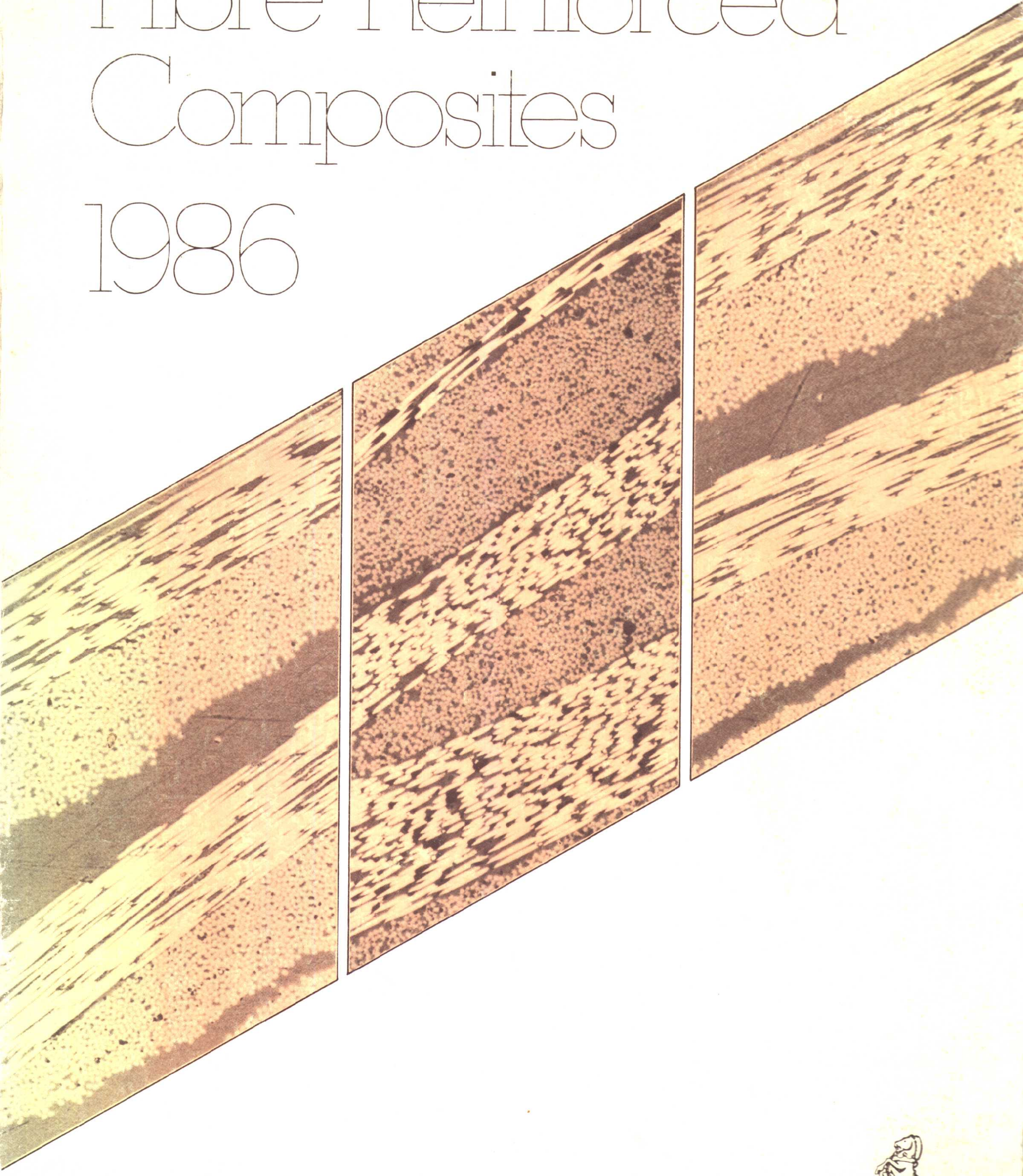
# Fibre Reinforced Composites 1986



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# *FIBRE REINFORCED COMPOSITES 1986*

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# CONTENTS

# Thermoplastic composites in woven fabric form

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SYNOPSIS : For thermoplastic composites we can identify at least three woven product forms based on: woven impregnated single tows, directly impregnated woven fabrics, and interpenetrated fibre systems. These complement and extend the usefulness of the archetype form of preimpregnated tape based on continuous unidirectional fibres. Each of those woven product forms is itself capable of an indefinite diversity. In this paper we seek to define the basic property profile of such woven composites in a simple biaxial structure and to relate those properties to the microstructure of the composite and its method of manufacture.

## 1 INTRODUCTION

The development of Aromatic Polymer Composite (APC) based on carbon fibre reinforced polyether etherketone (PEEK) has concentrated on the archetype product - a high loading of continuous collimated fibres wetted by resin to form a thin preimpregnated tape. In this development three criteria have been key elements of our materials philosophy : first, the product must be made in a continuous process; second, the fibres should, as far as possible, be completely wetted by the resin phase; and finally, the product chemistry, morphology and structure should be immutable under normal processing conditions.

