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Compressive behaviour of Kevlar 49 fibres and composites

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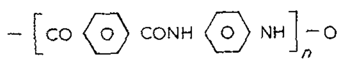
The low compressive strength of Kevlar 49® unidirectional composites cannot be satisfactorily explained in terms of current theories which assume that failure is due to the matrix material. For a given matrix, Kevlar 49 composites are considerably weaker in compression than those based on other comparable high strength, high modulus filaments. Fracture is found to occur before any plastic deformation of the matrix is observed.

This behaviour can be explained in terms of the very low compressive yield strength of the Kevlar 49 fibres themselves. Elastica loop tests show that non-Hookean deformation of the fibres occurs at quite low stresses corresponding to values of the order of those at which fracture takes place in the composite. This deformation is plastic in nature.

Buckled areas on the compression side of the elastica loop can be seen in the optical and scanning electron microscopes. It is suggested that the buckling follows from the separation of microfibrils under compression.

Introduction

Kevlar 49 fibres (formerly designated as PRD-49) are a product of the Du Pont Company. They are described by their producer as being an aromatic polyamide which Carter and Schenk [1] suggest is a poly(*p*-phenylene terephthalamide) with the structure



This material is very interesting as a reinforcing fibre for composite materials. It has a mean tensile strength of 2.75 GN m^{-2}, which is somewhat higher than that of commercially available E-glass fibres, and a mean Young's modulus of 120 GN m^{-2}, which is about 60% higher than for E-glass fibres. When the lower density of Kevlar 49 is taken into account, i.e. 1.45 g cm^{-3} as compared to 2.52 g cm^{-3} for glass and values between 1.8 and 2.1 g cm^{-3} for carbon fibres, then one has a material with very useful specific properties.

An important disadvantage of Kevlar 49 composites is their low compressive strength [2, 3]. Compared with practical values for other high modulus fibre composites, which can be expected to yield compressive strengths of the order of their tensile strengths, unidirectionally oriented Kevlar 49-epoxy resin systems, stressed in compression parallel to the fibres, yield only 15 to 20% of the corresponding tensile strengths. These results are well below those predicted by theories in which the compressive strength of unidirectional composites is considered to be limited by the properties of the resin matrix and indicates that the fibre itself may be exceptionally weak in compression. A comparison of the compressive behaviour of a Kevlar 49 composite with a similar glass fibre material helps to illustrate this, because although glass fibre composites are also weak in compression compared to other fibre reinforced resins, this can still be attributed to the resin matrix.

2. Composite compressive strengths

Well collimated, unidirectionally oriented specimens for testing in pure compression were prepared from E-glass and Kevlar 49 fibres using the Ciba-Geigy epoxy resin system Araldite® XB 2610/HT 972. The mean diameters of both fibre types were about 12 μm. The test itself

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For a mean fibre content of 53.2%, the Kevlas 49 composite yielded a compression strength of 227 MN m^{-2}, while the glass composite with a volume fraction of 50% gave a value of 456 MN m^{-2}, i.e. twice as large as for Kevlar 49.

According to the theory of the compressive strength for unidirectionally oriented compositer described by Rosen [5], the strength should be given by one of the following equations:

$$\sigma_c = \frac{G_m}{(1 - V_f)} \tag{1}$$

$$\sigma_c = 2V_f \cdot \left[\frac{V_f \cdot E_m \cdot E_f}{3(1 - V_f)}\right]^{\frac{1}{2}} \tag{2}$$

where V_f is the fibre volume fraction, G_m is the shear modulus of the resin matrix, E_m is the tensile elastic modulus of the resin matrix and E_f that of the fibres. Equation 1 describes the situation where the fibres buckle in phase and deform the matrix in shear.This is then called the shear mode deformation of the matrix. Equation 2 is for the case where the fibres buckle in anti-phase and produces the extensive mode deformation in the matrix. The compression strength for a given fibre volume fraction will then be given by the lower bound of σ_c predicted by the equations. In our case Equation 1 was found to give the lower bound value. G_m for the matrix resin was calculated from the tensile elastic modulus and Poisson's ratio to be 1.4 GN m^{-2}. Both composites should, according to Equation 1, have a compressive strength of approximately 3.0 GN m^{-2}. It has been reported elsewhere [4] that this theory predicts too high values and that a factor of 0.63 should be included in Equation 1 to allow for the effect of fibre packing. However, in both cases this would still yield compressive strength values which are much too large and for Kevlar 49 almost an order of magnitude larger.

