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A Mechanism of Fatigue Failure in Nylon Fibres

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The use of an apparatus which is able to fatigue test fibres in a new and original manner has revealed that a fatigue mechanism does exist in nylon fibres. This mechanism is revealed by a distinctive fracture morphology, as seen with the aid of a scanning electron microscope, and failure when the fibre is cycled to loads which, under steady conditions, would not result in fracture. It is shown that a necessary condition for fatigue failure is the cycling of the fibre to a zero minimum load. An explanation for the history and development of such a fatigue break is given.

1. Introduction

Previous studies of the fatigue properties of polymeric fibres have produced little conclusive evidence of the existence of a fatigue mechanism for failure in fibres subjected to uniaxial cyclic loading. In most of the earlier work, which has been reviewed by Hearle [1], cumulative extension cycling with a given imposed stroke and removal of slack at the end of each cycle was adopted for reasons of experimental simplicity. Rather low frequencies of the order of 1 Hz were used: this means that specimens need to be fatigued for nearly a day in order to exceed 10^5 cycles. In addition to the studies reviewed by Hearle, which include a long series of papers by Lyons and Prevorsek, the results of cumulative extension fatigue tests are described by Nath [2], Vaughn [3] and Hearle and Vaughn [4].

The general conclusion from all this work is that most test conditions will yield one of two results:

(a) At imposed strokes of low amplitude the fibres do not fail within the time of the test.

(b) At imposed strokes of high amplitude the maximum total extension of the fibre progressively increases with cycling as slack is removed, until the breaking extension of the fibre is reached and a normal tensile break occurs.

In principle, the two forms of behaviour can be predicted from an adequate knowledge of the viscoelastic deformation and rate-dependent breakage conditions of the fibre, together with the applied deformation pattern. No specific fatigue effects are involved.

There have, however, been indications of a limited amplitude range of imposed strokes between the low and high ranges in which fatigue failure does occur. Under these circumstances, which occur with strokes of about 9% strain in nylon (Hearle and Vaughn [4]), fracture has occasionally been seen to occur at around 10^5 cycles in association with an unusual fracture morphology. The progressive increase in load in cumulative extension cycling makes it difficult to achieve the conditions for this type of failure. Load-controlled fatigue-cycling would be a preferable procedure but has not been used in the past because of the experimental difficulties involved.

We have now made a fatigue tester capable of operation at higher frequencies, around 50 Hz. This apparatus, which is described elsewhere by Bunsell, Hearle and Hunter [5], can be used in various modes, in particular with control of maximum and oscillatory loads applied to the fibre. The present paper describes an initial investigation which clearly demonstrates the existence of a fatigue-failure mechanism in nylon. Further work will be needed to establish the full range and conditions under which the mechanism operates.

2. Fracture Morphology

Our understanding of the test results has been greatly helped by scanning electron microscopic studies of the fracture morphology of fibres broken under various conditions. In simple tensile testing of nylon fibres, Hearle and Cross [6] have shown that, after crack-initiation, a V-shaped notch develops in the fibre and increases in depth until catastrophic failure occurs. Fig. 1 shows such a break; this particular example was obtained by failure after creep for 50 min under a load of 69 g, in order to reproduce the time scale of fatigue tests.

Hearle and Vaughn [4] found that whilst most of the fracture morphologies from cumulative extension cycling tests are of this tensile type, a few revealed a different appearance. These unusual breaks had a short tail left on one side of the fibre with a corresponding piece stripped off the other broken end. From the root of the tail a morphology similar to a normal tensile break developed.

With the new apparatus it has proved possible to produce this type of break much more frequently and with the unusual fracture morphology enhanced. Fig. 2 shows such a fatigue failure obtained in some preliminary studies during development of the new fatigue tester which was being used at 50 Hz, manually controlled in the cumulative extension mode with an imposed stroke of approximately 8% strain. This break, typical of those obtained with the new apparatus, has a long tongue of material on the one fracture end; there was a complementary area stripped off the other end. This break occurred after 2.5×10^5 cycles.

