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The Fatigue of Synthetic Polymeric Fibers

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Synopsis

The fatigue properties of a number of different types of fibers have been investigated and failure under cyclic loading conditions compared to that caused by simple tensile loading. Polyamide, polyester, and polyacrylonitrile fibers have been studied and all have been found to fail by fatigue mechanisms. The loading conditions have been monitored by a fiber fatigue apparatus developed for this purpose and the fracture morphologies inspected by scanning electron microscopy. In all of the cases which are considered in detail, fatigue failure of the fibers has been found to occur when cycling from zero load to a maximum load of about 60% of the tensile strength. Fatigue failure is accompanied by a distinctive fracture morphology, clearly different from the tensile fracture morphology and involving crack propagation along the fiber at a slight angle to its axis, although the mechanism which causes this in the acrylic fiber is probably different from that for the polyamide and polyester fibers.

INTRODUCTION

Synthetic polymeric fibers are used in many situations in which they are subjected to high oscillatory tensile loads, possibly up to a high percentage of their simple tensile strength; for example, in brake parachutes and tire cords. It is important therefore to determine whether any fatigue mechanisms exist for these synthetic fibers which could cause unexpected failures in such situations. Fatigue has long been a primary consideration in the use of metals, and Andrews[1] has reviewed the work done with bulk polymers which has shown the deterioration of bulk plastics under cyclic conditions. Although a number of studies[2-4] have been made into the fatigue properties of fibers, the results have generally been inconclusive. This has been due largely to difficulties of testing filaments which are usually extensible, inelastic and viscoelastic, in such a way as to avoid ambiguous results. The time and inelastic effects can mean that failure after cycling may have been predictable from an adequate knowledge of the time dependence of the simple tensile strength and not be due to a specific fatigue mechanism.

The apparatus developed by Bunsell et al.[5] overcomes these problems and makes true fatigue testing of fibers possible by cycling them to constant maximum tensile loads, so avoiding the inevitable climb up the load–

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elongation curve which occurs in other methods of testing. These experiments have all been in the tensile–tensile or (zero load)–tensile loading situation as it is usually not possible to subject fine filaments to negative loads.

The use of the scanning electron microscope has become a standard method of examination of fiber fracture morphology and has enabled the classification of fractures to be made with regard to type of fiber and mode of failure.[6] Hearle and Cross[7] have examined the fracture morphologies, after simple tensile loading, of a number of thermoplastic textile fibers and have shown by this means how a greater understanding of the fracture development may be obtained. They showed that fibers have typical simple tensile fracture morphologies, and although complications caused by gross faults or multiinitiation of fractures can occur, the underlying mechanisms of failure remain the same and are predictable.

In a similar manner, the fibers which have been tested for their fatigue properties in this study have been examined in the scanning electron microscope. Typical fatigue fracture morphologies have been observed which help to reveal the processes of fatigue failure. The authors in earlier publications[8,9] have described the fatigue of medium-tenacity nylon 66 fibers and acrylic fibers. It was shown that these fibers can fail by true fatigue mechanisms leading to distinctive fracture morphologies although the two types considered failed in different ways.

The present paper considers the loading conditions for the fatigue failure of a number of fibers and compares their fatigue fracture morphologies to those obtained under simple tensile loading.

EXPERIMENTAL PROCEDURE

The fiber fatigue apparatus devised by Bunsell et al.[5] is capable of subjecting fibers to several modes of tensile loadings, and the one chosen as best for fatigue testing was load cycling. The fiber is subjected to oscillatory loading, usually at 50 Hz, although higher frequencies have also been used, in which it is taken from a minimum load up to a maximum tensile load in each sinusoidal cycle. This maximum load is kept constant throughout the experiment by an electronically controlled servosystem which detects and compensates for any change in the loading conditions on the fiber. Changes will generally occur because of the viscoelastic nature of the samples leading to creep and gradual extension. The effect of creep obtained by dead weight loading was investigated and will be reported elsewhere. Failures due to creep and to fatigue were found to be easily discernible as the creep fracture morphologies were the same as those from simple tensile breaks. The rate of extension and numbers of cycles to failure are also monitored. After testing, the sample is examined by optical microscopy and then in the scanning electron microscope.

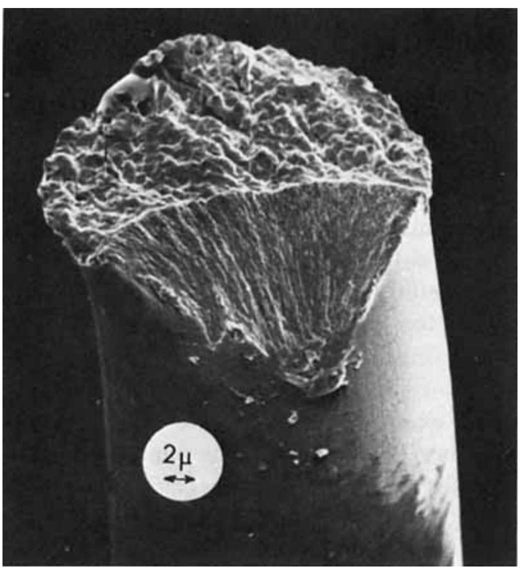
Most fibers tested were just as received from the manufacturer, but some were exposed to sunlight for varying periods, and others had small notches cut into their surfaces to investigate any change in fracture morphology which might be induced.

All tests were conducted at 20°C and 65% R.H.

NYLON 66

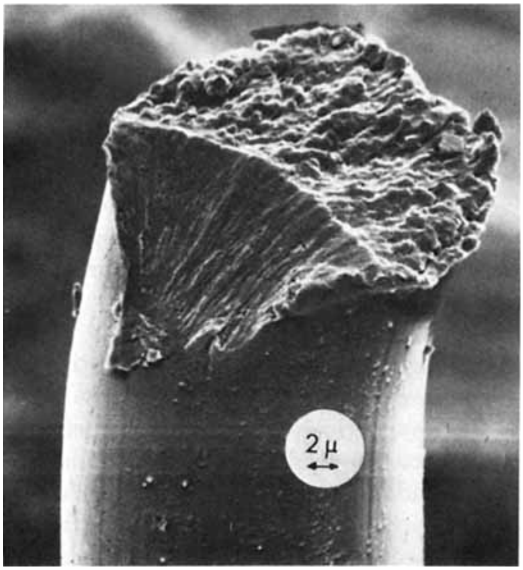
A study was made into the behavior of 0.7 tex (25 μm diameter) superhigh-tenacity ICI nylon 66 fibers, as well as additional studies to those reported earlier[8] on 1.7 tex (40 μm diameter) medium-tenacity ICI nylon 66 fibers. The high-tenacity fibers have undergone greater drawing in their manufacture than the medium fibers. Both types of nylon 66 fibers fail in the same manner under simple tensile loading. Plastic deformation ahead of the slow moving crack opens the fracture until a point is reached at which catastrophic failure occurs. This results in the type of fracture ends shown in Figure 1 for the superhigh-tenacity nylon fiber.