Evidence that glass fibre composites behave differently from high modulus materials has been given by Kossira [6]. He has demonstrated that glass fibre reinforced resin composites generally fail in compression once the supporting resin reaches its compressive elastic limit i.e. once plastic deformation of the resin commences. (Hayashi also proposed this criterion for boron fibre composites [7].) Our measurements with the pure XB 2610/HT 972 resin used in the glass and Kevlar 49 composites gave an elastic limit in compression at 1.4% strain. In the glass fibre composite the applied stress at which this strain would be achieved is 511 MN m^{-2} (for a compression modulus of 36.5 GN m^{-2}). This result is similar to the measured 456 MN m^{-2}. A similar calculation for the Kevlar 49 composite yields an expected compressive strength of 920 MN m^{-2}, i.e. a value some four times as large as that actually observed. Therefore, neither of the

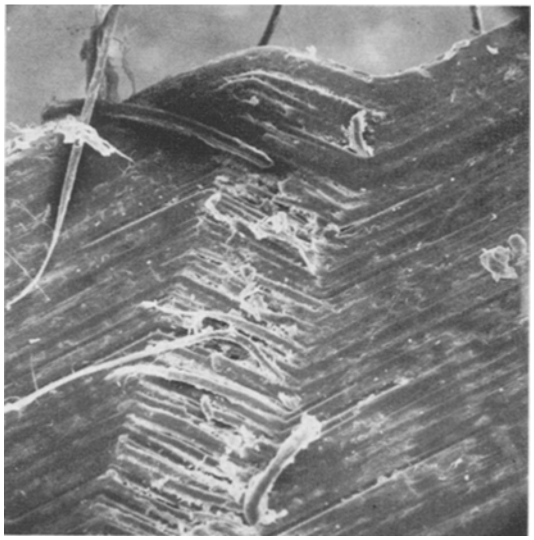

Figure 1 Buckled zone in a Kevlar 49 composite, × 82.

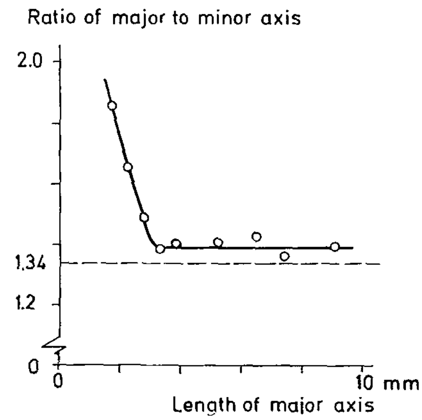

Figure 2 Ratio of major to minor axis of an elastica loop as it is made progressively smaller. This ratio increases sharply when the major axis is reduced below 3 mm.

theories which consider the matrix as the source of failure in compression predict the strength of the Kevlar 49 composite.

It is interesting to observe the type of failure exhibited by the Kevlar 49 composite in compression. A detail from a typical buckled region produced in compression and shown in Fig. 1 exhibits very little fibre fracture. At the edge of the buckled region the fibres bend through a very small radius, but without breaking. This is contrary to experience with glass and carbon fibre composites in which a great deal of fibre fracture is to be seen in the failure area. This is the behaviour which is to be expected from a polymer textile fibre reinforced resin. As Kevlar 49 is a linear polymer which is probably either uncrosslinked or insufficiently so to be completely elastic in compression, then it is a reasonable assumption that it is the fibre component that is weakest in compression. In order to test this assumption fibres have been examined using an elastica loop test.