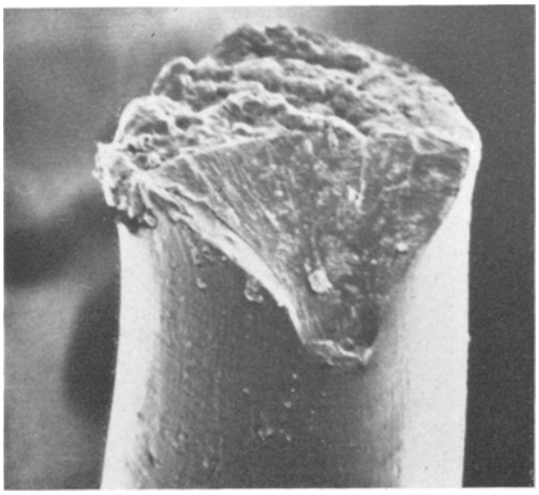

Figure 1 Example of creep fracture morphology in 1.67 tex nylon 66 monofilament which failed after 50 min under a load of 69 g (× 1130).

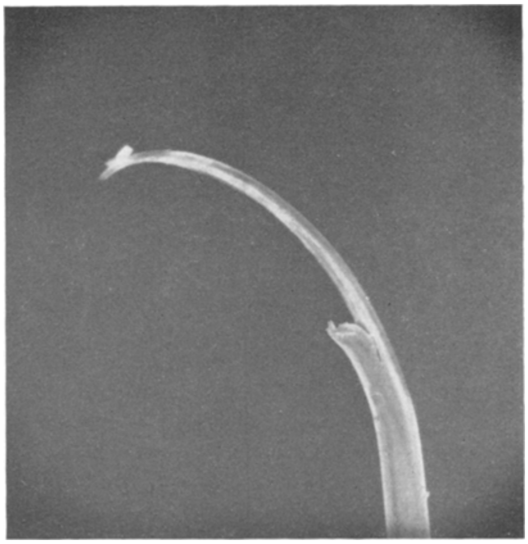

Figure 2 Fatigue fracture morphology of 1.65 tex nylon 66 after cycling at 50 Hz (× 103).

For convenience in the remainder of this paper the two forms of break will be referred to as *tensile* and *fatigue* breaks respectively.

3. Load-Controlled Fatigue Tests

With the completed apparatus a series of maximum-load-controlled tests, in which a sinusoidally varying load was superimposed on a steady load, was conducted on 15 denier (1.66 tex) nylon 66 fibres at 65% relative humidity and 21°C. The cycling was carried out at 50 Hz and the magnitudes of both the steady and oscillatory loads, which were held constant during each test, were varied. The fibres were subsequently examined in the scanning electron microscope. Because of the statistical demands of fatigue-testing and the variability in fibre properties, it will be necessary to carry out a large programme of testing in order to establish the relation between loading conditions and number of cycles to failure. However, the results reported here do demonstrate the main pattern of behaviour: they are all for fibres which failed (or survived) at around 10^5 cycles in the fatigue tester.

Creep tests were also carried out on the same type of fibre and will be reported in more detail later.

Fig. 3 shows the pattern of results. The fibres

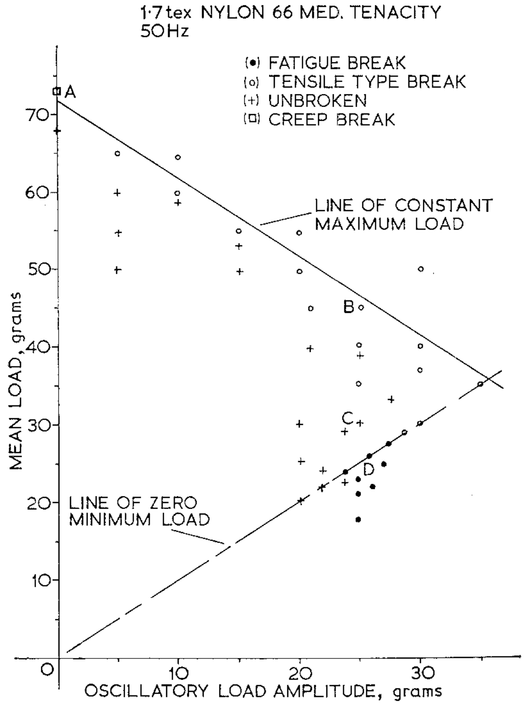

Figure 3 Graph of Mean Load/Oscillatory Load amplitude for fibres cycled into region of 10^5 cycles, or equivalent time for static loadings.