Under cyclic conditions, the loading pattern for failure of the superhigh-tenacity fibers was found to be similar to that reported for the medium-tenacity fibers, and is shown in Figure 2. A band of fractures with tensile-type morphologies lies around the line of constant maximum load equal to the steady tensile loading required for failure by creep in the same time as that for cycling. Another group of breaks, separated from these tensile breaks by a region of unbroken samples, is due to a true fatigue mechanism. At high oscillatory loads, the maximum load required to cause a tensile failure is seen to be reduced, possibly due to heating induced by the cycling, and the tensile and fatigue failure regions overlap. The maximum load to which those fibers which failed by fatigue were subjected was far below



(a)

Fig. 1. (*continued*)



(b)

Fig. 1. Typical tensile fracture morphology of superhigh-tenacity nylon 66 showing the two regions of slow crack growth with accompanying plastic deformation and catastrophic failure.

that which would cause creep failure, and they can be seen to be grouped around the line of zero minimum load. The fatigue fracture morphology of these superhigh-tenacity fibers was found to be similar to that for the medium-tenacity fibers, as shown in Figure 3.

The fatigue fracture initiates at the surface and develops a little way into the fiber along a radial plane before being sharply deflected to run at a slight angle to the axial direction. Sometimes, at the point of deflection, crack twinning occurs, and the crack develops in opposite directions along the fiber. The crack continues to develop until the load-bearing cross section is sufficiently reduced so as to fail by the simple tensile fracture mechanism under the prevailing loading conditions.

It can be seen, therefore, that both types of nylon 66 fiber behave in the manner schematically illustrated in Figure 4. Steady loading at level A will cause a creep failure after about 40 min, as will loading pattern B, even though only the peak loading is up to level A. Reducing the pattern to C, in which the oscillatory load amplitude is maintained but the mean load lowered, safeguards the fiber from failure. If the mean load is further reduced so that the fiber is taken down to zero load each cycle, as in D, fatigue failure will occur after about 10^5 cycles if the maximum load is greater than a threshold value of about 60% of the simple tensile strength.

Thus, the criteria for fatigue failure in both medium and superhigh-tenacity nylon 66 fibers are the same and result in similar fracture morphologies.

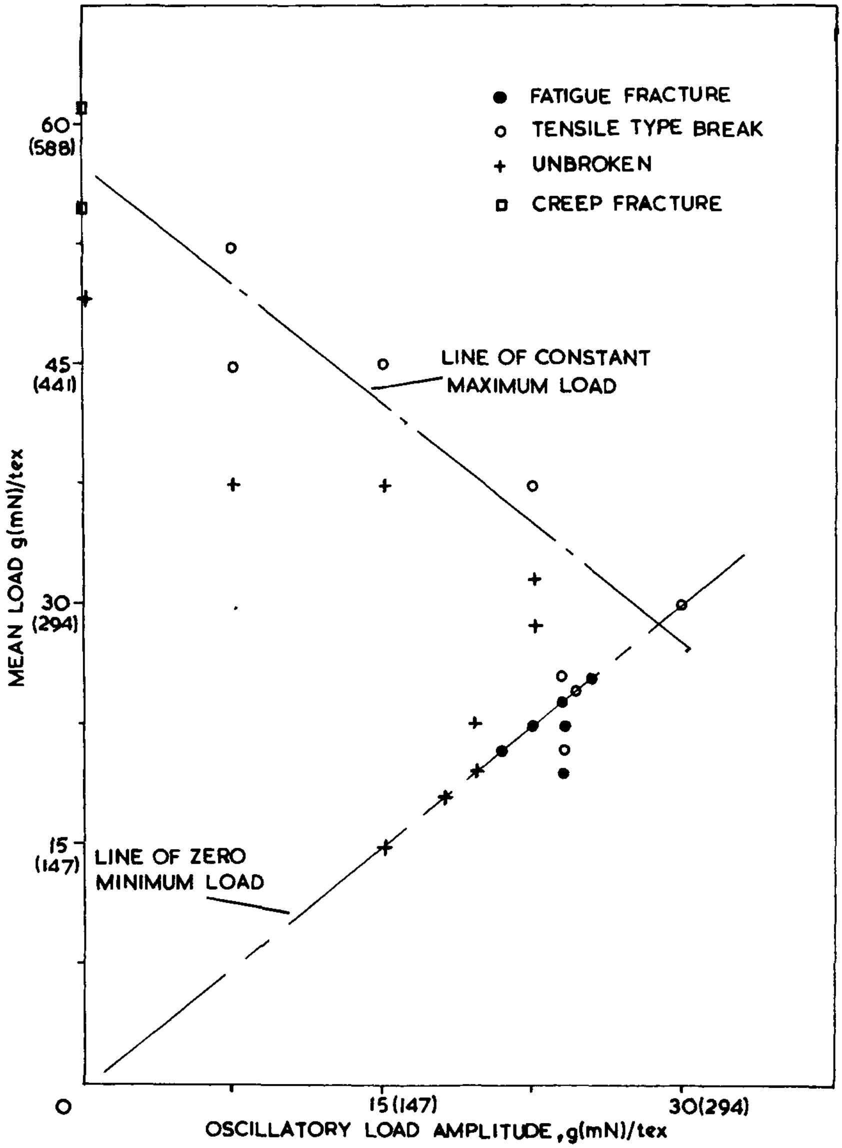
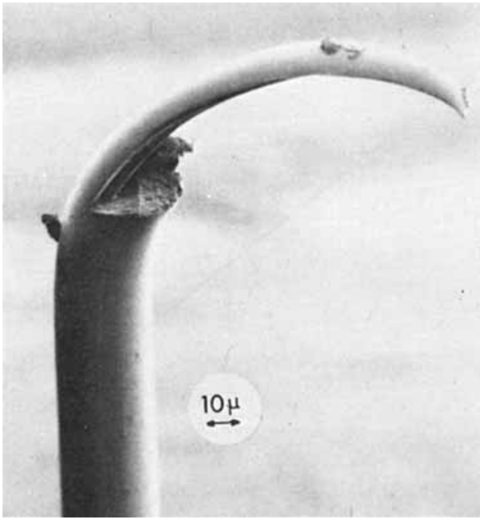


Fig. 2. Loading diagram for superhigh-tenacity nylon 66 fibers cycled for about 10^5 cycles at 50 Hz or equivalent time for static loadings.

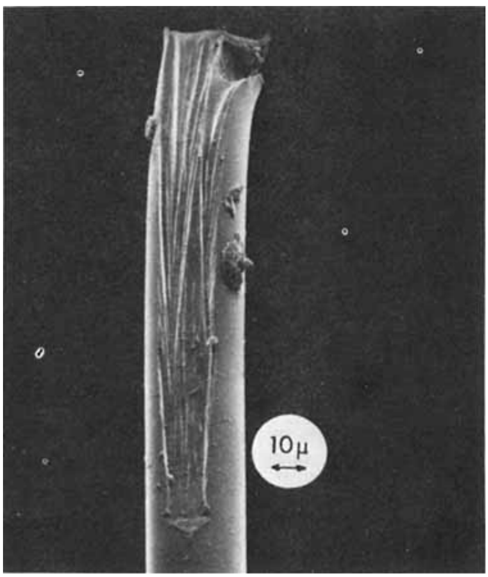
Medium-tenacity fibers were subjected to three frequencies of testing, 50 Hz, 75 Hz, and 90 Hz. The appearance of the fatigue breaks was similar, but there seemed to be an increasing chance of multiple fatigue cracks, as illustrated in Figure 5 with the higher frequencies.

Fatigue Lifetime

A survival diagram is given in Figure 6 which shows how the fatigue lifetimes of the medium-tenacity fibers were influenced by the maximum loads to which they were cycled. The average lifetime increased with decreasing maximum load, although this is not so distinct at high loadings. The fatigue lifetime was of the order of 10^5 cycles. Figure 7 shows how the average lifetime varies with maximum load. No medium-tenacity fibers



(a)



(b)

Fig. 3. Typical fatigue fracture morphology of a superhigh-tenacity nylon 66 fiber. The fracture initiated at the surface, turned sharply, and ran at a slight angle to the fiber axis until the load-bearing cross section was reduced sufficiently for a tensile failure to occur under the prevailing load conditions.

