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Interfacial Properties of Kevlar-49 Fiber-Reinforced Thermoplastics

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Synopsis

A single-filament pull-out test was used to study adhesion of Kevlar-49 fibers to thermoplastic polymers. The test involved pulling a partially embedded fiber out of a polymer film. Kevlar-49 fibers with three different surface treatments were used with five thermoplastic materials. The test resulted in the measurement of two properties, an interfacial bond strength and a frictional shear strength. The interfacial bond strength is an essential factor in determining the critical aspect ratio of discontinuous fibers in a composite. The frictional shear strength was found to correlate with the tensile strength of discontinuous fiber composites which fail by fiber pull-out. Scanning electron microscopy was used to examine the fiber pull-out specimens after testing. Observations of the fiber showed that the failure mode at the fiber–matrix interface was complex. The predominant failure mode was fracture at the interface (or in some weak boundary layer). In some cases, cohesive failure of the fiber surface was observed, with the result that strips of material were torn from the fiber surface.

INTRODUCTION

In discontinuous fiber-reinforced composites, the fiber–matrix interface plays an essential role in determining the mechanical properties. At the interface, loads are transferred from the matrix to the fiber. This load transfer is dependent on fiber-to-matrix adhesion and on the fiber aspect ratio. If the fiber aspect ratio is lower than the critical aspect ratio,[1] insufficient stress will be transferred to the fibers to fracture them and the reinforcement will be inefficient. Even when fiber length exceeds the critical length, short fibers are not as efficient as continuous fibers in reinforcing strength and stiffness. For example, a fiber of length equal to the critical length is only half as efficient as a continuous fiber. Even a fiber of length equal to five times the critical length has a maximum efficiency of 85%. Experimental work by Anderson and Lavengood[2] indicates that aspect ratios in the range of 50–100 are necessary before fibers are used efficiently. They also found that the fiber efficiency was a function of the ratio of fiber modulus to matrix modulus.

Greszczuk[3] and others[4,5] have recognized that there are three possible tensile failure modes in discontinuous fiber-reinforced composites. One of the possible failure mechanisms is matrix fracture. This failure mode occurs

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when the matrix ultimate strain is reached before the fiber ultimate strain. The mechanism is observed infrequently because most matrix materials are more ductile than reinforcing materials. The second possible failure mode is fiber pull-out, which results from interfacial bond failure, and the third failure mode is fiber fracture. The interfacial bond strength is essential in determining whether fiber pull-out or fiber fracture is the failure mechanism of a composite. Fibers which are shorter than the critical fiber length are pulled out of the matrix at failure because the maximum stress transferable to the fiber is less than the ultimate tensile strength of the fiber. Outwater[6] proposed that bond failure occurs at the fiber end initially and then travels along the fiber. The load on the composite is transferred from the resin to the fiber through frictional forces resulting from the fiber slipping through the matrix. Thus, the frictional shear stress controls the composite strength. Fibers which are equal to or longer than the critical length are fractured upon composite fracture. This fracture mechanism occurs because the stress transferred to the fiber is equal to the ultimate tensile strength of the fiber.

The critical aspect (fiber length ÷ diameter) ratio is inversely proportional to the interfacial bond strength and can be calculated from the following expression[1]:

$$(l/d)_c = \sigma_{uf}/2\tau_B$$

where τ_B is the interfacial bond strength, l/d is the fiber aspect ratio, and σ_{uf} is the ultimate strength of the fiber. In discontinuous fiber composites with fibers shorter than the critical aspect ratio, the failure mode of the composite is fiber pull-out. Because the strength of the interface is exceeded before the ultimate strength of the fiber is reached, composites made with fibers shorter than the critical aspect ratio are weaker than those exhibiting fiber fracture. The contribution of the fiber to the tensile strength of the composite is proportional to the aspect ratio of the fiber and is limited by the maximum amount of stress which can be transferred to the fiber. The Kelly and Tyson[7] model for tensile strength of short fiber composites is based upon a linear increase in stress from the fiber ends to a maximum at the center of the fiber.