which failed after about 10^5 cycles fall into two categories. The first group, which break with a typical tensile morphology, failed under conditions in which the maximum load was substantially constant and equal to the load which would lead to breakage in a creep test after a time comparable with the total fatigue time. This indicates that failure under these conditions does not involve any specific fatigue effects, and can be adequately predicted from a knowledge of the time-dependence of strength by assuming that the maximum load in the "fatigue test" is applied as a steady load for the same time. Hearle [7] has previously pointed out that Meredith's [8] equations for rate-dependence of breakage stress could be used to explain Kelly's [9] results for load-cycling on an Instron tester.

The second group, which lies close to a line of zero minimum load, is of more interest, and clearly demonstrates the existence of a fatigue mechanism. Examination of the fibre ends shows the fatigue morphology.

The pattern of loading, illustrated in fig. 4, shows that under steady loading conditions, A, the fibre will fail by a creep mechanism. When the fibre is subjected to cyclic loadings up to the level A, the fibre is found to fail with a similar morphology. Cycling the fibres to less than the level A and with a positive minimum load, C, safeguards the fibre from failure. However, lowering the loading pattern to D with zero minimum load, again leads to failure, provided the stress amplitude is great enough; but steady loading, even at the maximum level shown in D, would not lead to failure, so that the break is associated with repeated variation of load which is the classic definition of a fatigue situation.

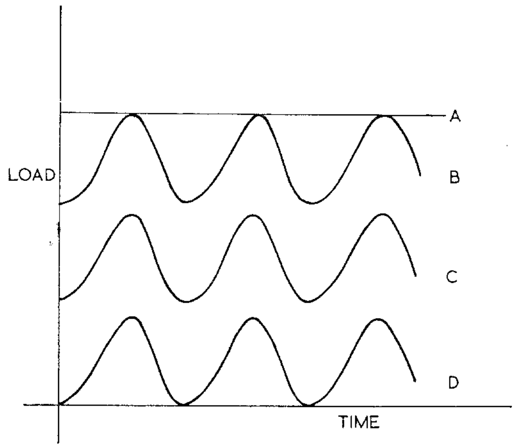

Figure 4 Comparison of different loading patterns.

Since a necessary condition for the fatigue failure is found to be a drop in the load to zero, or close to zero, during each cycle, we have the interesting finding that fatigue failure, which occurs under the loading pattern D, can be prevented by *increasing* the loads to the pattern C.

If, for a given level of oscillatory load, the maximum load, which is controlled during the test, is reduced to less than twice the amplitude of the oscillatory load (i.e. the mean load is less than the oscillatory load), the fibre will go slack and buckle during part of each cycle. Fatigue failure may occur under these conditions. Any buckling, however, is readily detected by observing the fibre specimen with the aid of a stroboscope during the test, or, more sensitively, by the oscilloscope trace of the signal from the piezoelectric transducer used to monitor the oscillatory load. This examination showed that, although the load has to fall very close to zero, buckling was not a necessary condition for fatigue failure.

Fig. 5 shows the breaking extensions

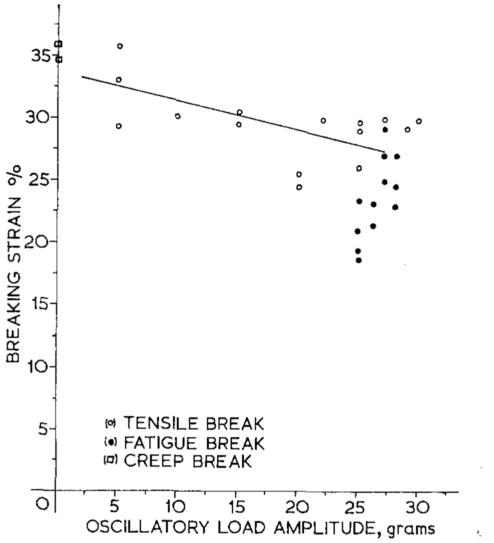

Figure 5 Breaking strain/oscillatory load.

(maximum extension in the last complete cycle) of the fibres which failed after about 10^5 cycles in the fatigue tester. Those which failed by the fatigue mechanism have markedly lower breaking extensions than those which failed with a tensile type break.