With the potential advantages of composites based on thermoplastics matrices now firmly established (1,2,3) and considerable experience with processing of such materials now available (4), we seek to make a full range of material forms available to the designer. In particular, with the uniaxial product, APC-2, currently made in widths up to 220 mm we appreciate the desirability of a "broadgoods" product based on woven fabric. In seeking a route to a woven "broadgoods" product we wish to retain all the virtues of APC-2 and full compatibility with that product in respect of processing technology and product performance.

Such materials, sometimes described as "Textile Structural Composites" (5) are well known in the field of thermoset composites representing at present about one half of the total market, and their mechanical performance has recently been subjected to fundamental scientific analysis (5,6). The field of "Textile Composites" ultimately includes three dimensionally woven, knitted and braided structures. In this paper we shall treat only of simple two dimensional fabric forms, in comparison with cross-plied laminates. All product forms evaluated here are based on similar grades of high strength carbon fibre (fibre modulus 230 GPa fibre strength 3600 MPa) at approximately 60% by volume of fibre.

## 2 QUALITATIVE COMPARISON BETWEEN CROSS PLIED LAMINATES AND WOVEN FABRIC FORMS

In making a qualitative comparison between structures built up from laminated uniaxial preimpregnated tapes and from woven fabric the latter form can be identified as having several disadvantages (7):

(i) They are usually based on more expensive 3000 filament tows to ensure a thin uniform sheet.

(ii) They involve an additional manufacturing stage - weaving.

(iii) Because the fibres are necessarily kinked

the product cannot be expected to yield its full potential strength (6).

and (iv) Although it is possible to produce 0/45° weaves as well as 0/90, the options for designed anisotropy are reduced.

These are powerful economic and design factors which require equally powerful technological and pragmatic arguments to be countered.

A preference for a woven cloth reinforcement usually cites one or more of the following advantages.

(i) Enhanced product toughness in respect of delamination processes - a product based on woven cloth has fewer layers (8) and the kinking of the fibres tends to deflect interlaminar cracking in such structures to give a higher fracture toughness;

(ii) The ability to make thin, single ply, laminates with balanced properties - a single ply of woven fabric may be as thick as two plies of collimated fibre but you need four plies of uniaxial product to balance a 0/90 lay up.

(iii) The close spacing of the fibre tows. The nature of the weave contrains lateral movement and 'fibre wash' so that enhanced thickness uniformity is possible.

(iv) The convenience of handling a "broad-goods" product is a factor which should not be under-estimated. Since each ply is inspected during lay up, inspect-ion time is effectively halved if you lay two plies at once.

(v) An associated aspect of handling is that any tendéncy to splitting is suppressed - with woven product there is no weak transverse direction.

(vi) The absence of a weak transverse direction ply may reduce crack initi-ation or rapidly arrest such cracks at the next fibre cross over with potential for enhanced fatigue life and damage tolerance.

(vii) Because the fibres are slightly crimped by the weave in a controlled manner, mis-handling during fabrication does not result in uncontrolled fibre wrinkling.

(viii) The drapeability of certain weaves is a special factor enhancing certain processing operations.

It should be emphasised that most advocates of woven fabric would wish to use selective reinforcement with uniaxial product in combina-tion with the weave so that woven products are seen as accessory to, rather than replacement of, uniaxial product forms.

## 3 THERMOPLASTIC WOVEN FABRIC PRODUCT FORMS

We can identify four distinct forms for a thermoplastic product based on a woven fabric. In principle all such forms should be capable of giving comparable mechanical performance as finished structures, they differ in their method of manufacture and the processes by which they can be formed into shapes.

### 3.1 Film Stacked Composite Materials

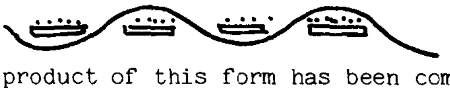
For many years film stacking technology (9,10, 11) has been widely used in the preparation of thermoplastic composites, and this technique has been most conveniently used with the rein-forcement in woven fabric form. The preferred fabrication technology involves presizing the fabric with a thermoplastic resin from solution and then sandwiching such layers between layers of film and applying pressure until the laminate is fully consolidated. However, as MacMahon (3) points out the pressure not only forces the resin into the fibre bed but also forces the fibres together. This effect was also observed by Post and Van Dreumel (12). The microsection of such mouldings shows the reinforcement and resin in distinctly striated form - Figure 1.

Film stacked composites are either directly formed into their final shape or may be consolidated flat and subsequently reformed using the inherent thermoplasticity of the resin (12). Consolidation is usually carried out at one hundred atmospheres for about two hours in the melt.

### 3.2 Interpenetration of Reinforcement Fibres with Resin in Film, Fibre or Powder Form

A second approach to producing a woven fabric form is to intermingle or interweave the reinforcement fibres with the resin in the form of film, fibre or powder. These approaches can provide highly drapeable product forms which can be conveniently shaped at ambient temperature before consolidating them by melting.

The product form which follows most directly from film stacking involves co-weaving a tow of carbon fibre with a layer of slit film. Such a product typically has the form



and a product of this form has been commercially developed (13).

An alternative product form replaces the resin film with resin monofilaments which are usually large in diameter by comparison with the reinforcement fibre (14). In both this, and the previous case it will be clear that there remains a considerable amount of work to do to achieve a fully wetted composite although not quite as much as is the case with film stacking.