Cottrell[8] and others have observed that composites with fibers shorter than the critical aspect ratio may exhibit good toughness since the failure mechanism, fiber pull-out, is a substantial energy-absorbing process. The fracture toughness of the composite is maximized as the fiber aspect ratio approaches the critical aspect ratio.

Efforts have been made to increase tensile strength and fracture toughness of composites by increasing the bond strength of the fiber–matrix interface.[9,10] This is based on the theory that increased bond strength will lead to an increase in the stress transferred to the fiber. However, it should be noted that an increase in interfacial bond strength will decrease the critical aspect ratio, quite possibly to the point where the fiber aspect ratio exceeds the critical aspect ratio. As long as the fiber aspect ratio does not exceed the critical aspect ratio, increased interfacial bond strength will enhance tensile strength and fracture toughness, and fiber pull-out will be the mode of failure.

In composites with fibers equal to or longer than the critical aspect ratio, failure mode is fiber fracture since the ultimate strength of the fiber is

reached before debonding occurs. Since fibers are fractured, composites made with fibers longer than the critical aspect ratio are stronger than those made with fibers shorter than the critical aspect ratio. The fracture toughness of these composites is frequently less than the toughness of composites exhibiting fiber pull-out during failure.

In principle, efforts to increase the interfacial bond strength of the fiber–matrix interface are of little effect when the fiber aspect ratio is greater than the critical aspect ratio. Although an increase in interfacial bond strength will decrease the critical aspect ratio, this will not change the failure mode and will have a relatively small effect on the contribution the fiber makes to composite strength.

Several experimental techniques have been used to measure the properties of the fiber–matrix interface. Single-filament pull-out tests have been used by Bowden,[11] Andreevska and Gorbatkina,[12] and others.[13–15] These techniques measure the shear strength of the interface by pulling or pushing a rod through a resin disk cast around a portion of the rod. Completely embedded single filaments have been used to measure debonding strengths.[16,17] A trapezoidal-shaped specimen and a curved-neck specimen have been used. The trapezoidal-shaped specimen was designed to measure shear debonding strengths while loaded in compression, and the curved-neck specimen was designed to measure tensile debonding strengths.

Flat-plate specimens consisting of two plates bonded with a polymer adhesive have also been used to measure bond strengths.[18] This method does not have the advantages of the embedded fiber technique. However, specimens are easy to prepare, and the data are relatively easy to analyze.

Speri and Jenkins[19] have used x-ray diffraction techniques to measure the interfacial bond strength of whisker-reinforced composites. This technique measures the shift in Bragg angle of the crystalline reinforcement when stress is applied to the composite.

EXPERIMENTAL

Materials

The matrix materials were five thermoplastic resins. Four of these are ductile and one is brittle. Table I lists the physical and mechanical properties of the polymers according to the manufacturers' data.

The ionomer matrix used was du Pont's Surlyn 1558 type 30. It is a ductile, semicrystalline polymer with low modulus and good toughness properties. The polyethylene used was du Pont's Alathon 7140 high-density polyethylene. This semicrystalline polymer has a narrow molecular weight distribution and exhibits good ductility and dimensional stability. The nylon 12 used was Huels Grade L-1901 Nylon 12. Nylon 12 is a semicrystalline, ductile polymer with low moisture absorption. The polycarbonate resin used was General Electric's Lexan 105-111. This resin exhibits good ductility, dimensional stability, and excellent impact strength. The only brittle matrix used was du Pont's Lucite 47 poly(methyl methacrylate). This amorphous resin is characterized by good mechanical properties and dimensional stability.