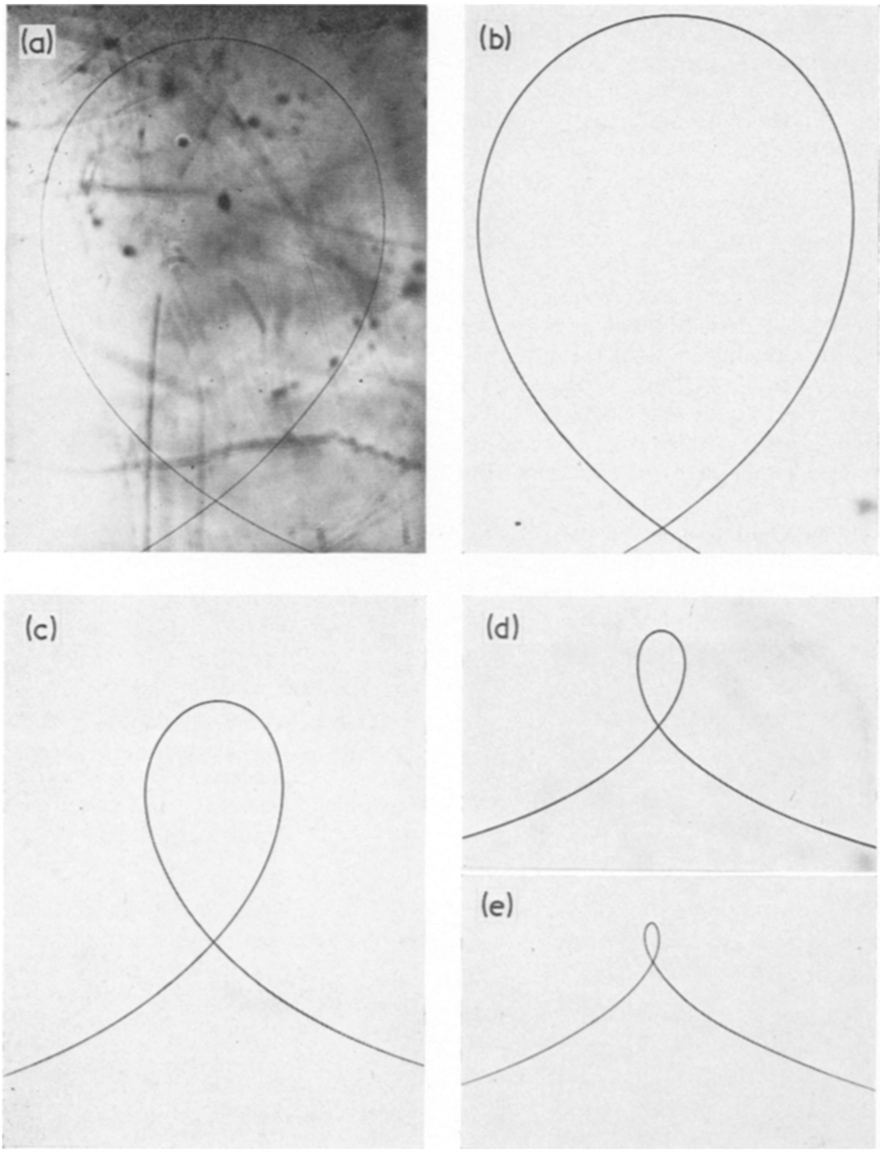

Figure 3 Progressive stages (a) to (e) in the elastica loop test. (a) × 7, (b) to (e) × 21. The shape of the loop in (a) and (b) is the same and becomes progressively narrower in (c) to (e).

3. Elastica tests

Single fibres were subjected to the elastica test devised by Sinclair [8]. Loops with a diameter of about 10 mm were placed in light oil between glass slides spaced about 150 μm apart. The ends were led out at opposite ends of the slides. The size of the loop was reduced in stages by pulling the ends of the fibre, and the major and minor axes were measured accurately at each stage by means of a large graduated projection screen attached to the microscope objective.

In theory the ratio of major to minor axis should stay constant and equal to 1.34 as long as the fibre behaves elastically [9]. We observed the behaviour shown in Fig. 2. The ratio lies between 1.34 and 1.44 until the major axis is reduced to about 3 mm. At this point the loop becomes narrower and the ratio increases rapidly to a value of 2 (Fig. 3). There is a marked decrease in the radius of curvature at the head of the loop, and this indicates that some form of non-Hookean behaviour is taking place there.

The major axis at which this behaviour begins was taken from Fig. 2 and the corresponding radius of curvature calculated using the appropriate formula [8]. Results for ten specimens gave an average radius of curvature of 0.93 ± 0.21 mm. The mean tensile elastic modulus of the fibres was measured on nine individual filaments from the same batch and gave a value of 120 ± 13 GN m^{-2}. The mean fibre diameter was 12.3 ± 0.2 μm, and the bending stress at the calculated radius of curvature was then equal to 790 ± 200 MN m^{-2}, assuming the modulus in bending to be the same as that in tension.