4. Further Studies of Fatigue Failure Morphology

Further studies have been made of fibres which have failed by the fatigue mechanism, or which have been removed from a test under conditions leading to fatigue failure before break occurred. The latter situation is most conveniently studied with test conditions in which buckling occurs. At early stages in the test, the buckling is shallow and random in direction. When a fatigue failure is imminent, the buckling settles into one direction and the apex becomes sharp at one point on the fibre. Sometimes more than one such crease may be seen along the fibre length. When the fibres are removed and examined in an optical microscope, the creases can be seen to be fatigue breaks in the process of formation. The general pattern of behaviour, confirmed by many observations, shows a similarity independent of whether the test conditions were those of the cumulative extension test, which in this apparatus operates from zero minimum load, or of the later load-controlled tests.

It has been possible with the scanning electron microscope to obtain many illustrations of the different types of fracture in various stages of evolution. Those shown here are chosen as being typical of many others.

From observations obtained by prematurely stopping such fatigue tests, it is possible to describe the development of fatigue breaks. The initiation sites appear as small notches in the fibre surface (figs. 6a and b), usually normal to the axial direction although some have been seen inclined to this orientation. A fracture with such an inclined initiation region is shown in fig. 7. This type of initiation may be the result of local damage due to past bending or kinking of the

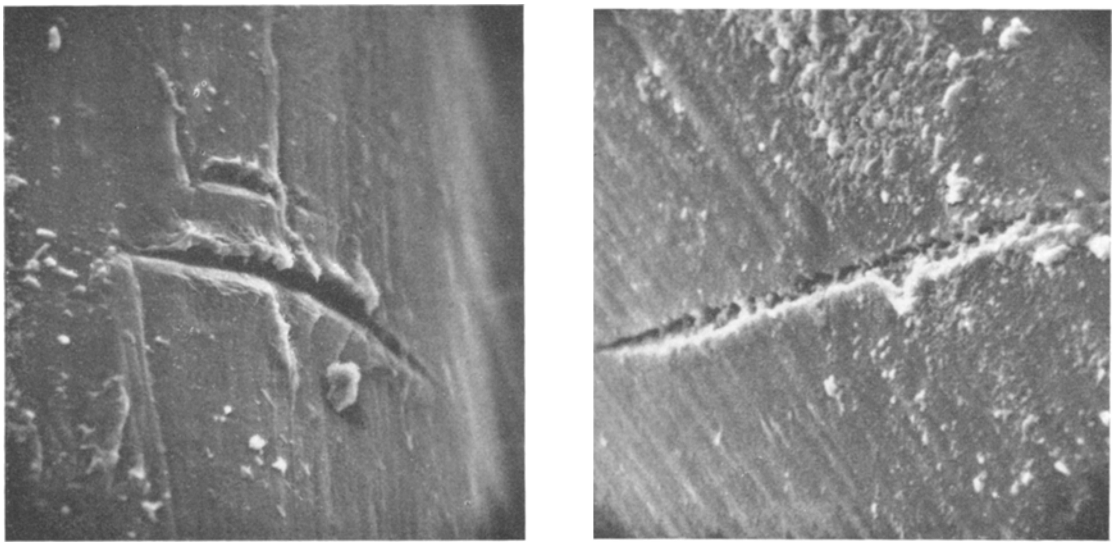

Figure 6 Points of fracture initiation in nylon 66 mono-filament (*a* × 3600; *b* × 4650).

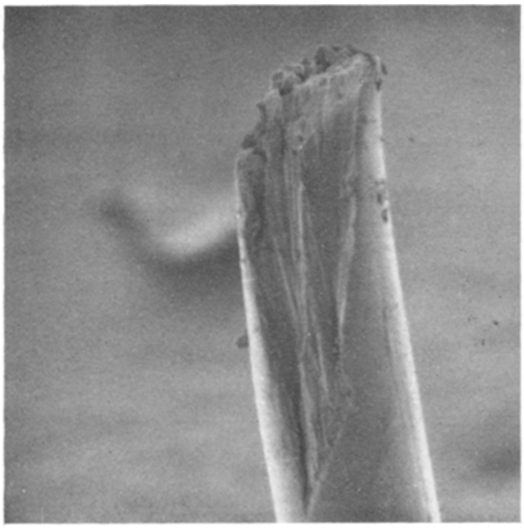

Figure 7 Fatigue fracture surface showing inclined initiation points (× 515).