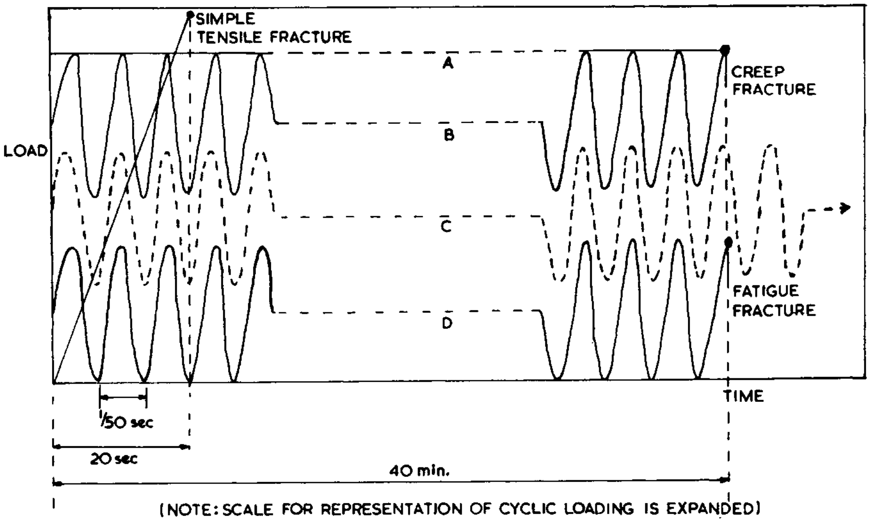


Fig. 4. A schematic loading diagram for nylon 66 fibers showing the patterns of loading for simple tensile, creep, and fatigue failure at 50 Hz.

subjected to maximum loads of 27 gf (266 mN/tex) or less failed even after tens of millions of cycles, but fibers always failed by fatigue within a million cycles at 50 Hz if the maximum load exceeded 30 gf (294 mN)/tex. The simple tensile strength was about 50 gf (491 mN)/tex. While more experiments are necessary to obtain definite indications of the effects of different frequencies of testing, the initial results are shown as dotted lines. The number of cycles to failure at higher frequencies are increased, but in terms of seconds the lifetimes remain about the same. The maximun load threshold level is increased by raising the frequency.

Temperature Rise

To make a true comparison between the fatigue and simple tensile strengths, it is important to estimate any rise in temperature which the fibers may undergo during large cycling conditions. From the cyclic loading pattern, which is shown on an oscilloscope screen used in conjunction with the fiber fatigue apparatus, the work done on the fiber during each cycle may be obtained by measuring the hysteresis loop traced out, as shown in Figure 8. It was assumed that the energy absorbed by the fibers during each cycle was totally converted to heat. This is reasonable, as the cycling is largely elastic in nature and any large internal structural changes occur within the first few cycles. The extension of the fiber in each cycle was obtained by illuminating the specimen and vibrator with a stroboscope and measuring the maximum movement.

Arthur and Jones[10] gives values of heat transfer coefficients for various diameters of highly twisted nylon 66 yarn and assume in their calculations that the yarn acts as a cylindrical homogeneous filament. From their results, a value of 4×10^{-3} cal cm^{-2}°C^{-1} sec^{-1} (9.6×10^{-4} Joules cm^{-2}-

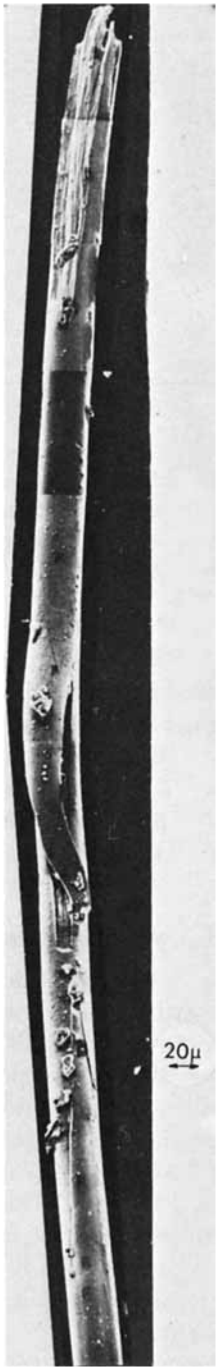


Fig. 5. A fatigued nylon 66 medium-tenacity fiber showing several developing fatigue fractures. Tested at 75 Hz.

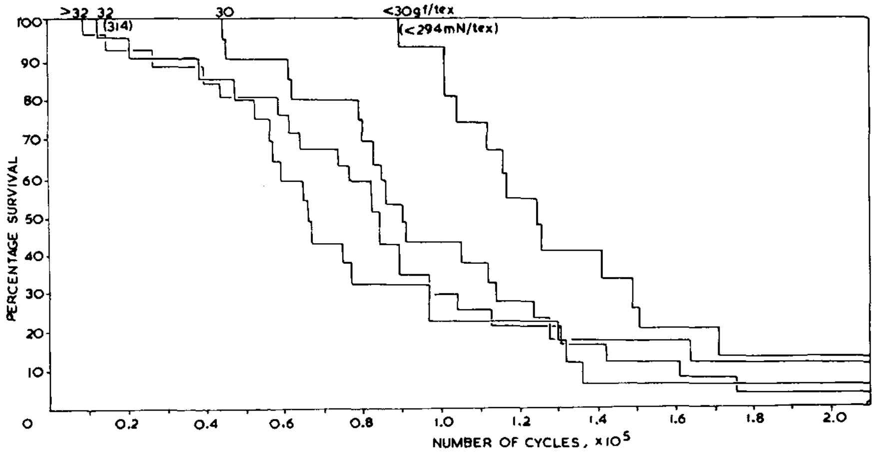


Fig. 6. Survival graphs of nylon 66 medium-tenacity fibers which failed by fatigue after being cycled at 50 Hz to different maximum loads, which are shown, in g/tex (mN/tex in brackets), at the top of each graph.

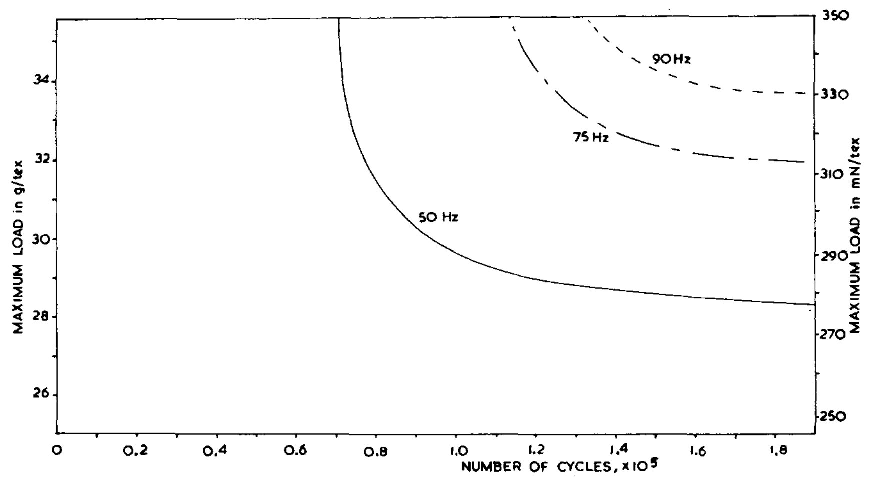


Fig. 7. Probable lifetime for fatigue failure of nylon 66 medium-tenacity fibers compared to maximum load in load cycling.