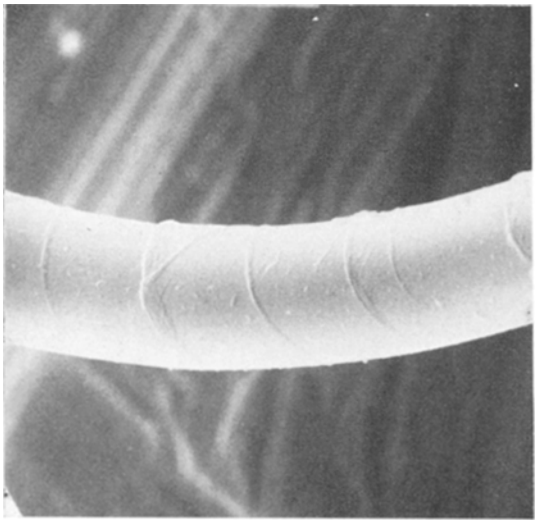

Figure 4 SEM micrograph of buckled areas on the compression surface of a loop, × 1280.

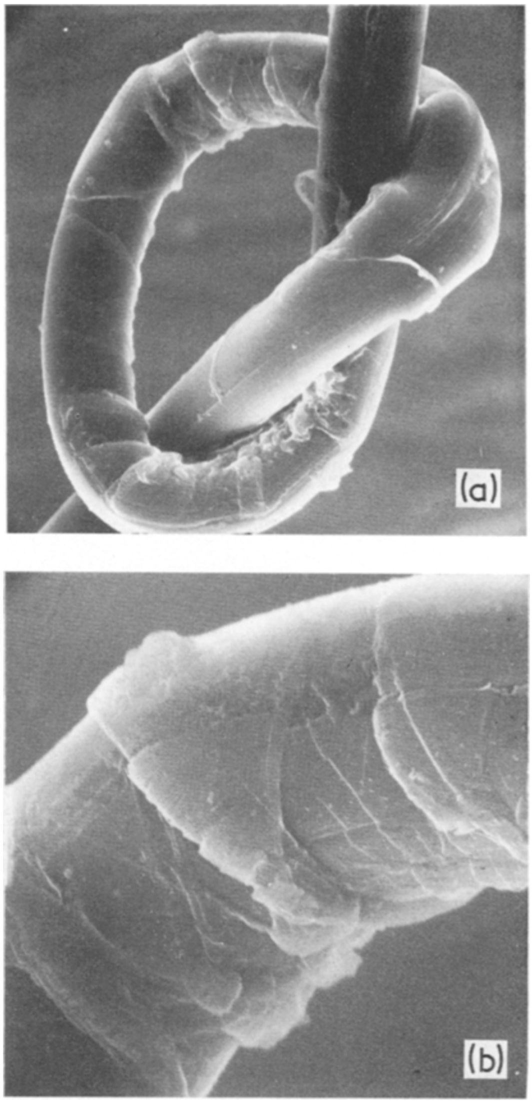

Figure 5 The extreme case. A tight knot is tied in a Kevlar 49 fibre. No tensile fracture occurs, but there is extensive buckling on the inside surfaces, a detail of which is shown in (b). (a) × 810, (b) × 3250.

If we assume that the onset of non-Hookean behaviour in the elastica loop corresponds to the appearance of plastic deformation in the fibre under compression, then the stress at which it first occurs should correspond to the compressive strength of the composite, i.e. for our Kevlar 49 composite containing 53.2% fibres by volume, we should expect a compressive strength of 420 ± 110 MN m^{-2}. This is higher than the actually measured value of 227 MN m^{-2} and might appear to invalidate our initial assumption. We also observed, however, that the first departure from the Hookean elastic behaviour shown by the transition in Figs. 2 and 3 is accompanied by the appearance of buckling on the compression face of the fibre. This is illustrated by the SEM micrograph in Fig. 4, which shows a loop stressed beyond its elastic limit, at which point many buckles have appeared on the compressive side of the loop. That these buckles represent plastic deformation and not non-Hookean elastic deformation as in carbon fibres [9] can be easily demonstrated by simply allowing the loop to relax. This shows the fibre to be permanently kinked where the deformation has occurred and, in fact, the degree of kinking is very large even for those fibres which have only been stressed to the first point of non-elastic distortion. For very large loop stresses the permanent nature of the deformation is apparent from observing the buckles themselves, as can be seen in the SEM-micrograph in Fig. 5.