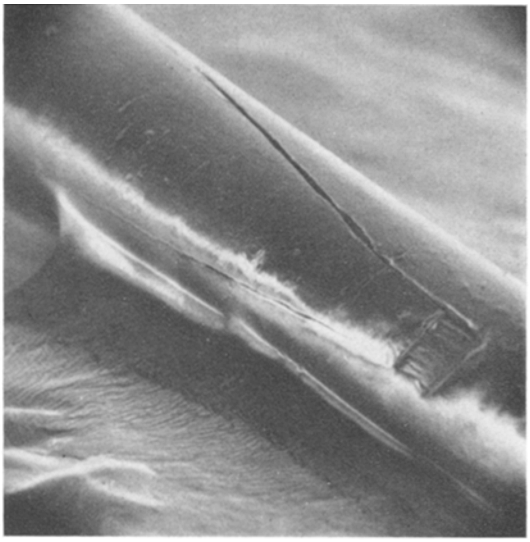

Figure 8 Fatigue fracture in process of developing (× 470).

fibre. Having developed in a radial direction, as though through a skin on the fibre surface, the crack deviates sharply and begins to travel predominantly along the axial direction whilst still working deeper into the fibre and becoming wider (fig. 8). The crack travels in this way for several fibre diameters along the fibre until, having worked deeply into the fibre, the fracture propagation changes back to a radial direction and a normal tensile fracture completes the break. Fig. 9a shows the tensile type break at the root of the tail whilst fig. 9b shows the tip of the tail. A few fibres have shown evidence of splitting in two directions near the point of crack initiation (fig. 10). This will be discussed below.

Those breaks described as being of a tensile type do not always exactly fit the description of the typical tensile break as seen in fig. 1. Some unusual fracture morphologies have been seen which, while still clearly of a tensile nature, differ from the usual form; an example is shown in fig. 11.

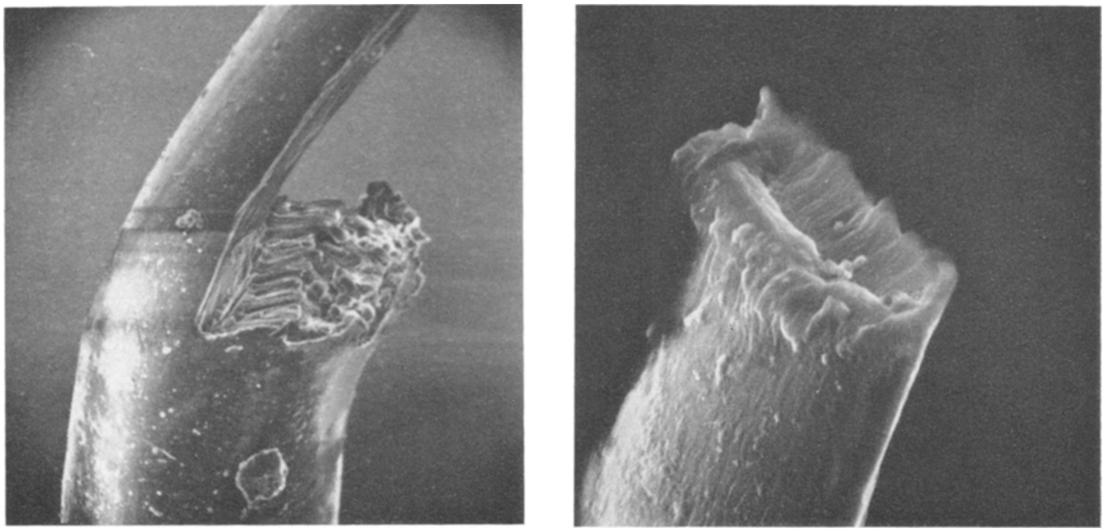

Figure 9 a Tensile type morphology at the root of the tail in a fatigue break (× 755); *b* The tip of the tail (× 1690).