The principle of fabricating reinforced composites from mixtures of resin and reinforcement fibres (15) includes the hybridisation of resin and reinforcement fibres of comparable diameter so that, in principle, a fully consolidated product form can be achieved by melting alone without the need for further work. However, a simple statistical model reveals that, even if the resin and reinforce-ment fibres are the same diameter and randomly dispersed, a 50/50 mixture will only produce 50% wetting of the reinforcement fibres leaving typically five fibres in a bundle. This is an excellent starting point for complete wetting, and one which may even be improved by invoking a positive dispersion mechanism, but it is a starting point at which it is difficult to arrive with thermoplastic fibres, and, having arrived there, if the resin fibres are oriented (as such small fibres will usually be), secondary phenomena may complex the melting process. These are formidable obstacles to overcome to which a satisfactory solution is currently being sought.

A further variant replaces the resin fibre by resin in powdered form (16) and sheathes this product in a "sausage skin" of the same, or different, resin to provide a highly flexible "Fibre Impregnated Thermo-plastic" (FIT) (17). As with the 'hybridisation' of resin and reinforcement fibres this route requires that the resin particles be very finely divided in order to achieve a high level of impregnation.

We have used the interpenetration route to produce a soft fabric capable of being moulded by hand into complex forms prior to consolidation. However the quality of wetting obtained depends substantially on the pressure and thermal history of the consolidation stage : a satisfactory quality of wetting - Figure 2 (a) - is achieved after one hour at pressures of forty atmospheres.

### 3.3 Directly Impregnated Woven Fabric

The option of directly impregnating a woven fabric has the attraction of separating the stage of weaving from that of impregnation so allowing the weaver the full freedom of his art in the construction of optimised fabrics and providing a readily recognised fabric to the designer. However the product, once impregnated with thermoplastic, is boardy and the inherent drape characteristics of the weave are only revealed when the resin is melted.

This product, based on carbon fibre reinforced polyether etherketone, has been described in detail in an earlier publication (79). As a fully preimpregnated product total consolidation is achieved under minimum moulding conditions : the recommended conditions for full consolidation (fifteen minutes at 380°C and ten atmospheres) yield a good uniform microstructure - Figure 3.

### 3.4 Woven Uniaxial Tapes

Uniaxial tapes such as APC-2 based on continuous collimated fibre, can be slit to convenient width and woven or braided into a fabric form. However, the uniformity in thickness, width and a real weight of such slit tape falls some way short of optimum and as a feedstock it is much more desirable to use an impregnated single tow product of controlled width, thickness and fibre content. Research quantities of such material based on 6,000 and 12,000 filament tows are now available and have been braided and woven into fabric forms.

Such narrow tapes have an important role to play in the development of processing technology such as filament winding, and, they can also be woven (18) or braided (19) into structures. Although the tapes themselves are fully impregnated they are thin and flexible so that the weave structure, which may be of carpet width, possesses a measure of dry drapeability which is especially appropriate for large area aerofoil sections. Naturally, since the tapes are impregnated to the quality of APC-2, structures consolidated from the woven tapes demonstrate excellent fibre distribution after short moulding process (fifteen minutes at 380°C and ten atmospheres) - Figure 4.

### 3.5 Cross-plied Laminate Structures

For completeness, and as control, we include cross-plied laminate structures consolidated from APC-2 preimpregnated tape - Figure 5.

## 4 COMPARATIVE MECHANICAL PERFORMANCE OF DIFFERENT PRODUCT FORMS

The properties of APC-2 laminate structures have received exhaustive evaluation (20). In Table 1 we compare some of the key mechanical properties for the various ways of producing a balanced (0/90) laminate structure. In this section we relate those properties to the quality of fibre dispersion as judged from the micrographs of Figures 1 - 5.

The reduced tensile strength of the woven structure is typical of the observations made on qualitively similar comparisons for cross-plied laminates and woven cloth structures impregnated with epoxy resins (8). This reduction is usually assumed to result from stress concentrations at the weave cross over combined with the departures from optimum fibre alignment at such points (5,6).

The maintenance of compression strength in the woven fabric composite is particularly satisfying - in such systems the natural kinking of the fibres could have been expected to produce low results.

There is some evidence of reduced interlaminar shear strength (evidenced by the short beam shear flexure test) in those panels made by interpenetrated fibres or film stacking where the uniformity of fibre distribution is reduced. It is unclear whether this is associated with premature yielding in the thicker resin layers or weakness due to incomplete wetting of the fibre bed. There is no loss of property associated with the homogeneous microstructure of woven single tow products or directly impregnated woven fabrics.

The single most significant difference is in the impact resistance where the "Interpenetrated Fibres" and "Film Stacked" systems offer dramatically less energy adsorption than cross-plied laminates, woven single tow products or directly impregnated woven fabrics. This is not associated with the degree of wetting those systems since comparable composites with a reduced level of fibre wetting can be shown to give increased energy absorption under impact (21), further, all other things being equal, structures which delaminate readily also give higher energy absorption to failure (22). An alternative explanation is that consolidation of the interpenetrated fibre systems and film stacked composites involves applying work to the system before the fibres are fully wetted and this involves abrading fibres against one another before they are protected. We have some evidence that such work can damage the fibres and suggest that it is such damage which is responsible for reducing the impact resistance of the product.