The higher compressive strength calculated from the yield stress of the elastica loop could have several origins. The first is the normal comparison between bending and tensile or compressive tests. The calculated compressive stress in bending is the maximum present at the outermost surface of the fibre. The volume subjected to this stress is vanishingly small. Buckling would not be expected until a certain portion of the fibre cross-section is subjected to the necessary stress. In the composite, in pure compression, the entire cross-section of the fibre is under the same stress. This would be accentuated if, as is apparent in some micrographs, the fibre has a strong skin. We should then be measuring the yield stress of this. In the composite compression test the entire fibre volume will be stressed and so, if the fibre is weaker in the interior, this will lead to a lower compressive strength.

A further possible explanation would be that of the statistical nature of the strength of materials. In the elastica test we are testing a very small randomly selected volume which implies a small probability of the occurrence of a flaw in the test gauge length. A flaw might take the form of regions of lower fibre preferred orientation, cavities or inclusions. All of which could lead to a lower yield stress and have a considerably greater probability of appearing in the bulk composite test piece.

4. Discussion

The poor stability of Kevlar 49 in compression emphasizes an intrinsic feature of the structure of textile fibres, which separates them completely from fibres such as carbon and boron. This is that the basic structural units, the polymer chain molecules or probably aggregates of these called "fibrils", are not elastic in compression. The high modulus and strength in tension derives from the very high preferred orientation of the molecules, which are in an extended state, oriented parallel to the fibre axis. Therefore, tensile stresses are carried by the covalent bonds of the carbon backbone. In compression the stability of the fibre will be controlled by hydrogen bonding, van der Waal's forces and possibly to some extent by inter-chain cross-links. But this represents a very limited restraint on the chain molecules, which relax viscously with applied stress. (From Fig. 2 it can be seen that the ratio of the major to minor axis is already above 1.34 at minimal stresses indicating the possibility of plastic flow before the buckling occurs.)

Kevlar 49 fibres exhibit a tendency to fibrillate (see Fig. 6) which indicates that they probably possess a microfibrillar structure, as do many highly oriented textile fibres. This would suggest that the deformation in compression might proceed by the mutual separation of the fibrils under the compression surface. Optical observations of fibre loops in transmitted polarized light show the existence of pairs of extinction bands where the buckles occur. These can be seen from the micrograph of a loop in Fig. 7.

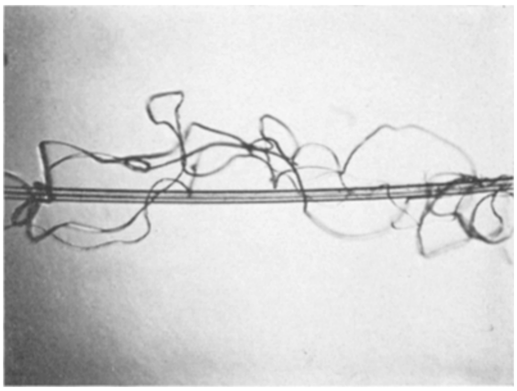

Figure 6 Small fibrils attached to an otherwise untouched section of Kevlar 49 fibre, × 125.

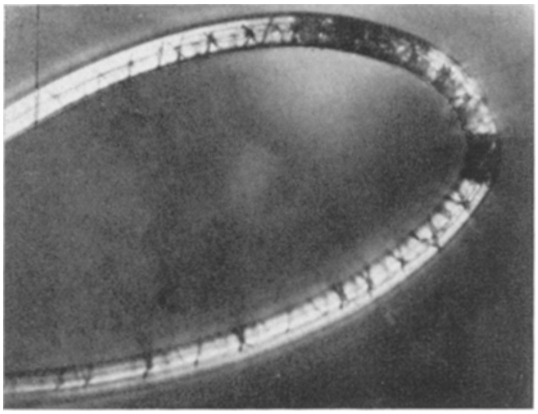

Figure 7 Optical micrograph of a small elastica loop, taken in polarized light to show the V-shaped buckled areas, × 340.

These "V"-shaped features result from the loss of ordered structure and might be described as kink- or slip-bands. They could result from the mutual separation of the microfibrils leading to boundaries on each side of the buckled region which are permanently kinked due to plastic deformation. This is in contrast to the mechanism proposed by Williams *et al.* [10] for carbon fibres, in which the defibrillation is considered to be elastically recoverable. We have not actually observed fibrils in the buckled regions of the Kevlar 49 fibres but this may be because of the presence of a surface skin.

5. Conclusion

The low compressive strength of Kevlar 49 composites is due to compressive failure in the fibres themselves, and not to the resin or to the interfacial bond. Improvement of this strength must, therefore, be concentrated on the fibre structure.

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