that they had been stabilized for different times; the total time in the oven for full stabilization was 90 minutes. In addition to wear of the surface, as seen in **14E(1),(3)**, there is axial splitting, **14E(2)**, before the breaks shown in **14E(4)–(6)**.



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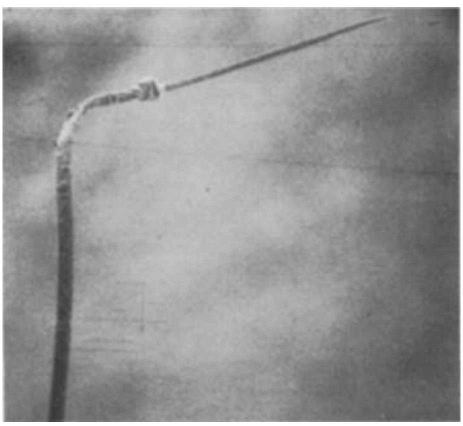

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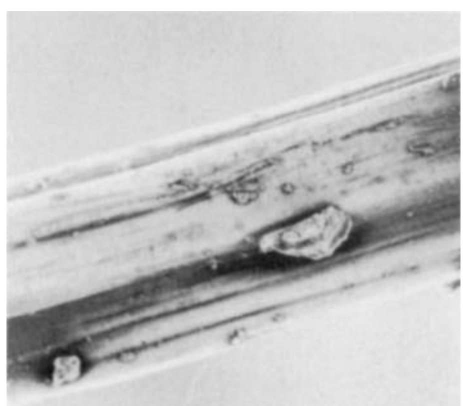

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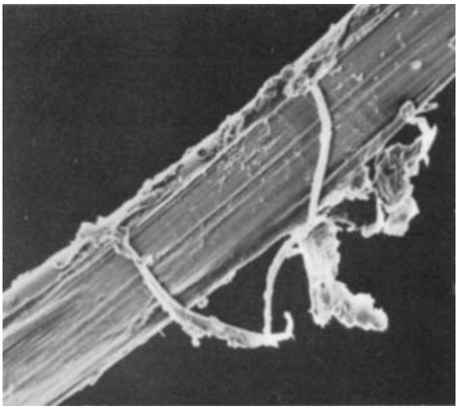
**Plate 14A — After pulling to and fro over a pin.**
(1) Kevlar 29 (para-aramid) after 45 000 cycles of flexing, with an apparent bending strain of 4.7% under a tensile stress of 0.2 N/tex.

**After abrasion against a rotating pin.**
(2) Kevlar 29 broken after abrasion under relatively high tension. (3) Kevlar 29 broken after abrasion under relatively low tension. (4) Wool. (5) Cotton. (6) Viscose rayon.



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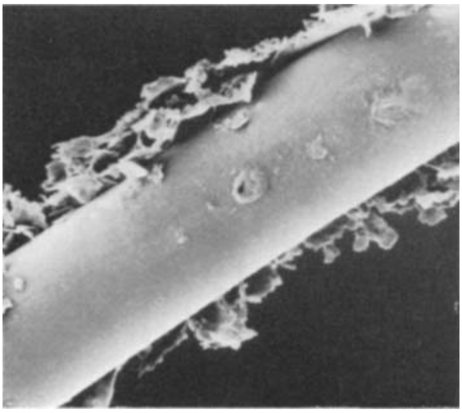

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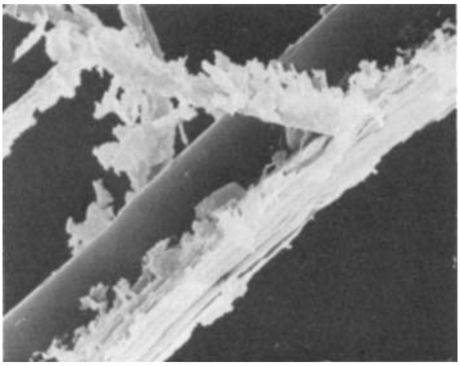

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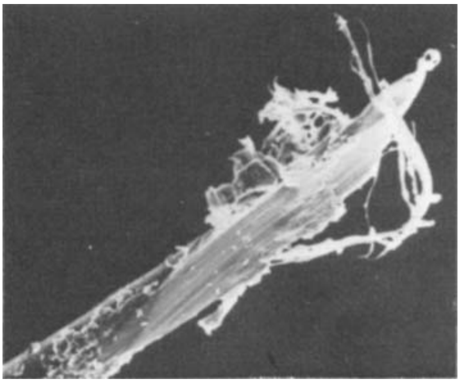

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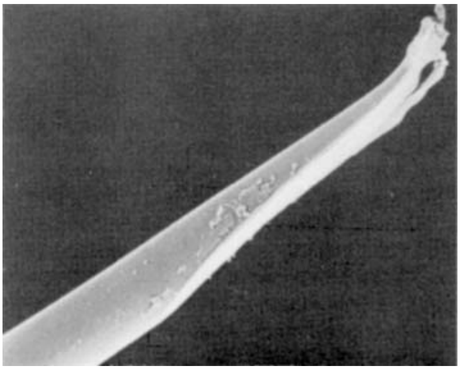