## 5 COMPARATIVE FORMING TECHNOLOGIES

One of the more remarkable features of continuous fibre reinforced thermoplastic is the facility with which inextensible uniaxial tape can be formed into complex double curvature shapes

(22). The same processing strategies can be utilised with woven fabric forms. Highly complex shapes are most conveniently moulded from interpenetrated fibre systems taking full advantage of the ease with which such fabrics can be draped at room temperature. Particular problems which may be encountered with such systems include shrinkage of the resin when it melts which may lead to local distortion of the reinforcing fibres.

The directly impregnated woven fabric is best suited for thin (1 mm) skin structures of modest curvature. Because of the very high number of fibre tow intersections in this product such thin sheets have an excellent uniform thickness, however, such intersections are also the key areas where excess resin congregates and is squeezed out of the structure and this is particularly noticeable where tight radii of curvature (10 mm) are used. It is also a particularly useful feedstock form for processes such as pultrusion and roll forming, in conjunction with the uniaxial tape product where some degree of transverse strength must be incorporated without undertaking a complex lay up.

## 6 CONCLUSIONS : COMPLEMENTARY PRODUCT FORMS

With thermoplastic composites we have at least four complementary product forms :

Uniaxial tape will remain the standard form where the greatest possible mechanical property and product definition are required and especially where the full benefits of anisotropic design are to be incorporated.

Woven uniaxial tape will become a standard broadgoods product especially suitable for very large area mouldings with gentle double curvature.

Interpenetrated fibres will be a class of materials especially suited to complex shapes where "hand lay up" into the tool will still be essential and where long moulding times will be acceptable. Because such components are likely to be relatively lightly loaded some compromise in mechanical performance in comparison with totally wetted, well dispersed, fibres will be acceptable.

Directly impregnated woven fabrics will initially be most widely used for thin skin structures and as a feedstock for precision forming technologies such as roll forming. This product form is also likely to be widely used in conjunction with continuous collimated fibres in continuous lamination or pultrusion processes.

All these product forms - Figure 6 - will be mutually compatible, so that complete thermoplastic structures may frequently contain elements formed from different "prepreg" forms, and this diversity will encourage the development of novel fabrication technology.

## 7 ACKNOWLEDGEMENTS

We are indebted to N Hayman who prepared the interpenetrated fibre systems, to D C Leach who supervised the mechanical evaluation and to D Coverdale who carried out the microscopy studies reported here.

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Table 1 Mechanical properties at 23° C*

| Microstructure | Most Uniform | | | Least Uniform | |
|---|---|---|---|---|---|
| Test / Structure | Cross Plied Laminate 3.5 | Woven** Single Tow 3.4 | Impregnated Woven Fabric 3.3 | Interpenetrated Fibres 3.2 | Film Stacked 3.1 |
| **Tension** | | | | | |
| Modulus GPa | 72 | 60 | 70 | | |
| Strength MPa | 1100 | 772 | 769 | | |
| **Compression(1)** | | | | | |
| Strength MPa | 680 | 580 | 694 | | |
| **Flexure** | | | | | |
| Modulus GPa | 62 | 50 | 61 | 65 | 57 |
| Strength MPa | 907 | 929 | 1052 | 782 | 680 |
| Shear MPa | 76 | 68 | 80 | 60 | 67 |
| **Impact(2)** | | | | | |
| Initiation Energy J | 5.9 | 8.5 | 7.5 | 3.6 | 3.4 |
| Failure Energy J | 22.6 | 22.8 | 29 | 12.7 | 9.3 |
| **Interlaminar Fracture Toughness** (3) | | | | | |
| $J / m^3$ | 2400 | | 2100 | | |

1) ITRII Compression Test

2) Instrumented Falling Weight Impact Test on Panels 2 mm Thick

3) Double Cantilever Beam Method

*All measurements are averaged results of measurements taken in the two directions of the balanced cross plied structure. Such averaging is especially necessary for flexure studies on 0,90 laminates where the surface ply orientation dominates stiffness. The co-efficient of variation on impact measurements is typically 10% that on stiffness and strength is typically 5%. A more detailed comparison of certain of these measurement is available (7).