$°C^{-1}$ sec^{-1}) is taken for the heat transfer coefficient for the nylon fibers in these tests. Knowing the mean diameter of the fibers and the gauge length, an estimate of the temperature rise which the fiber undergoes to reach an equilibrium with the input energy can be calculated.

If we assume that during load cycling the fiber rapidly attains a state of thermodynamic equilibrium, the first law of thermodynamics may be expressed as

$$\text{energy input} = \text{energy output}$$

or

$$dW = -dQ. \qquad (1)$$

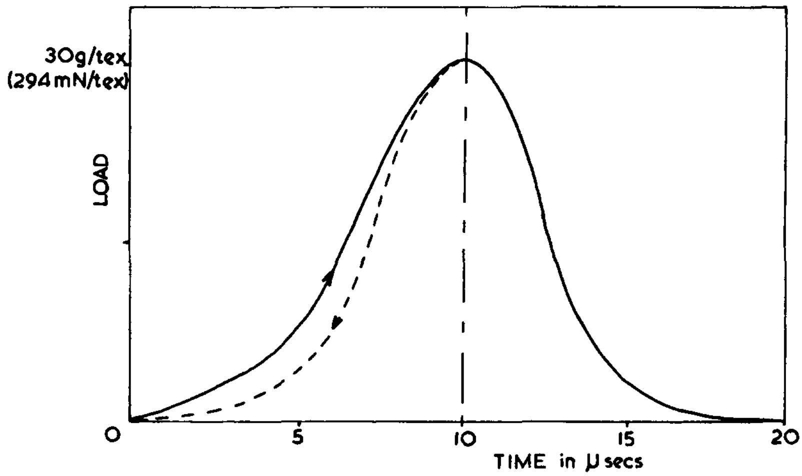


Fig. 8. Hysteresis loop of a nylon 66 medium-tenacity fiber undergoing load cycling at 50 Hz. The dotted line is the mirror image of the recovery section and shows the hysteresis.

Now let us consider the fiber under test to be homogenous and cylindrical, with length L and radius r. Let the heat transfer coefficient be η and the temperature rise θ. Then

$$\text{energy input per second} = dW \cdot \nu \tag{2}$$

where ν is the frequency of vibration. The

$$\text{energy output per second} = -dQ = 2\pi r L \eta \theta. \tag{3}$$

So, from eqs. (1), (2), and (3),

$$\theta = \frac{dW \cdot \nu}{2\pi r L \eta}. \tag{4}$$

In this way a temperature rise of 6°C has been estimated for the 1.7-tex medium-tenacity nylon 66 fibers when they are cycled between load levels 30 gf (298 mN)/tex apart at 50 Hz.

This estimate can only be approximate, but as a guide it can be taken that the fibers are raised in temperature by only a few degrees, not enough to seriously affect their behavior. Hall[11] has used a similar approach to determine the influence of strain rate on the stress–strain curve of oriented polymers.

There may be additional local heating at the crack tip, but this is an integral part of the phenomenon of fatigue failure, whereas general heating can be regarded as merely a disturbance of the conditions of test.

Breaking Extensions

Another important consideration is the total extension of the fibers in the last complete cycle. These are shown for the medium-tenacity nylon 66

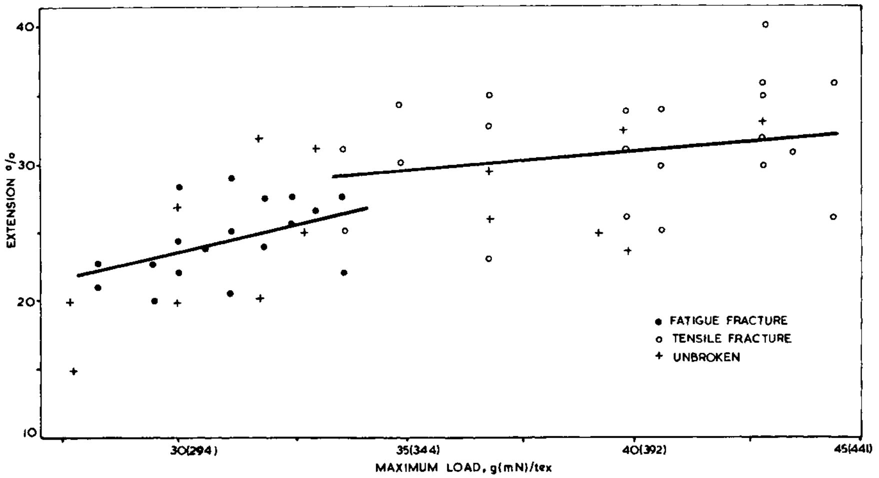


Fig. 9. Extensions of nylon 66 medium-tenacity fibers in load cycling. Lines are least-squares plots of the fatigue and tensile fractures showing that the fatigue breaks have broken at distinctly lower extensions than the tensile breaks.

fibers which have failed after about 10^5 cycles in Figure 9. The lines plotted are least-squares lines for the fatigue and tensile-type failure. Also shown are the extensions achieved by some fibers which were subjected to cyclic loading with a positive minimum load and which did not fail. There is a large amount of scatter in these points because of the variations of tensile properties along a monofilament. The extensions of those fibers which failed by the fatigue mechanism are markedly less than those which failed with a simple tensile-type fracture morphology. This is to be expected as the loadings for fatigue failure were considerably less than those which caused tensile failure. Fatigue failure therefore is not linked with the breaking extension of the fiber under simple tensile loading conditions as has been shown to be the case for many results obtained from cumulative extension cycling.[4]

Notch Effect

From observations of fibers subjected to fatigue conditions but removed for examination at regular intervals, the development of the initial notch on the surface of the fiber just prior to the crack deflection seems to take about 0.4×10^5/cycles. The development of the fatigue crack along the fiber can occur over 0.3×10^5 cycles. Most of this development is probably very slow near to the point of final failure as it seems that, once the crack has turned, propagation is at first rapid.

To investigate the possibility of any surface skin effect, and also to begin to see if the zero minimum load criterion is determined by notch initiation, artificial notches were cut into the surfaces of some nylon fibers before testing. It is too early to comment on the influence of the initiation notch on the fracture criteria, but such artificial notches have developed into typical fatigue fractures after load cycling. As the depth of the notch has been varied considerably, a specific skin effect to account for the fatigue fracture morphology may be discounted. This does not mean that a possible gradation of properties from the surface to the core of the fiber does not exist and may influence fracture development.

The Effect of Light Degradation

From the work of Hearle and Lomas[12] it can be seen that strong sunlight can have a noticeable effect on the fracture morphology of nylon 66 in as short a period as two days. With increasing exposure to sunlight, the two distinct regions of slow propagation and catastrophic failure found in fibers broken by a simple tensile pull become more and more irregular. Voids are seen to appear in the fiber, probably associated with the particles of titanium dioxide used as a delustering agent. After three months of exposure to sunlight, fibers of nylon 66 fail by simple tensile loading with fracture morphologies seemingly unrelated to the usual tensile fracture. On a larger scale, however, the tensile mechanisms are still operating, as local tensile failures occur across the specimen between voids which have developed. This leads to a very irregular tensile fracture morphology, as can be seen in Figure 10 (by courtesy of B. Lomas).