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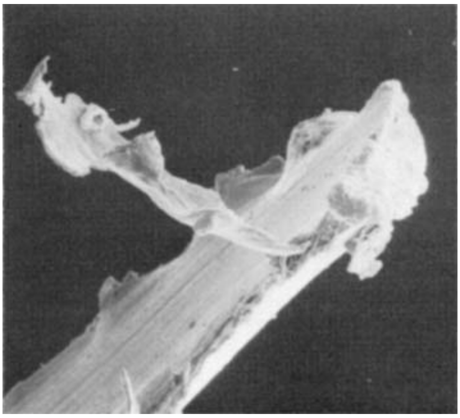

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**Plate 14B — Nylon fibre held under tension against a rotating pin.**
(1–3) Intermediate stages of surface wear. (4–6) Final breaks.

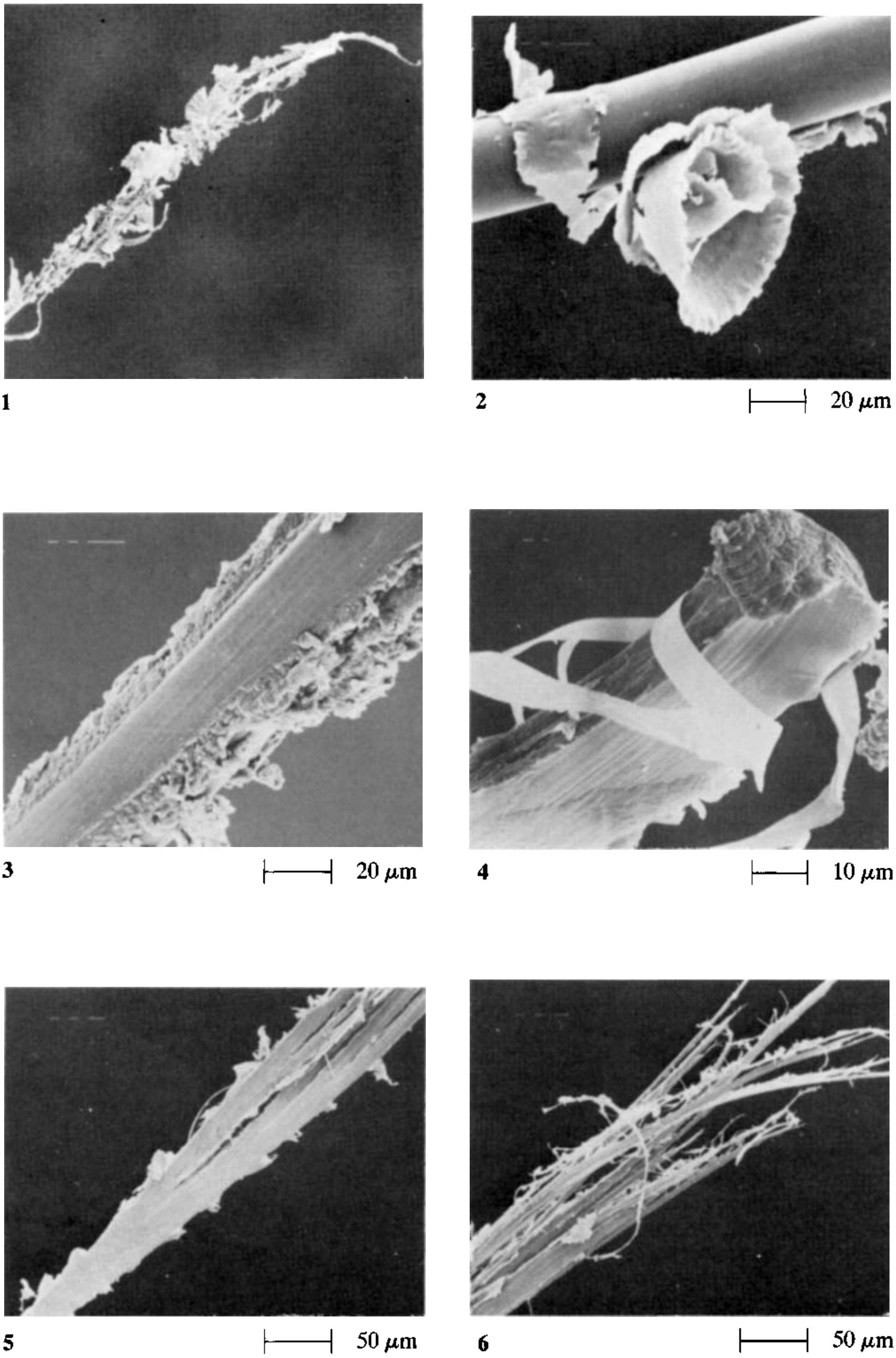
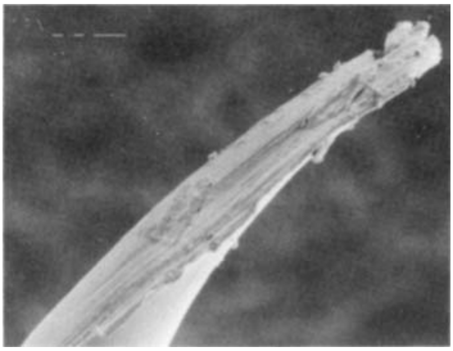



**Plate 14C — Polyester fibre held under tension against a rotating pin.**
(1) Final break. (2),(3) Detail of wear. (4) Final break.
**Kevlar (para-aramid) fibre held under tension against a rotating pin.**
(5) Surface wear. (6) Final break.