**The volume fraction of fibre in this composite was measured at 50% compared with other systems which was 60%.

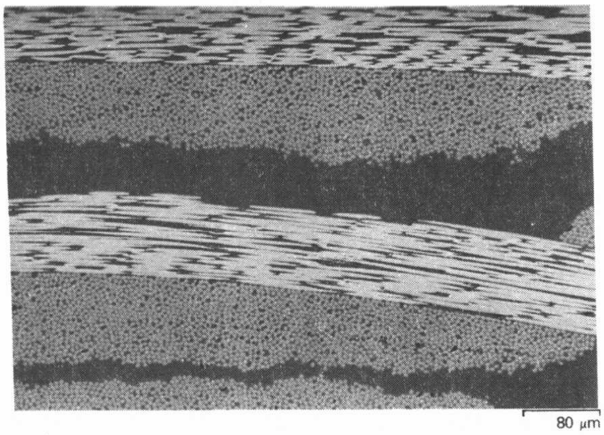


Fig 1 Film stacked composite presized fibre

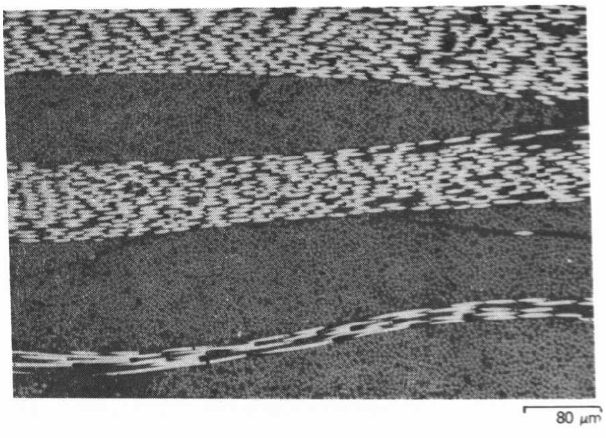


Fig 2 Interpenetrated fibre composites

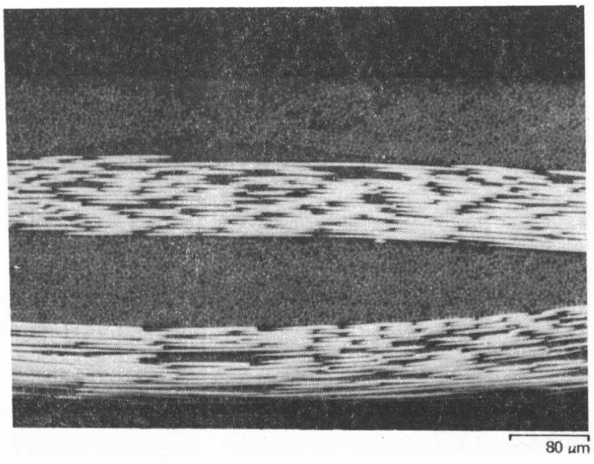


Fig 3 Direct impregnated woven fibre

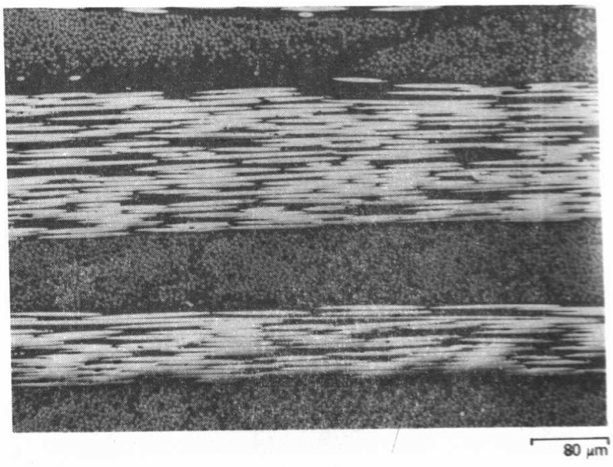


Fig 4 Woven single tow

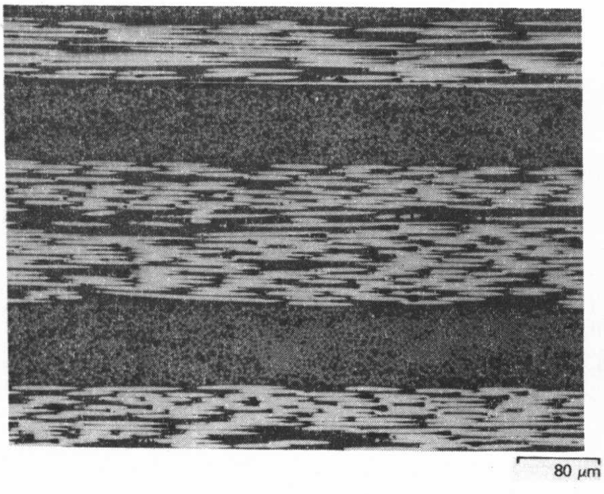


Fig 5 Cross-plied laminate

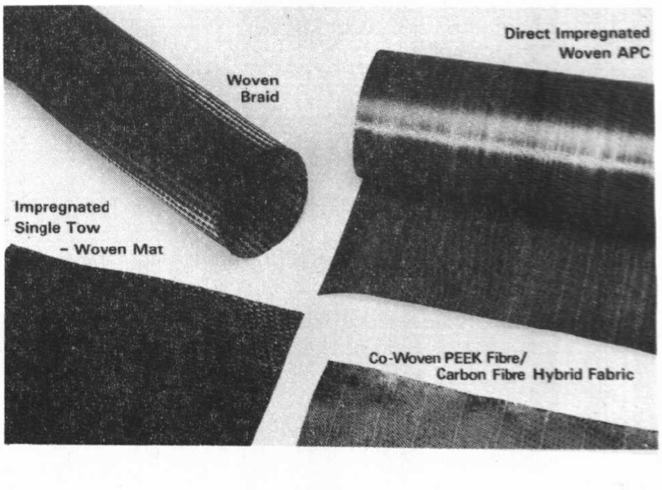


Fig 6 Woven products

C34/86

# The preparation and properties of ultra high modulus polyethylene

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SYNOPSIS Comparative data have been obtained for the behaviour of epoxy composites where the reinforcing phase is ultra high modulus polyethylene (UHMPE), carbon, glass or Kevlar fibres, and for hybrid composites incorporating UHMPE and carbon or glass fibres. It has been found that the combination of high strength and high extension to break of the UHMPE fibres leads to high energy absorption of the UHMPE composites. The most useful application of the UHMPE fibres may, however, be in hybrid composites containing glass or carbon fibre. In this way the good compressive properties of glass composites, and the exceptional stiffness and strength of carbon fibre composites can be combined with the high energy absorption and non-shattering capabilities of UHMPE composites.