TABLE I
Properties of Matrix Materials

Property	Units	Ionomer	Poly-ethylene	Nylon 12	Poly-carbonate	Poly(methyl methacrylate)
Specific gravity	—	0.95	0.95	1.01	1.20	1.19
Ultimate tensile strength	psi	3,900	3,700	7,400	9,500	10,500
Tensile yield strength	psi	2,600	—	6,400	9,000	—
Tensile modulus	psi	—	—	—	345,000	4–500,000
Ultimate elongation	%	390	900	280	110	4–7
Flexural strength	psi	—	—	9,000	13,500	17,000
Flexural modulus	psi	23,000	175,000	200,000	340,000	4–500,000
Coefficient of linear thermal expansion	$\frac{1}{°C}$	12	12	10	7	6

TABLE II
Mechanical Properties of Kevlar-49

Property	Units	Kevlar-49
Specific gravity	—	1.45
Ultimate tensile strength	psi	400,000
Tensile modulus	psi	19,000,000
Ultimate elongation	%	2.0
Fiber diameter	in.	0.00046

All of the resins, except for the Huels Grade L-1901 Nylon 12, were used in powder form. The resins were dried for three days in a vacuum oven at 80°C prior to molding.

The reinforcement used in this study was du Pont's Type III Kevlar-49. Kevlar-49 is a high-strength, high-modulus organic fiber which exhibits nearly elastic behavior to fracture. The properties of this fiber are listed in Table II. du Pont describes the fiber as an aromatic polyamide, but it has not published its chemical structure. It has been suggested[20] that the material is a poly(*p*-phenylene terephthalamide). The excellent tensile properties of Kevlar-49 are attributed to an essentially extended chain conformation produced during a solution spinning process.

Three preparations of this fiber were used: an unfinished fiber, a sized fiber, and an unfinished fiber boiled in water. The unfinished fiber was obtained in the form of a 380-denier continuous yarn with low twist. The sizing on the finished fiber was du Pont's 5259-18. The chemical structure of this material has not been published. It was anticipated that this finish would enhance the adhesion of the fiber to the matrix materials. The presence of the sizing had a marked effect on the ease of dispersion of the cut fiber bundles. The filaments in the unfinished yarn dispersed readily, while those in the sized yarn did not. This significantly affected the mechanical properties of bulk composites which were made. The third fiber treatment was produced by placing 12-in. lengths of unfinished Kevlar-49 yarn in boiling distilled water for six and one half days.

TABLE III
Molding Conditions for Film Preparation and Single-Filament Pull-Out Samples

Matrix	Compression molding		Single-filament pull-out preparation
	Platen temperature, °C	Molding pressure, psi	Oven temperature, °C
Ionomer	175	400	130
Polyethylene	175	600	140
Nylon 12	180	600	225
Polycarbonate	240	600	250
Poly(methyl methacrylate)	200	600	230

Preparation of Single-Filament Pull-Out Samples

Single-filament pull-out samples were prepared by partially embedding a fiber in a film of matrix material. The film of matrix material was prepared by compression molding the resin in a 3 in. × 5 in. mold. Film thickness was 0.005 to 0.015 in. Table III lists the molding conditions used. The 3 in. × 5 in. film of matrix was cut into twenty ½ in. × ⅜ in. pieces, each piece serving to make one test specimen. A single hole was made in each film with a fine pin. This was done at room temperature for all matrix materials except poly(methyl methacrylate), which was heated in an oven at 220°C for 5 min before the hole was made.

A 12-in. filament of Kevlar-49 was threaded through the hole, and the ends of the fiber were bonded to paper clips with epoxy adhesive. The adhesive was allowed to cure at room temperature, and then the specimen was mounted in a jig which held the fiber perpendicular to the film. The jig was placed into a preheated, forced-air circulation oven for 5 min. Table III lists the oven temperature used for each matrix material. At this temperature, the film softened and the pinhole closed around the fiber. The specimen was removed from the oven and allowed to cool to room temperature. Complete bonding at the surface of the fiber occurred in most cases. Specimens which had incomplete bonding were discarded. The suspended fiber was cut approximately ⅛ in. below the film to produce a specimen ready for the pull-out test.