When light-degraded fibers are subjected to cyclic loadings, they are found to behave in a similar manner to fresh fibers. The loading conditions for fatigue are identical although the mean lifetimes of these degraded fibers appear slightly reduced. The appearance of the fatigue fracture morphol-

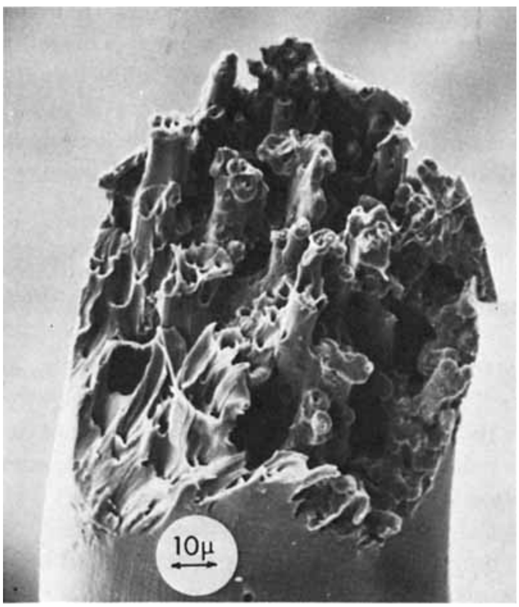
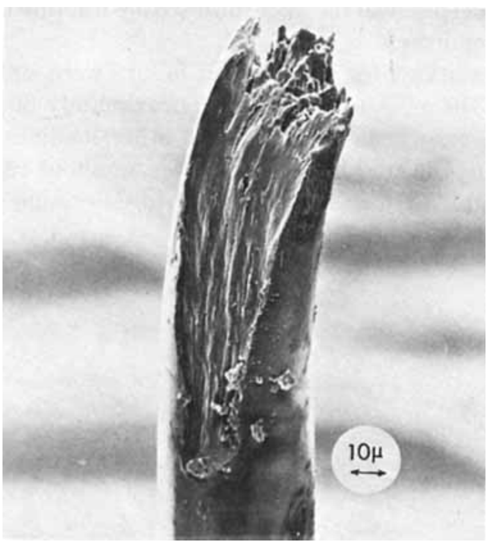


Fig. 10. Typical tensile fracture morphology of light-degraded nylon 66 medium-tenacity fibers. (By courtesy of B. Lomas).

(a)



(b)

Fig. 11. Typical fatigue fracture of a light-degraded nylon 66 medium-tenacity fiber.

ogy of light-degraded fibers is similar to that of ordinary fatigue breaks but is usually shorter in length of tail. This is due to the weaker nature of the specimen because of the presence of the voids. The fatigue fracture reveals that the voids occur throughout the fiber. At the root of the tail, a very irregular morphology is seen, similar to the simple tensile fracture morphology of light-degraded fibers (Fig. 11).

NOMEX

Nomex is a high-temperature aromatic polyamide manufactured by du Pont. Unlike the nylon 66 fibers described above, the cross section of a Nomex fiber is not circular but peanut shaped. Instead of a smooth surface, it has a coarser texture with greater roughness on the concave parts of the fiber.

A simple tensile pull on a Nomex fiber results in the fracture morphology shown in Figure 12. Essentially, this is the same as seen in the other nylon fibers tested but modified in appearance by the different cross section. A region of slow crack growth can be seen originating from the concave part of the fiber. All of the Nomex fibers broken in this manner failed from the concave region.

At 50-Hz Nomex was found to fail by a fatigue mechanism which quickly caused the fiber to fracture. A fatigued Nomex fiber has a fracture morphology strikingly similar to the other nylon fibers and is usually found to have many fatigue fractures in the process of development along its surface (Figs. 13, 14, and 15). The fatigue fracture initiates at the surface, although initiation lines of the type found in nylon 66 fibers are not seen. The fracture develops deeply into the fiber until tensile fracture occurs under the imposed loading conditions.

The loading conditions for this type of failure were sinusoidal loadings from 0 to 35 gf (340 mN)/tex which is approximately 60% of the simple tensile strength. Few tests were done at other loadings because of the difficulties of testing the very fine fibers (0.2 tex, or about 15 μm in diameter) which were available. It was not possible to determine whether cycling

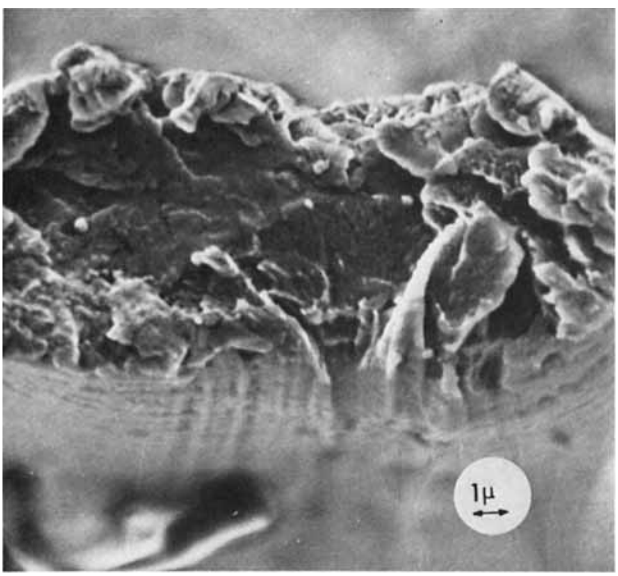


Fig. 12. Tensile fracture of a Nomex fiber showing region of slow crack propagation initiated from the concave surface region.

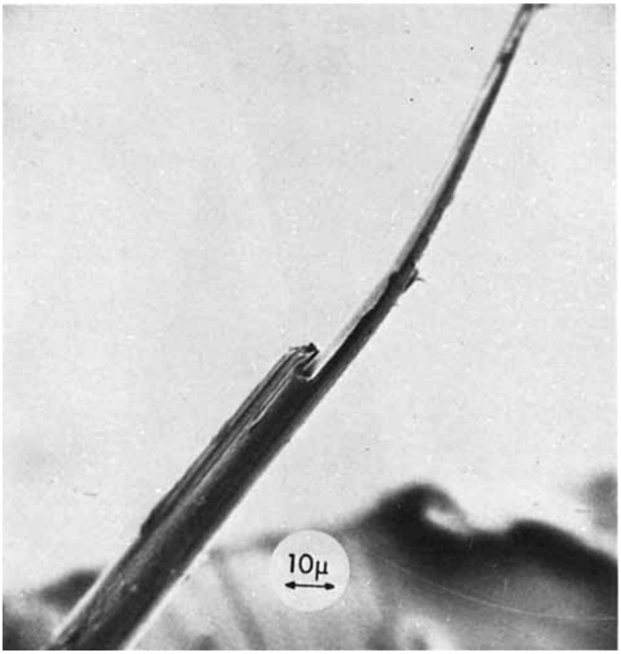
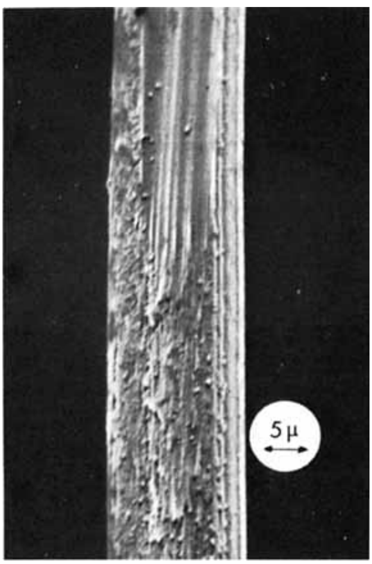


Fig. 13. Fatigue fracture of a Nomex fiber.