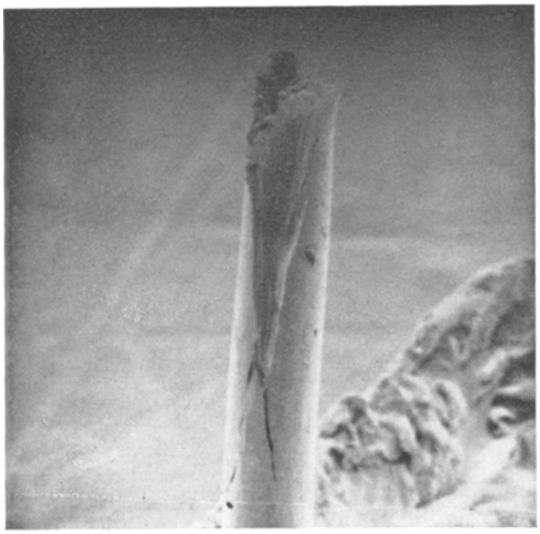

Figure 10 Crack splitting and point of initiation (× 192).

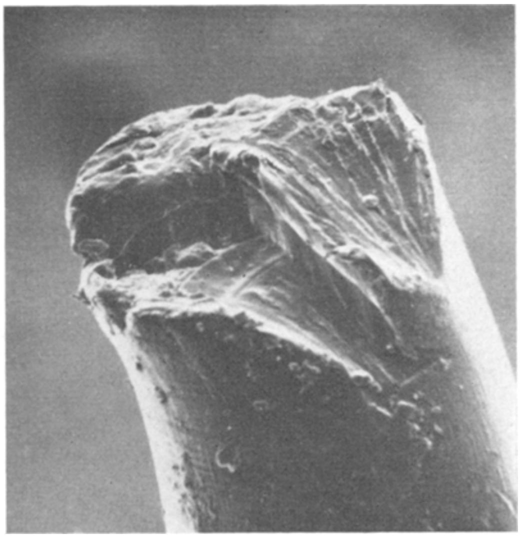

Figure 11 Unusual tensile fracture (× 1125).

5. Discussion

The observed morphology for the *tensile* failure of nylon, reported by Hearle and Cross [6] and extended in this paper to include creep failure and failure in a cyclic loading test under a high maximum load, is explicable in terms of crack-propagation across the fibre under the influence of the axial stress at the tip of the crack. The maximum stress which governs the crack-propagation is along the line of the crack, which then grows straight across. The crack opens into a V-notch because of the large plastic extension of the remaining material as it comes under increasing stress. There are some unsolved features of the mechanism, notably whether crack-propagation which is by stable tearing, and is not catastrophic, can be explained solely in terms of stress distributions and stress-strain properties or whether, as proposed by Brunt [10], time-dependent behaviour is a necessary feature of the explanation. Although there has been no quantitative analysis, the explanation will follow in the line of development of the analysis of crack-propagation which began with Inglis's [11] work on stress-concentrations in the region of voids, and Griffith's [12] discussion of the energy balance for crack growth, which was extended to more complex materials by Rivlin and Thomas [13] and reviewed in its application to polymers by Andrews [14].

The other type of break described in this paper fits the criteria for *dynamic fatigue failure* given

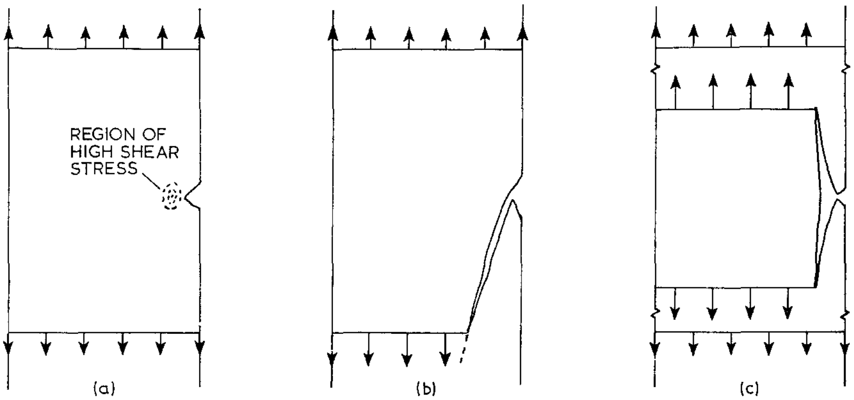

Figure 12 a, b and *c* Fatigue crack growth under influence of shear stress.