Pull-out tests were performed with an Instron tensile testing machine. The cross-head speed used was 0.2 in./min. Specimens with defects were discarded, including those in which the fiber broke before pull-out occurred. Each experimental result was an average of four single filament pull-out tests.

Scanning Electron Microscopy

A Cwikscan-100 field emission scanning electron microscope was used to measure fiber diameter and embedded fiber length. After the pull-out test, the matrix film was dipped into liquid nitrogen and fractured so that a crack traveled through the hole left by the fiber. This exposed the hole cross section and allowed the embedded fiber length to be measured. Prior to micro-

scopic examination, fiber and film specimens were coated with chromium, using a vacuum evaporator. In addition to the measurement of the fiber diameter and the embedded fiber length, microscopy provided information on the adhesion of the fiber to the thermoplastic film and on the mechanism of fracture which occurred when the fiber was pulled from the matrix.

RESULTS AND DISCUSSION

The single-filament pull-out test was used to study the properties of the fiber–matrix interface. Figure 1 illustrates the Instron output of a test in which a filament of Kevlar-49 was pulled out of a film of ionomer. The output is typical of the response exhibited by the single-filament pull-out tests. Test results allow the measurement of two stress levels, the interfacial bond strength τ_B and the frictional shear strength τ_F. The interfacial bond strength is the stress level at which the bonding forces between the fiber and matrix are overcome, and the frictional shear strength is the stress at which the fiber slips through the matrix after the adhesive bond has been fractured. As shown in Figure 1, fiber friction is characterized by a slip stick phenomenon.

After the pull-out test, the fiber was examined using scanning electron microscopy to measure the fiber diameter and gather qualitative information about the fracture mechanism. Fracture in the fiber pull-out test can occur at the fiber–matrix interface, in the fiber, or in the matrix. In our tests, the observed failure mode was frequently complex. The predominant mode was fracture at the interface or in some weak boundary layer. However, in some cases, cohesive failure of the fiber surface occurred during the test, resulting in a thin layer of material being stripped from the fiber surface. This thin layer tended to form into a helix owing to stresses present in the fiber because of its high degree of orientation. Figure 2 shows such strips formed by cohesive fiber failure. Multilayer fiber fracture was also observed with the electron microscope. These cohesive fiber failures were observed with all of the matrix materials and fiber preparations of Kevlar-49. Fibrillation of Kevlar-

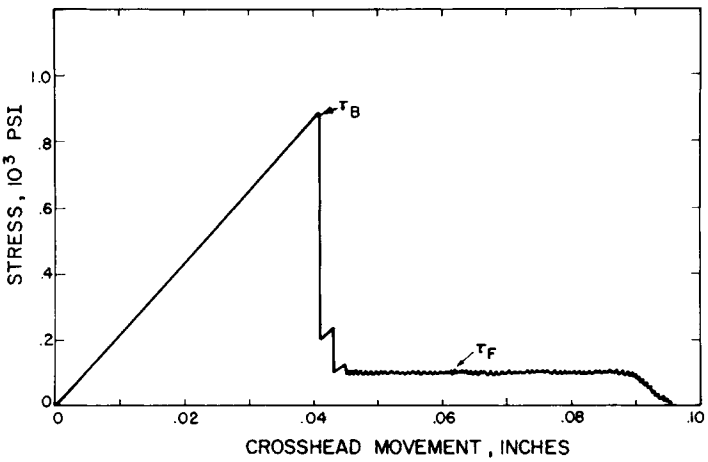
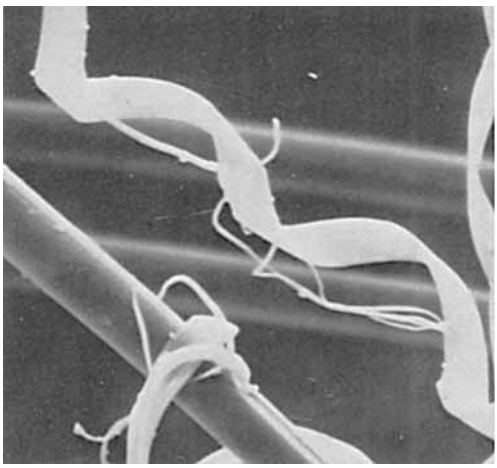


Fig. 1. Stress–Displacement curve for a single filament pull-out test.

