retractive force of the highly-crazed HIPS is controlled by energy effects rather than entropy. The environmental dependency of the time-independent stress suggests that the retractive force results from surface-energy effects, as in the case of PE, if it is assumed that the silicone oil lowers the surface energy of the fibrils.

Pre-crazed HIPS specimens could be reversibly strained to over 40% and thus exhibited "hard elastic" behaviour. The stress–strain and stress–relaxation behaviour of the highly-crazed HIPS showed the same features as those of "hard elastic" PE, verifying the prediction of the model based on the geometrical structure of the strained state, and indicating that the retractive force is generated by a surface-energy effect in the craze fibrils. Not only does this lend support to the model proposed by Miles *et al.* [4], it also demonstrates the possibility of a new type of material: a "hard elastic" glass.

References

1. Canadian Celanese Ltd, B. P. 962 231 (1 July, 1964).
2. E. S. CLARK, "Structure and Properties of Polymer Films", edited by R. W. Lenz and R. S. Stein, (Plenum, New York, 1973).
3. B. S. SPRAGUE, *J. Macromol. Sci. Phys.* **8** (1973) 157.
4. M. J. MILES, J. PETERMANN and H. GLEITER, *ibid* **12** (1976) 549.
5. S. WELLINGHOFF and E. BAER, *ibid* **11** (1975) 367.
6. P. BEAHAN, M. BEVIS and D. HULL, *Phil. Mag.* **24** (1971) 1267.
7. R. P. KAMBOUR, *Polymer Eng. Sci.* **8** (1968) 281.

Received 31 July
and accepted 20 September 1978.

M. J. MILES
E. BAER
Department of Macromolecular Science,
Case Western Reserve University,
Cleveland, Ohio, USA

The toughness of fibre composites with inhomogeneous fibre packing

A recent paper by [4] refers to the possible effect of fibre bunching on the fracture toughness of glass-fibre and carbon-fibre reinforced plastics. This effect was first postulated and demonstrated for brittle fibre–ductile matrix composites [1, 2] from a consideration of the existing theory of the toughness of such composites [3]. The effect of fibre bunching in such composites is to increase the work-to-fracture in an unnotched Charpy impact test by a factor of two or three. This increased energy absorbtion is postulated to be due basically to the non-linear variation of absorbed energy with fibre volume fraction which is such that regions of low fibre-volume fraction have a disproportionately high work-to-fracture. The effect of fibre bunching is to produce such regions in the composite and their effect outweighs that of the regions of high fibre-volume fraction.

In the case of brittle fibre–brittle matrix composites the energy absorption mechanisms are different and ostensibly one would not expect fibre bunching to have the same effect. There have, however, been suggestions that fibre bunching is

TABLE I Relationship between number of fibres in a group and the work of fracture of the material for a material composed of groups of fibres spaced 50 mm apart along the line of the crack path

Number of fibres in group, n	Work of fracture of the material W (J m^{-2})
1	110
2	100
3	125
4	300
5	400

an effective method of increasing the toughness of such composites since the fibre bundles can be regarded as single fibres of large diameter and there are indications that the toughness of composites increases with increasing fibre diameter [1, 3]. The present author (unpublished work) has seen indications of a beneficial effect due to increasing the modulation of fibre-volume fraction in laminates of carbon-fibre reinforced plastic. Harris and Ankara [4] have looked for the effect in fibre composites and their data are summarized in Table I. They conclude that since an increase in n, the number of fibres per group, from 1 to 5 (and hence an increase of fibre-volume fraction of a factor of five) gives only a four-fold increase in work-to-fracture then the effect of fibre bunching is slightly deleterious.

Their data can, however, be interpreted in an alternative manner. If fibre bunching were to have no effect on toughness we would have $W \propto n$. It can be seen, however, that for $n \geqslant 3$ the effect of n on work-to-fracture is $W \propto 4/3\,n$, indicating a beneficial effect due to fibre bunching but with a threshold value of three fibres per group before this beneficial effect begins. Calculations from data in the paper show that the fibre volume fraction for this threshold is only 0.2% and the threshold phenomenon can, therefore, be ignored for practical composites.

In summary, therefore, the data of Harris and Ankara tend to support the existing suggestions that fibre bunching can increase the fracture toughness of brittle fibre–brittle matrix composites as well as of brittle fibre–ductile matrix composites.

References

1. R. E. COOPER, *J. Mech. Phys. Solids* **18** (1970) 179.
2. *Idem*, British Patent no. 1 289 823 (1972).
3. G. A. COOPER and A. KELLY, *J. Mech. Phys. Solids* **15** (1967) 279.
4. B. HARRIS and A. O. ANKARA, *Proc. Roy. Soc. Lond. A* **359** (1978) 229.

Received 31 July and accepted 3 November 1978.

R. E. COOPER
*Metallurgy Division,
AWRE,
Aldermaston,
Berks, UK*

A fracture energy spectrometer for polymers

This letter describes a simple technique for measuring the fracture energy spectrum of a polymer by slowly tearing a strip of the material while continually increasing its temperature. Plotting the tear force against the temperature yields the fracture energy spectrum of the polymer. Both experimental and theoretical studies demonstrate that this spectrum reflects the mechanical relaxation behaviour of the material.

The experimental system closely follows the trouser leg geometry used to study crack growth in rubber by Rivlin and Thomas [1]. In this configuration, a polymer strip is torn at constant speed on a testing machine and the tearing force is measured. Thomas and his colleagues later extended the method to look at rubbers over wide ranges of rate and temperature, allowing a spectrum of tear energy to be plotted [2].

Our only modification of this apparatus, shown in Fig. 1, was the incorporation of deep fissures cut along the sides of the polymer sample (compression moulded, 1 mm thick, 20 mm wide) by means of a tool containing two steel blades set 0.22 mm apart. These cuts were necessary for three reasons:

(1) to allow tough, cold-drawing polymers to be tested; low-density polyethylene, for example, will not tear unless notched in this way;

(2) to guide the crack along the desired path; the tear will only go straight when deep cuts are made;

(3) to allow adjustment of the tearing force to suit the bending of the legs of the specimen; with brittle materials, such as polyvinylchloride at low temperatures, deeper cuts are necessary to prevent excessive bending and consequent cracking of the legs.

This tearing method has a number of fundamental advantages when compared with the conventional tensile or impact tests which have previously been used, not altogether successfully, in attempts to relate ultimate properties to relaxation behaviour [3–6]. In the first place, the tearing test is continuous rather than catastrophic so that a single sample can be used over the complete temperature range. This avoids the inaccuracies of different samples for each data point and the inconvenience of inserting a multiplicity of specimens into the controlled temperature cabinet. Secondly, the crack speed is held closely at a constant value in the tearing geometry. This factor is important because fracture energy is often a strong function of crack speed, and tests which allow speed to vary (such as impact and tensile tests) usually give irreproducible results. Last, but not least, the theory of the tear test is much simpler than that of tensile or flex