(a)

Fig. 14. (*continued*)

(b)

Fig. 14. Initiation points of fatigue fracture on the surface of a Nomex fiber.

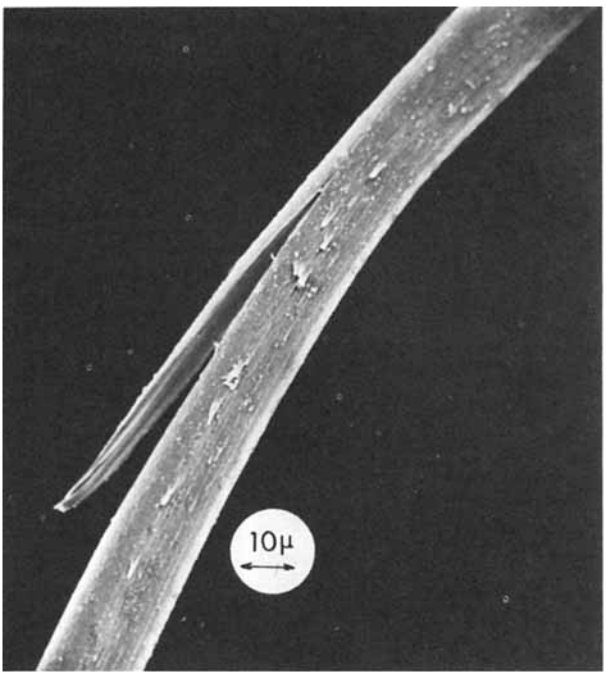


Fig. 15. Developing fatigue fracture along a Nomex fiber.

with zero minimum load is a necessary criterion for fatigue failure. The number of cycles to failure was in the region of 0.2×10^5, much less than for the nylon 66 fibers tested. This is probably due to ease of crack initiation for fatigue fracture at the rough surface of the Nomex fiber.

POLYESTER

The appearance of a polyester fiber is of a smooth cylinder, similar to that of nylon 66; and when broken by a simple tensile pull, it also shows a region of slow crack growth followed by a catastrophic failure region. High-tenacity polyester filaments (made by ICI) which had breaking strengths of around 85 gf (830 mN)/tex were used in this study. A wider range of tensile properties was found with these samples than is normally experienced with a monofilament as they were taken from a multifilament yarn. Each sample was of 0.6 tex, which is about 25 μm in diameter.

These fibers were found to fail by a fatigue mechanism, under load cycling condition, when the maximum load was about 70% of the simple tensile strength. Fibers did not always fail under these conditions, but this was probably due to the spread of tensile properties. Because of these difficulties, it is not as yet certain whether the zero minimum load criterion for the fatigue of nylon also holds for polyester fibers.

The appearance of the broken ends of the fatigued polyester fibers is similar to that of fatigued nylon, except that the crack growth along the

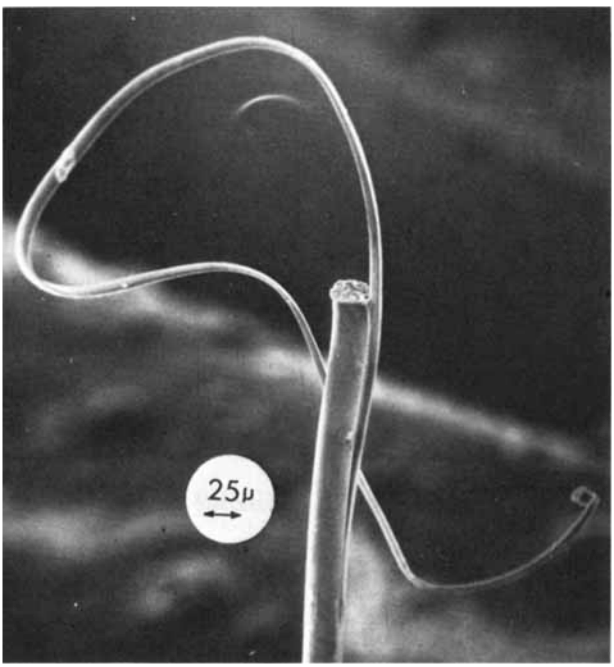


Fig. 16. Fatigue fracture of a polyester fiber showing the long crack development from the surface to the point of final tensile failure.

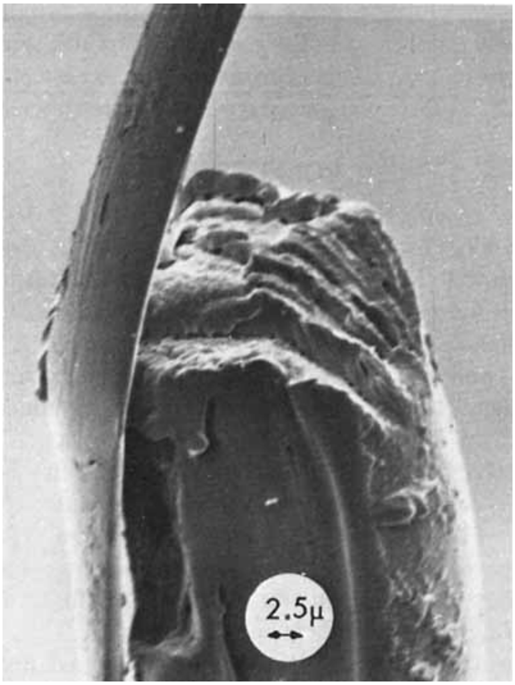


Fig. 17. Final tensile failure region in a polyester fiber showing that the initiation point for this stage of failure was from the virgin fiber surface and not from the newly formed fracture surface.

fiber is very much longer (Fig. 16). This is because the angle of penetration of the fatigue crack is less than in nylon, and the fracture must be much more developed before the load-bearing cross section is sufficiently reduced to cause a tensile failure. The final failure region shows all of the characteristics of a tensile fracture (Figs. 17 and 18). This region is often somewhat behind the tip of the crack growth along the fiber and may originate from the virgin surface, unlike the nylon fibers in which the initiation of the tensile stage is always from the fatigue fracture surface.

The breaking extensions under fatigue conditions were usually around 12%, compared to 20% in a simple tensile break. Fatigue lifetime was found to be considerably greater for polyester than for nylon and with a wider spread. A typical lifetime would be 2.0×10^5 cycles.

ACRYLIC FIBERS

The acrylic fiber studied was Courtauld's Courtelle fiber. These fibers are circular in cross section and have very rough surfaces. Many striations or grooves running parallel to the axial direction can be seen on the surface of the untested fiber.

Under simple tensile loading conditions, the fiber usually fractures across a radial plane, showing little evidence of any slow crack growth across the

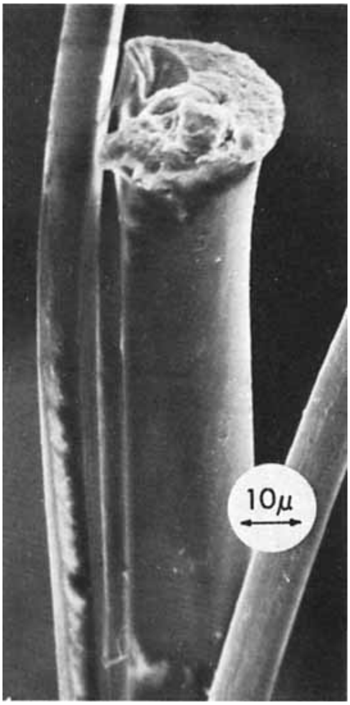


Fig. 18. Region of final failure in a fatigued polyester fiber showing that the final tensile fracture has occurred some way behind the crack front formed during the stage of propagation along the fiber.