49 fibers in composites under compressive stress has been reported,[22] but this type of fiber fracture has not been noted in composites subjected to tensile stress.

If fracture occurs at the interface (or in a weak boundary layer), an accurate measure of the interfacial bond strength is obtained by the pull-out test. If fracture occurs in the fiber or in the matrix, the measured value for the interfacial bond strength is lower than the actual value, since the interfacial bond did not fail before the fiber or the matrix fractured. Thus, the pull-out test used here gives minimum values for the interfacial bond strength and actual values may be somewhat higher. Results obtained with the single-fiber pull-out test should be applicable to multifiber composites when defects such as fiber end effects are taken into consideration.

Scanning electron microscopy was used to observe the hole in the matrix material. Samples were prepared by fracturing the film so that the cross section of the hole could be observed. This procedure made it possible to accu-



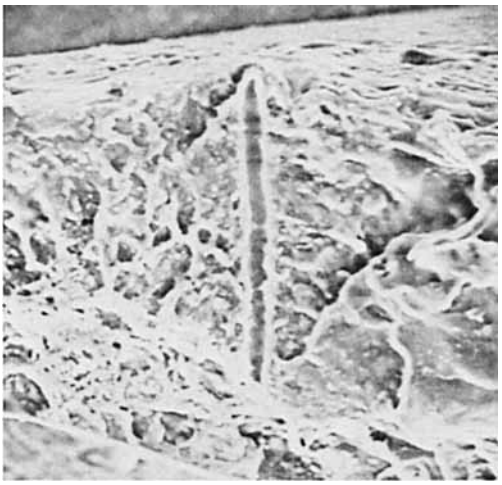
(a)

(b)

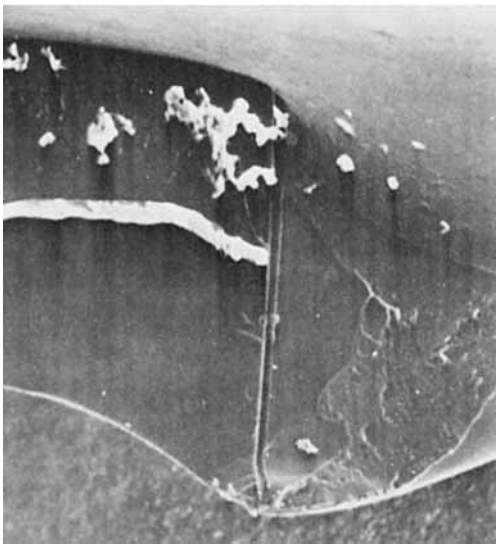
Fig. 2. Helices resulting from cohesive failure of fiber. Fiber diameter is approximately 12 microns.

rately measure the embedded fiber length. In many cases, the embedded fiber length was significantly greater than the nominal film thickness due to surface tension forces developed during the heat sealing of the fiber in the hole. Figures 3a and 3b, respectively, show the cross sections of holes produced by pulling a Kevlar-49 fiber from films of polyethylene and poly(methyl methacrylate).

The results of single-filament pull-out tests performed with Kevlar-49 fibers with no surface finish, and the five matrix materials are summarized in Table IV. Nylon 12 has a very high interfacial bond strength in comparison to the other matrix materials. This fact might be explained by the presence of hydrogen bonds between amide groups of Kevlar-49 and nylon 12 which greatly increased the bond strength.