## 1 INTRODUCTION

The research described in this paper forms part of an extensive ongoing research programme at Leeds University on highly oriented polymers and fibre-reinforced composites. The present paper is concerned with the behaviour of epoxy composites incorporating ultra high modulus polyethylene (UHMPE) fibres as the reinforcing phase. Basic research at Leeds University in the period 1970-5 established the guidelines for the production of UHMPE fibres by the melt spinning and drawing route [1-4]. A small scale pilot plant was put into operation for the production of kgm quantities of multifilament yarns and monofilaments. The materials were used to make the first UHMPE composites described in this paper, and to find methods for improving fibre-resin adhesion.

More recently, the Leeds technology has been licenced by the British Technology Group to the Celanese Fibres Company USA, so that larger quantities of fibre have become available for development applications trials. The second stage of research on UHMPE composites was therefore based on the commercial route of lamination of pre-pregs in either a compression moulding press or an autoclave. At this stage hybrid composites were also produced with a sandwich structure of glass or carbon fibre layers enclosed symmetrically between UHMPE fibre layers.

In this paper the properties of the UHMPE fibres will be discussed, followed by a brief account of the preparation of the composites and a more detailed consideration of the properties of the composites, especially with regard to a comparison of their behaviour with those of composites incorporating glass, carbon and Kevlar fibres.

## 2 ULTRA HIGH MODULUS POLYETHYLENE FIBRES

### 2.1 Comparison of fibre properties

In Table 1 the principal mechanical characteristics of UHMPE fibres presently available from the melt spinning and drawing route are compared with those of carbon, glass and Kevlar fibres. The properties quoted for the UHMPE fibres are conservative, to reflect those which can readily be achieved in practice at economical production rates. Fibres with higher tensile strengths (~ 2.5 GPa) and somewhat higher tensile moduli (~ 100 GPa) can be obtained by gel spinning[5], but these involve a costly solvent recovery process, and are therefore intrinsically more expensive to produce.

In terms of absolute mechanical properties UHMPE fibres are comparable in stiffness to glass fibre, but less stiff and less strong than carbon, glass or Kevlar fibres. The specific properties of UHMPE fibres are, however, more nearly comparable to the other fibres, although the specific modulus of carbon fibres is very much higher than the specific modulus of UHMPE fibres or the other commercial fibres. It is clear from this comparison that UHMPE fibres will challenge both glass and Kevlar fibres in terms of specific properties. Moreover, UHMPE fibres have a significantly greater extension to break than the other fibres. This suggests that UHMPE fibres are likely to be useful in situations where the fracture energy to failure is important i.e. in impact and other ballistic applications. It will be shown that the impact behaviour of the UHMPE composites, and their general damage tolerance reflects the high extensibility and comparatively high strength of the fibres.

## 2.2 Strength, Creep and Strain Rate Sensitivity

A very important feature of UHMPE fibres which contrasts with the behaviour of the other fibres in Table 1 is their high strain-rate sensitivity[3]. At high strain rates even low molecular weight fibres of comparatively low draw ratio (~ 25) can show tensile strengths of nearly 1.5 GPa, and high molecular weight fibres of much high draw ratio (~ 50) show strengths of at least 2.5 GPa. This is clearly of outstanding interest, especially when associated with a breaking extensibility of 4-5%.

At low strain rates, on the other hand, creep occurs and the effective strengths of the UHMPE fibres falls, depending on molecular weight, to the range 0.1 - 0.5 GPa[7]. The melt spun and drawn fibres can be improved by cross-linking using electron-beam irradiation so that these fibres (but not the gel spun fibres) can retain a substantial proportion of their high strain rate strengths[8]. The present position is that the long term strengths of the UHMPE fibres, irrespective of their origin, is in the range 0.3-0.5 GPa, which should be borne in mind if the UHMPE fibre composites are being considered for permanent load-bearing applications.

# 3 PREPARATION OF FIBRE COMPOSITES

## 3.1 Fibre/resin Adhesion

It was appreciated that due to the chemical inertness of polyethylene, and the absence of any polar groups in the molecular chain, there was likely to be a poor bond between the UHMPE fibres and conventional resins, in the absence of some special surface treatment of the fibres. A thorough study was therefore undertaken of the adhesion of the fibres to both epoxy and polyester resins, with particular reference to the effects of speculative surface treatments[9].