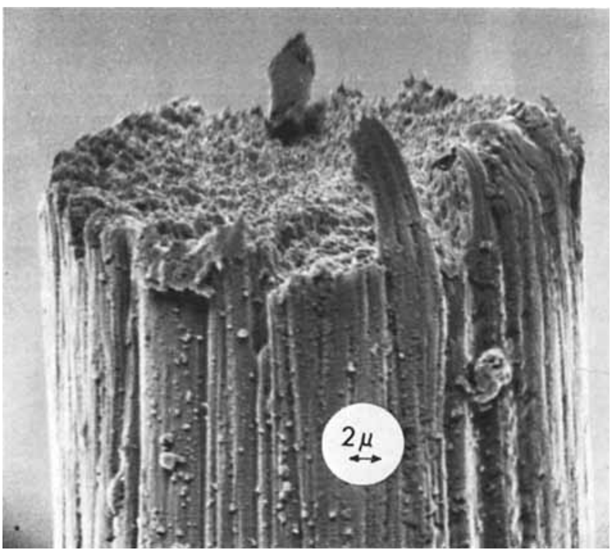


Fig. 19. Typical tensile fracture of a Courtelle fiber showing a nearly flat morphology with some bunches of fibrils projecting along the general fracture plane.

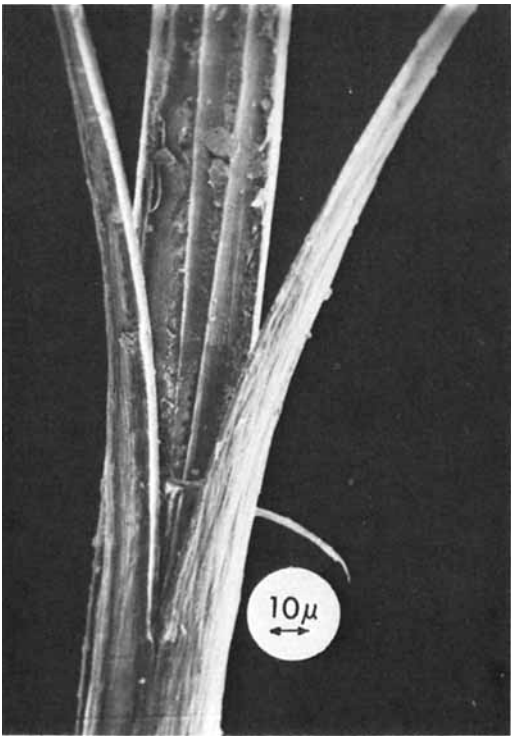


Fig. 20. Splitting of a Courtelle fiber induced under cyclic loading conditions.

fiber. This is not so for all acrylic fibers.[9] The appearance of the Courtelle fiber broken under these conditions is of a very fibrillar structure made up of separate bunches of fibrils, and sometimes bunches may be seen to project above the general fracture plane (Fig. 19).

Under load cycling conditions, Courtelle fibers were found to fail when cycled to a maximum load of about 65% of their simple tensile strength. Superficially, the fatigue fracture morphology of these acrylic fibers resembles that of the other fibers so far described with a long tongue of material on the one fracture end which has been stripped off the other. The mechanism of failure, however, is different. Instead of the fracture developing through distinct stages, fatigue failure in Courtelle occurs by splitting of the structure, possibly originating internally (Fig. 20). By this means, the fiber is weakened and failure occurs. Splitting of this type occurs with even a small oscillatory load superimposed on a high average load (see Fig. 21). The fatigue lifetime for these fibers varied considerably from 0.04×10^5 to 2.6×10^5 cycles, with no definite typical value.

Fibers of this type which are further drawn and their structures more greatly aligned are used as precursor fibers in the manufacture of carbon fibers. Those available for this study were very fine (about 8 μm in diameter) and consequently very difficult to handle. On testing these fibers it

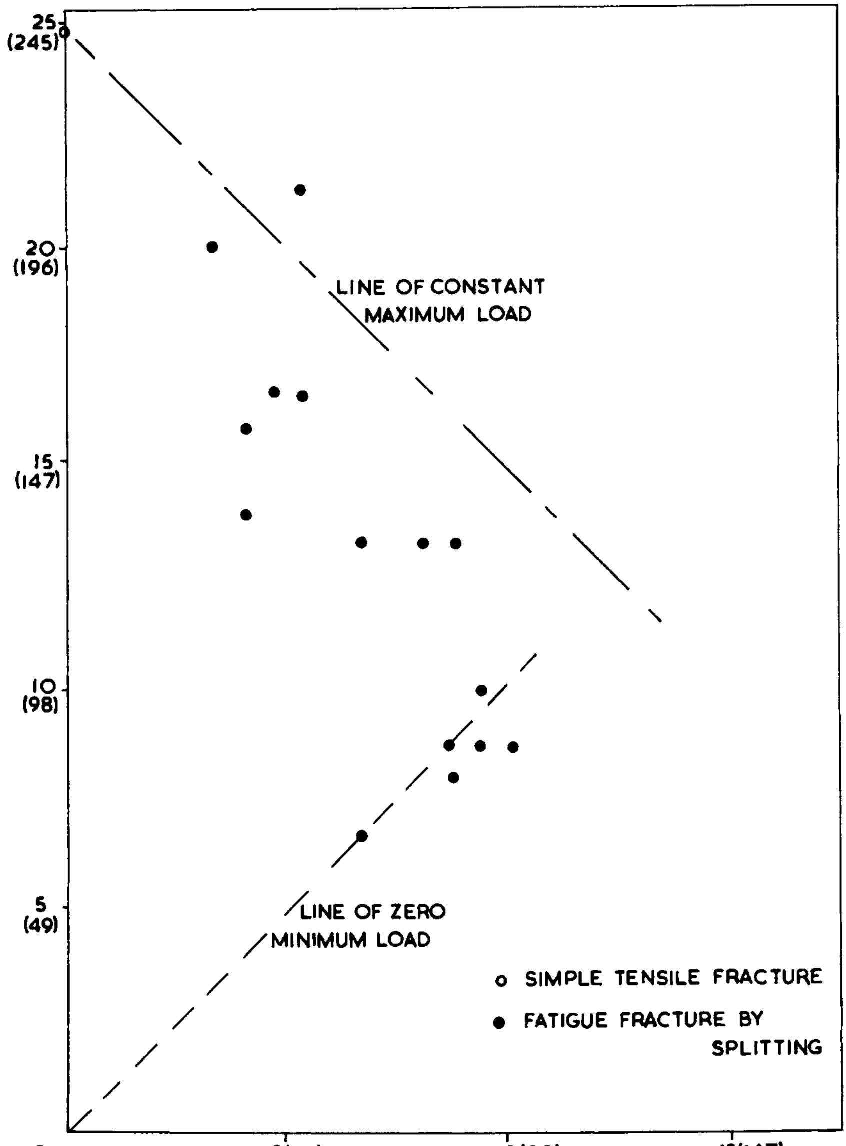


Fig. 21. Load diagram of Courtelle fibers which failed after splitting during fatigue and shows how fatigue failure can be induced in Courtelle fibers over a wide range of cyclic conditions.

was found that fibrillation occurred even under simple tensile loading conditions. This is in contrast to the carbon fibers, which were not found to split, presumably because of the crosslinking induced in their manufacture. The carbon fibers which were tested, both by simple tensile pulls and under cyclic conditions, broke straight across radial planes; however, insufficient tests were conducted for conclusions to be drawn about their fatigue properties.