(a)



(b)

Fig. 3. Scanning electron micrograph of matrix cavity after single-filament pull-out test: (a) polyethylene; (b) poly(methyl methacrylate).

TABLE IV
Interfacial Bond Strengths and Frictional Shear Strength of Unfinished Kevlar-49

Matrix material	Interfacial bond strength, psi	Frictional shear strength, psi
Ionomer	884	100
Polyethylene	1150	213
Nylon 12	6640	292
Polycarbonate	1290	310
Poly(methyl methacrylate)	1650	411

TABLE V
Values for Interfacial Bond Strength with Glass Fibers[a]

Test method	Matrix material	Glass treatment	Interface failure mode	Bond strength, psi
Rod-disk (push test)	polyester	acetone cleaned	shear	605
Rod-disk (push test)	polyester	silane finish	shear	680
Trapezoidal fiber	polyester	acetone cleaned	shear	1000
Trapezoidal fiber	epoxy	acetone cleaned	shear	3000–3500
Curved-neck fiber	polyester	heat cleaned	tension	750
Curved-neck fiber	polyester	silane finish	tension	1220
Curved-neck fiber	epoxy	toluene cleaned	tension	>1540

[a] L. J. Broutman, *Interfaces in Composites*, ASTM STP 452, 1969, pp. 27–41.

Table V shows data from the literature on the interfacial bond strength of glass fibers in thermosetting polymers. The values were determined using partially embedded and completely embedded single filaments. The bond strengths of the glass fibers are of the same order as the strengths of the Kevlar-49, although the organic fiber tends to form stronger interfacial bonds.

If the matrix material shrinks more than the fiber upon cooling from the molding temperature, a compressive stress is applied to the fiber.[21] The magnitude of this stress is dependent upon the difference in coefficients of thermal expansion for the two materials if no stress relaxation occurs. A compressive stress on the fiber should act to increase both the interfacial bond strength and the frictional shear strength. In the experimental test specimen, this stress on the fiber is difficult to measure. However, the coefficient of thermal expansion of Kevlar-49 fiber in the radial direction should approximate the coefficient of thermal expansion of the matrix materials. In this work, the stress due to differences in thermal expansion between fiber and matrix probably has a relatively small effect on the pull-out strength and was, therefore, neglected.

Bowden[11] found that the interfacial bond strength was equal to the shear yield strength of the matrix in a short fiber-reinforced composite. The data from the single filament pull-out test exhibited little correlation with the yield strengths of the thermoplastics used in this work. In addition, correlation between the ultimate tensile strength of the matrix material and the interfacial bond strength was not found in these data. Apparently, surface properties of the materials are of greater influence than matrix mechanical properties.

Outwater[6] has proposed that the frictional shear strength controls the strength of composites which fail by the fiber pull-out mechanism. The theory states that failure is initiated by concentrated shear stresses at the fiber ends, causing debonding first at the fiber end and then along the length of the fiber. After debonding, fiber pull-out begins and the load is transferred from the matrix to the fiber by frictional forces. Thus, it appears that the frictional shear strength data should correlate with the tensile strength data of composites which fail by fiber pull-out. Figure 4 shows a comparison of frictional shear strength data from the single-fiber pull-out test with data on the published tensile strength properties of discontinuous Kevlar-49 fiber-reinforced thermoplastics.[23] In Figures 4 and 5, the following symbols have been used to identify matrix materials: (○) ionomer, (□) polyethylene, (●)