These adhesion studies were made easier by the fact that UHMPE fibres can be produced with identical structures in a very wide range of filament diameters. In fact, by varying the process from tensile drawing to die-drawing, products with diameters from ~ 20μ up to several cms can be produced at commercially acceptable production rates. For the adhesion studies it was most convenient to determine the force required to pull one end of a monofilament of diameter 0.26 - 0.55 mm out of a thin disc of resin. The experimental arrangement is shown in Figure 1. A commercial epoxy resin (Ciba-Geigy XD 927), devised for high strength composite structures, was used for most of the comparative tests of surface treatment. This resin is cured at room temperature for ~ 16 hr and post cured for 5 hr at 80°C in an air oven. The pull-out adhesion strength $\sigma_p$ was defined as the failure load F divided by the surface area of contact between the fibre and the resin

$$\text{i.e.} \quad \sigma_p = \frac{F}{\pi d \ell}$$

where d is the filament diameter and $\ell$ the immersion length.

Monofilaments were prepared at the three draw ratios of 8:1, 15:1 and 30:1 and subjected to different surface treatments. It was found that immersion in chromic acid at room temperature, and plasma treatment with oxygen as the carrier gas, were both effective in increasing the pull-out strength. Key results are summarised in Table 2. The chromic acid treatment is quite effective for the low draw ratio monofilaments, but the high draw ratio monofilaments are not affected so much. This result is consistent with the known improvements in chemical resistance of the UHMPE fibres with increasing orientation. The plasma treatment, on the other hand, increases in effectiveness with increasing draw ratio.

The examination of the fibre surfaces in a scanning electron microscope (SEM) provided the basis for an explanation of these results. The untreated monofilaments show smooth surfaces, and these are not significantly affected by chromic acid treatment. Pull-out tests show that the failure occurs by sliding the monofilaments out of the resin. The improvement in adhesion can therefore be attributed to surface oxidation and the consequent increase in electrostatic interaction between treated fibre with oxygen containing groups and the resin. Plasma etched monofilaments are quite different in showing a unique cellular surface texture (Figure 2) at the highest draw ratio. This texture is much less developed at low draw ratio. It can therefore be concluded that the plasma treatment with the oxygen gas is effective in improving the adhesion for two reasons. First, at all draw ratios there is an effect similar to that found for chromic acid treatment, which improves the wetting of the monofilament by the resin. Secondly, small pits are found on the monofilament surface. Penetration of these pits by the resin provides a mechanical keying of the monofilament to the resin. This increases the pull-out adhesion strengths from~ 2.5 MPa to~ 5.0 MPa. The SEM photographs show that the surface layer of the monofilament is removed in the pull-out test, suggesting that the limitation in adhesion strength is now determined by the shear strength of UHMPE which is comparatively low, as for all oriented synthetic fibres of this type.

It can be seen from Table 2 that the plasma etching treatment can produce an order of magnitude improvement in the pull-out adhesion strength as determined by this test. Both chromic acid and plasma treatments can also cause a fall in the tensile strength of the monofilaments. In subsequent work, a continuous treatment method was devised for plasma etching multifilament yarns, and care was taken to obtain satisfactory improvements in fibre/resin adhesion without producing any detectable reduction in fibre tensile strength. This is confirmed by the mechanical tests on the composites to be presented.

## 3.2 Preparation of Fibre Composites

As indicated in the Introduction section fibre composites were prepared in the laboratories at Leeds University prior to adopting a more commercially acceptable procedure.

In the laboratory the composites were prepared by one of two methods

(a) A bundle of fibres was placed in a rectangular loose-fitting mould (the so-called leaky mould). The fibre bundle was fully wetted with liquid resin and then compressed by the smooth fitting top of the mould, which allows excess resin to escape. XD 927 resin was used in the experiments to be discussed in the present paper. The curing conditions were identical to those described above for the adhesion pull-out tests. This procedure produced a rectangular bar containing ~ 55% by volume of UHMPE fibres, the fibre alignment being along the length of the bar.

(b) Layers of square weave UHMPE fabric were laid down in the leaky mould between layers of liquid resin. Excess resin was removed by compressing the layers as in (a) above, and an identical curing procedure was also adopted. The fabric layers were placed in the mould so as to ensure that the warp and weft threads are closely aligned with the axes of the mould. The rectangular bar composites are therefore comparable to those obtained using the fibre bundle, and again contain ~ 55% by volume of UHMPE fibre.

Finally, fibre composites were prepared by lamination of pre-impregnated sheets of fibre. Pre-pregs containing UHMPE, carbon, glass and Kevlar were produced by Rotorways, Bridgewater, UK. In this case CODE 91 epoxy resin was used, and the pre-pregs moulded in a hot press (or more recently in autoclave) to obtain laminated sheets containing either one type of fibre or in a sandwich construction with 2 layers of UHMPE enclosing 3 layers of carbon or glass fibre. In all cases the total fibre content was again ~ 55% by volume. The orientation of the fibres was varied, but in this paper we will discuss lamination where all the fibres are aligned parallel to one chosen direction.

## 4 MECHANICAL BEHAVIOUR OF FIBRE COMPOSITES

### 4.1 Test Procedures

The mechanical tests on the fibre composites followed standard test procedures developed at the Royal Aircraft Establishment, Farnborough UK.

In all cases the composite samples were of 2 mm thickness and 10 mm width. To determine the interlaminar shear strength (ILSS) a short beam test was performed. This was a three point bend test with a gauge length of 10 mm. For the determination of flexural modulus (FM) the gauge length was 160 mm, and for the ultimate flexural strength (UFS) the gauge length was 80 mm. Full details of these tests have been given by Sturgeon[10]. The FM was determined for an equivalent tensile strain of 0.03%.