by Andrews [15], namely periodic loading and reduced stress. Although further studies are needed to clarify the position, there appear to be two stages in the fatigue process, each of which takes a considerable number of cycles; these are (1) the initiation stage, leading to the formation of a crack or notch on the fibre surface, either normal or inclined to the fibre axis, and (2) the subsequent propagation of a crack along the fibre, going progressively wider and deeper. Eventually the fatigue mechanism leads to the final third stage of failure: as the crack penetrates to greater depths in the fibre, the area remaining to take the load reduces and eventually the stress reaches a level at which a tensile type break, with a V-notch followed by a catastrophic region, can be initiated from the root of the crack.

This description of what happens raises a number of interesting questions which cannot be answered conclusively but on which some comment can be made:

(a) Why is it necessary for the load to drop to zero for the fatigue mechanism to operate?

(b) What is the mechanism of initial crack formation?

(c) Why does the crack then propagate along the fibre?

The reasons for the crack initiation are obscure – the generality of the statement is emphasised by Andrews [15] – but it may be related to the fact that, under compressive stress, strain-bands develop in fibres, as described for example by Bosley [16]. We [17] have found that under periodic deformation, failure occurs along these bands. Possibly owing to radial inhomogeneity, the surface layers of the fibre may go into compression and eventually the cracks develop. However, a variety of other explanations – stress corrosion, fatigue growth of micro voids, inhomogeneities or surface damage giving rise to stress concentrations, etc. – are possible. Observation shows that initial crack growth is widespread on the surface of the material: many cracks in various stages of growth may be found in a fatigued specimen. Once an initial crack has formed, then, as discussed in detail by Cook and Gordon [18], there is a high shear stress just ahead of the tip of a crack. This is indicated in fig. 12a. Under the influence of this shear stress a crack may propagate along the fibre, as in fig. 12b or c. This certainly happens in fibre-reinforced materials where the matrix provides lines of weakness in the axial direction; similar effects occur within some of our fibres in tensile tests. In the case which we are discussing it would be necessary to understand why axial crack propagation was favoured in fatigue and transverse propagation in static tension. The work of Andrews, discussed below, offers a possible explanation.

The turning of the crack would relieve the shear stress and so the propagation would be in only one direction, as in fig. 12b. In some circumstances, presumably when there is no local bias favouring one direction, the shear stress would initially lead to a crack extending across the end of the initial notch: this would then propagate in both directions (fig. 12c).

Once the crack has turned, the continuing propagation along the fibre would be a result of the stress distribution shown in fig. 13. The shear stress, which is needed to transfer load from the whole cross-section below the crack to the reduced cross-section alongside the crack, would generate the continued crack propagation.

There remains the question of why the cracks initiate and propagate under reduced stress in periodic loading conditions. Andrews [19] has explained fatigue failure in rubber as being due

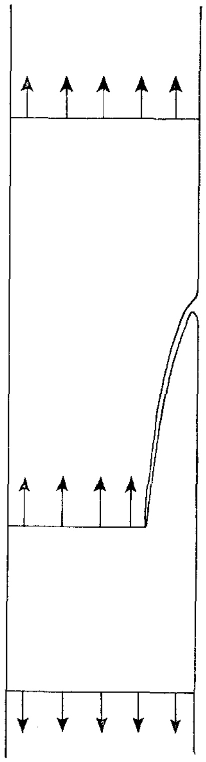

Figure 13 Stress distribution with axial crack growth.

to the effects of hysteresis brought on by strain-induced crystallisation in a natural rubber or by the presence of a filler in a SBR rubber. The argument starts from the statement that under dynamic loading conditions (as contrasted with static loading) the material is continually being stressed and recovering, so that both the ascending and descending parts of the stress-strain curve are involved, whereas in static tests only the ascending part is involved. The mechanical hysteresis gives rise to structural changes which Andrews refers to as a "frozen stress-field". The interaction of the successive cycles of stress with the frozen stress-field may give rise to crack growth by a fatigue mechanism.

It seems to us, however, that hysteresis is not enough, in itself, to explain the effects observed in fibres. In some fibres, as indicated schematically in fig. 14, the recovery, although on a different line, is essentially an elastic recovery, and re-stressing takes one back to the same situation as existed at the end of the first extension. In nylon, the hysteresis in tensile tests is ordinarily purely visco-elastic in origin, and this would not seem to imply a sufficient structural change to explain the fatigue effects.