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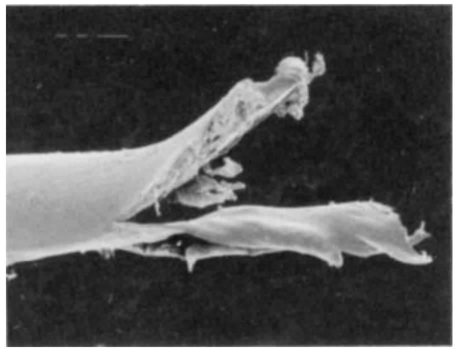

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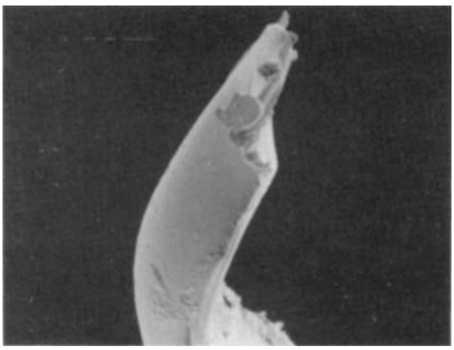

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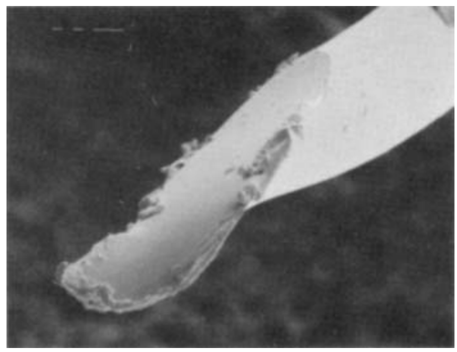

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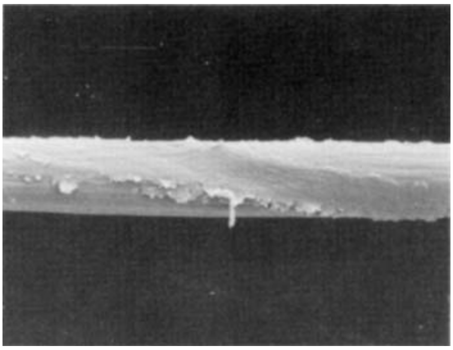
**Plate 14D — Fibre-to-metal abrasion of nylon fibres.**
(1),(2) and (3),(4) Opposite ends of break of nylon 66 fibres. (5),(6) Opposite ends of break of nylon 6 fibre.



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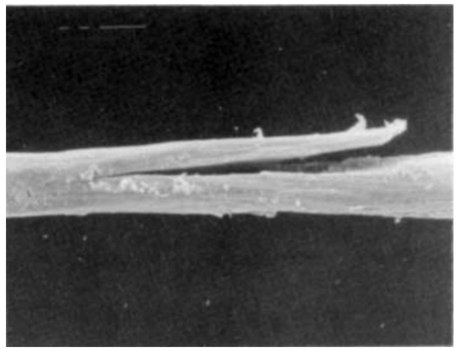

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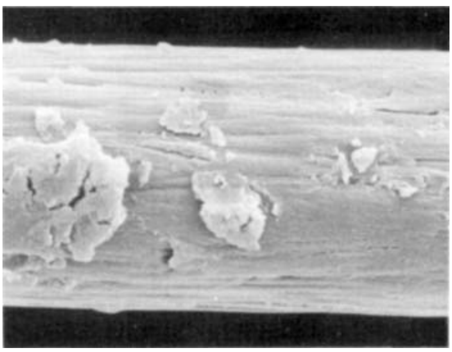

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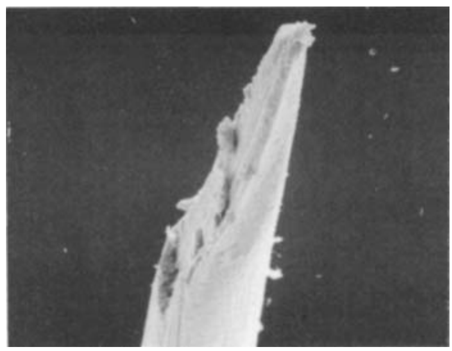

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**Plate 14E — Wrapped fibre-to-fibre abrasion of oxidised PAN fibres.**
(1) Stabilized for 15 minutes, after 3600 cycles. (2) Stabilized for 15 minutes, after 7200 cycles. (3) Stabilized for 60 minutes, after 6000 cycles. (4) Stabilized for 45 minutes, after 13300 cycles. (5),(6) Stabilized for 60 minutes, after 15000 cycles.