The measurements of tensile modulus (TM) tensile strength (TS) and compressive strength (CS) were undertaken on samples whose ends were sandwiched between soft aluminium alloy plates bonded to the sample surfaces over a 50 mm length at each end. For the TM measurements the gauge length was 50 mm and again the modulus was determined at 0.03% strain. For TS measurements the thickness dimension was waisted with a continuous radius of 1000 mm, to give a minimum thickness of 1.2 mm. For CS measurements the sample gauge length was 10 mm. Full details of these tests are given by Ewins[11].

The UHMPE fibre composites are extremely tough and notch-insensitive. We therefore followed procedures recommended by Dorey[12] where unnotched specimens are subjected to impact on their broad face, using a custom-built Charpy impact machine with a fixed impact energy of 5.33 kJ.

### 4.2 Results of Mechanical Tests

The first results were obtained on the leaky mould composites, incorporating fibres or woven yarn and are summarized in Table 3. The major interest at this stage was to evaluate the influence of surface treatments on the interlaminar shear strength. As can be seen the ILSS values for the unidirectional fibre composite are approximately doubled by the plasma treatment of the fibres. Acid treatment produces an intermediate result. The effectiveness of the surface treatments is therefore confirmed, although the magnitude of the effect is less than observed for the single monofilaments. Table 3 indicates that there is no significant reduction in the tensile properties of the UHMPE fibres due to surface treatment. It can be seen that the tensile modulus, flexural modulus and tensile strength of the composites are comparatively low, considering the fibre properties quoted in Table 1. This is because these composites were made using UHMPE fibres produced at Leeds University where fibre properties were not as good as those obtained more recently, as will be apparent from results to be presented below on the composites made using Celanese Fibers Company fibres. However the TM and TS values in Table 3 do reflect the fibre properties very well, taking into account this factor and also the less than perfect fibre alignment achieved in the leaky mould method.

The compressive strength of the UHMPE composites is low, and as we have already mentioned, is consistent with the low compressive strength of the fibres. The ultimate flexural strengths reflect, in part, this low compressive strength but it is important to note that because of the very high ductility of the fibres, specimens can be restraightened after the UFS test, and retested with only a small reduction in measured UFS (typical reduction after three UFS tests is 5-8% in strength).

The most encouraging feature of the results shown in Table 3 is the comparatively high values of impact strength. Moreover the samples retain their integrity and can be straightened and retested, showing a substantial reduction in impact energy after each test. In this respect the effect of surface treatment of the fibres is marginal. Plasma treatment does reduce resin cracking and hence reduce the impact energy, but this is not a major effect and has been found to be comparable to changing the resin formulation to give a ductile rather than a brittle resin. This result is illustrated in Figure 3. These results are consistent with the view that a major source of energy absorption is due to deformation of the UHMPE fibres. This is confirmed by the Charpy impact data shown in Table 3 for the woven fabric composites, where the impact energies are approximately one half of those for the unidirectional fibre composites, exactly in line with the reductions in TM and TS shown in this table.

The results of this preliminary study emphasised the importance of utilizing the UHMPE fibres to improve the impact behaviour of fibre composites and led to the comparative study of UHMPE fibre composites with composites incorporating carbon, glass and Kevlar fibres and with the hybrid composites. The key results of this study are presented in Table 4. At this stage only untreated UHMPE fibres were available.

The results in Table 4 may be commented on as follows. First, the ILSS values for the hybrid composites are intermediate to those obtained with the corresponding single component fibre composites, suggesting that if plasma treated UHMPE fibres had been used acceptable ILSS values would have been obtained. Secondly, the values of TM, FM and TS are much greater than those shown in Table 3, corresponding to the better mechanical properties of the Celanese fibres.

As anticipated on the basis of the fibres properties of Table 1, the absolute values of stiffness and strength for the UHMPE composite are lower than those for the commercial fibre composites, with the exception of the glass fibre composite. The hybrid composites, however, show an interesting range of properties, especially if it is borne in mind that in addition to high impact energies these materials retain their integrity on impact as illustrated in Figure 4. Furthermore, the incorporation of UHMPE fibres produces a marked reduction in density so that a comparison in terms of specific properties is more favourable to the hybrid systems. These specific properties are compared in Table 5 for the carbon and glass fibre composites and the hybrids. It can be seen that excellent impact energies and damage tolerance can be obtained, still retaining good stiffness and strength.

## 5 CONCLUSIONS

In this paper recent research on the preparation and properties of UHMPE fibre composites has been reviewed. It has been shown that UHMPE fibres can be incorporated into existing resin formulations in a straightforward way, using available techniques. Surface treatments have been developed to give improvements in interlaminar shear strength.

The UHMPE fibres show a potentially valuable combination of properties, namely low specific mass, comparatively high tensile modulus and strength, and a high extension at break. The UHMPE fibre composites therefore offer some possibilities for light weight structures with high energy absorption on impact. It appears that hybrid composites, where the UHMPE fibres are combined with carbon or glass fibres may be of greater interest. The hybrid composites offer the possibility of combining the advantages obtained from the high ductility of UHMPE fibres, in terms of impact energy and damage tolerance, with the outstanding stiffness and strength of carbon fibres, or the good compressive strength of glass fibres.

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