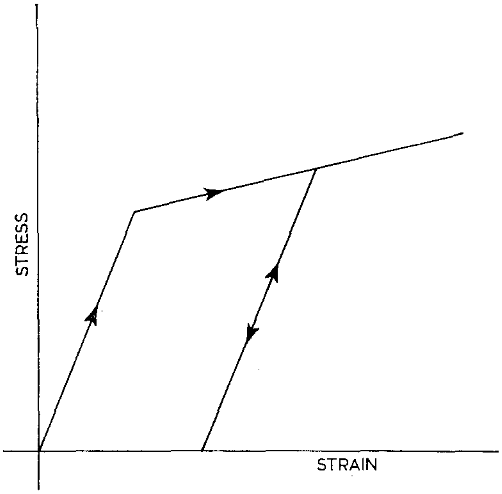

Figure 14 Idealised recovery behaviour for certain fibres.

By contrast, in the material studied by Andrews [15], the hysteresis was associated with more severe structural changes occurring in each cycle of extension and recovery. This gives a clue as to why the fatigue mechanism operates in nylon only when the load is allowed to fall to zero. If some degree of positive tension is continuously applied, it is reasonable to suppose that the deformation can only follow one route of internal change, albeit intermittently; but, if the tension is completely released in each cycle, then a change in internal structure, which may be loosely described as crystal deformation or recrystallisation effects, may occur in each cycle of extension and recovery. The change during the recovery cycle means that the stress in the next extension cycle is acting on a new structure and this can lead to further crack growth.

It also seems likely that a detailed stress analysis, taking account of fibre inhomogeneity, would show that the crack growth is associated with the fact that gross structural changes of the kind variously referred to as strain-bands, kink-bands and the like, occur along lines of high shear stress particularly when the material is in hydrostatic compression. Such regions are likely to be particularly prone to fatigue-failure.

There is one feature of Andrews' analysis which is particularly relevant. He shows that the maximum stress trajectories some distance ahead of the crack, diverge from the line of the crack, and then states:

> "Usually when a crack grows, the whole stress field moves at the same velocity as the tip itself so that maximum stresses are always encountered 'on axis'. Hence a crack usually goes in a straight line. If, for some reason, the stress-distribution travels more slowly than the crack advances, the crack may grow into the stress field and reach a point where it encounters off-axis maximum stress. It will then either fork symmetrically or turn to one side or the other. In the case of natural rubber it appears that the stress distribution is virtually immobile when the crack grows, because of severe hysteresis. The consequence is not only deviation from the axis, but also that the crack can only advance a certain distance before the stress at its tip becomes too low to sustain further fracture; for the crack to continue the overall stress level in the specimen must be raised."

This is a possible explanation of the reason why the cracks in nylon fibres turn or fork. The subsequent behaviour, however, is different: in rubber fatigue, the turning or forking occurs repeatedly and the crack propagates in successive steps across the specimen but in the nylon fibres it continues along the fibre, possibly due to the anisotropy of the structure.

6. Conclusions

A region of true fatigue behaviour has been shown to exist for nylon 66 fibres under cyclic loading conditions. This fatigue mechanism reveals itself in a distinctive fracture morphology and a lower breaking load for the fibre. A necessary requisite for failure by this fatigue mechanism is cycling down to zero loads. When this is the case, the fibres are seen to break when cycled to a maximum load which is less than 70% of their normal breaking load. This is a region in which loadings under steady conditions would not result in failure of the fibre.

These results have strong implications concerning the mechanism of the fatigue failure in such fibres. It seems probable that strain-induced crystallisation arrests the stress-field in the neighbourhood of small faults at the fibre surface and this also has the effect of deflecting the crack from its original axis. Relaxing allows the redistribution of stress around the new position of the crack tip and further crack propagation is possible. Retaining a minimum positive stress maintains the induced crystallisation pattern, redistribution of the stress pattern is not then possible, and the crack is frozen.

The effects of various mean and oscillatory loadings on different types of fibre are being studied in detail; later work will include a study of the effects of frequency of loading and temperature on the fatigue properties of fibres.

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