DISCUSSION AND CONCLUSIONS

The fatigue mechanism shown to exist in nylon 66 medium-tenacity fibers[8] has also been demonstrated in superhigh-tenacity nylon 66, Nomex, and polyester fibers. The explanation offered by the authors[8] for the development of the fatigue fracture is applicable to the cases considered above. The development of the initial notch may be due to a gradation of properties through the fiber from surface to core which causes the surface to go into compression when the fiber is nominally under zero load. This could lead to the initiation of the crack and provide a reason for the zero minimum load criterion observed in the nylon 66 fibers. The deflection of the crack along the fiber seems likely to be due to a change of material properties induced by the high stress concentrations ahead of the crack. Once the crack has turned, the highly anisotropic nature of the fiber would greatly assist crack development in this direction. Finally, a tensile failure occurs when the reduced load-supporting area cannot sustain the maximum load to which the fiber is cycled.

The most general form of fatigue fracture growth of this type is shown in schematic form in Figure 22. The splitting into two directions at the point of initiation, which has been observed in many cases, presumably occurs when there is no local bias to deflect the crack one way or another.

The cause of failure in the Courtelle fibers is different. These fibers behave as though composed of bunches of fibrils aligned in the axial direction and bound together by low cohesive forces. In a simple tensile break, failure probably starts at the weakest fibril and then, as the load is taken by neighboring fibrils, spreads across a radial section through the fiber. Under cyclic conditions, the low cohesion between fibrils causes splitting to occur. As the splitting develops along the fiber, it inevitably deviates from the axial direction and so reduces the load-supporting region until this results in complete failure under the maximum applied load.

Both types of failure involve fracture growth along the fiber at a slight angle to the fiber axis. This situation can be generalized (see Fig. 23) with the crack growing, from an internal fault, at a small angle θ to the axis by an average amount δ each cycle. Knowing the ratio of simple tensile strength to maximum applied load in the cyclic case, the ratio of fiber cross section to the area remaining at the point when the splitting gives way to the tensile mechanism may be calculated. As the length of the tongue of material left on the one end of fatigued fibers is typically about 300 μm and this growth is estimated to occur often over 3×10^4 cycles, a rough value of 100 Å is obtained for δ. It should be remembered that the rate of crack growth during a test is not likely to be constant and may change greatly in some, if not all, types of fiber, as the crack deepens. The above consideration is concerned only with the propagation stage of the crack growth and does not

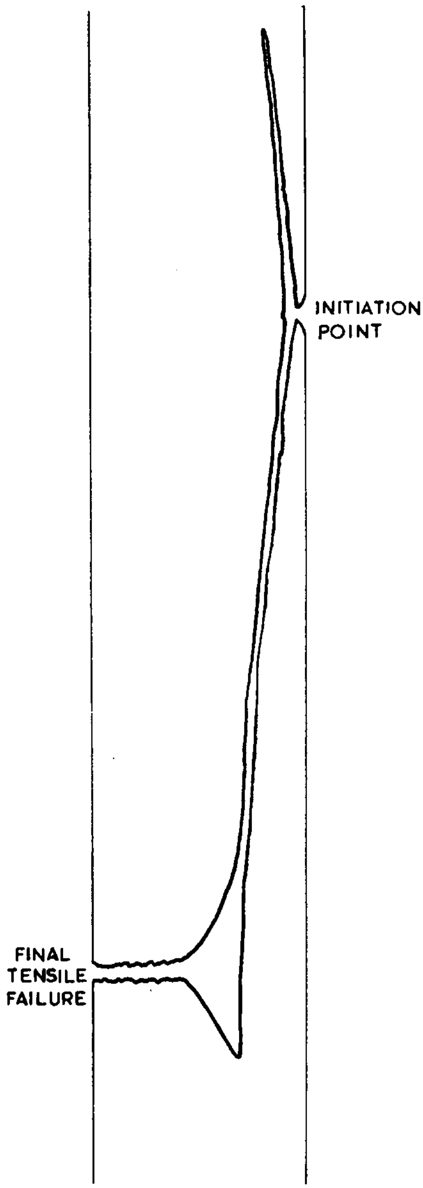


Fig. 22. Schematic representation of the most general type of fatigue fracture of a nylon 66 fiber.

include the initiation period, which may be a considerable fraction of the lifetime in these tests.

The failure conditions for these fibers under simple tensile loading and the fatigue situation are compared in Table I, which shows that the maximum safe tensile loading, under oscillatory conditions, is typically less than two

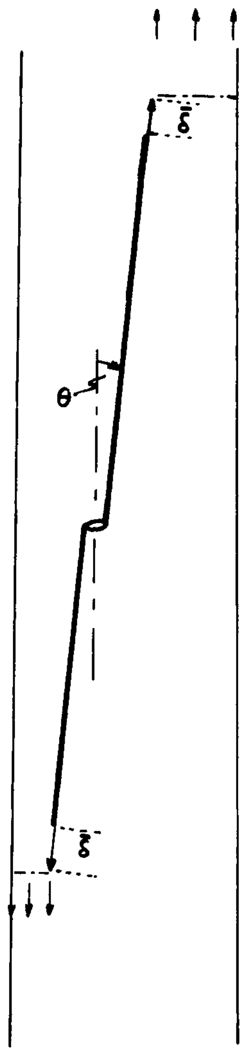


Fig. 23. Idealized fatigue fracture along a fiber.

thirds of the breaking load measured in a simple tensile test or a creep test. This has technological significance in the design of textile materials, particularly for industrial end uses. In addition, it must be noted that most fiber structures contain millions of filaments, and any loading will be distributed throughout the system to the individual fibers. As the fibers will be arranged at different angles to one another, they will experience a distribution of loads. In this way, a nominally low oscillatory load could induce fatigue failure in a small percentage of fibers, so causing weakening of the whole structure and possibly eventual failure.

It appears from these studies that failure by fatigue is found generally in fibers, certainly in those synthetic fibers, which have been tested. So what are the possibilities of reducing the tendency for fibers to fail by fatigue?

TABLE I
Summary of Tensile and Fatigue Fracture Conditions

Fiber type	Typical tensile strength, g/tex (mN/tex)	Mean tensile breaking strain, %	Typical fatigue loading range, g/tex (mN/tex)	Mean fatigue breaking strain, %	Typical fatigue life, cycles × 10^5
Nylon 66 medium tenacity	48 (470)	36	0–30 (294)	25	0.85
Nylon 66 superhigh tenacity	78 (765)	17	0–43 (425)	11	0.5
Nomex	50 (490)	20	0–35 (343)	14	0.18
Polyester	85 (835)	20	0–55 (541)	12	2.0
Courtelle	25 (245)	55	5–25 (49–245)	45	0.04–2.66

It is possible that improvements can be made to fibers by the manufacturers now that this type of failure is recognized. Furthermore, in those fibers where the fatigue failure occurs only where the load drops to zero, it may be possible to avoid the problem in some applications by ensuring that the fibers remain under tension.

Concurrent studies of failure in used clothing materials[13] have shown that simple tensile failure is a rare occurrence. Breaks in these materials have on occasion been seen which have features similar to those described in this paper, although the commonest forms of failure are more like those which have failed in flex fatigue studies.[14] The flex fatigue condition necessarily involves compression, and it appears at present that the order of increasing severity in causing fatigue failure is tension–tension, tension–zero, zero–compression, and tension–compression cyclic loading.

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