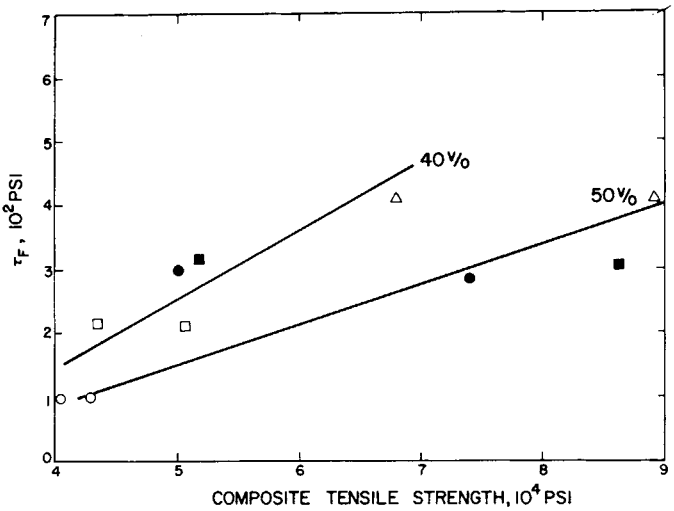


Fig. 4. Frictional shear stress vs. tensile strength of 40% and 50% unidirectional short fiber composites.

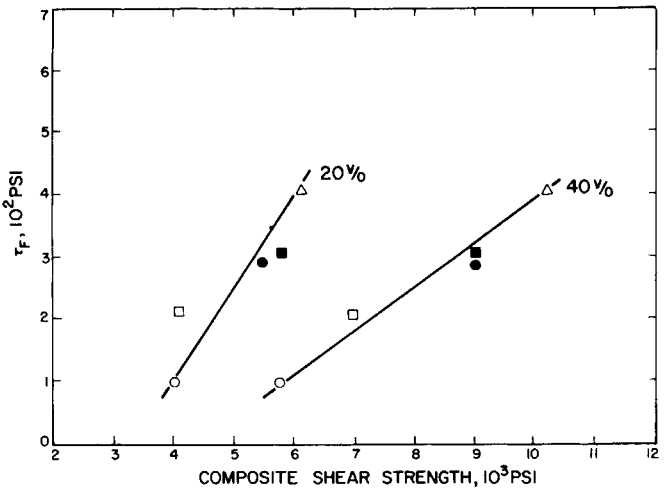


Fig. 5. Frictional shear stress vs. shear strength of 20% and 40% unidirectional short fiber composites.

TABLE VI
Calculated Critical Lengths for Unfinished Kevlar-49[a]

Matrix material	l_c, in.	l/l_c
Ionomer	0.104	3.6
Polyethylene	0.080	4.7
Nylon 12	0.014	27.0
Polycarbonate	0.071	5.3
Poly(methyl methacrylate)	0.056	6.7

[a] $l_c = \sigma_{uf} r/\tau_B$, where $r = 2.3 \times 10^{-4}$ in., and $\sigma_{uf} = 4.0 \times 10^5$ psi.

nylon 12, (■) polycarbonate, and (△) poly(methyl methacrylate). These composites contained 40% and 50% by volume Kevlar fibers. Fiber length was ⅜ in., and the fibers were unidirectionally oriented parallel to the applied stress. The correlation of the data indicates that frictional shear strength may be a controlling parameter of tensile strength in discontinuous fiber composites. Attempts to find a relation between interfacial bond strength and tensile strength of the composites were unsuccessful. This was due primarily to the high bond strength exhibited by nylon 12. Although it does not appear that interfacial bond strength is a controlling parameter of tensile strength in these composites, it should be remembered that interfacial bond strength influences tensile strength of discontinuous fiber composites by determining the critical fiber length.

Blumentritt[24] measured the shear strength of unidirectional discontinuous fiber composites with a double-notched specimen. A comparison of the shear strength data of 20% and 40% unidirectional discontinuous Kevlar-49 fiber composites with frictional shear strength data is shown in Figure 5. The data show good correlation. The proportionality between the frictional shear strength data and the composite shear strength is explained by the fact that the failure mode was primarily fiber pull-out and experimental evidence indicates that frictional shear strength controls the strength of composites which fail by fiber pull-out.

The critical aspect ratio of Kevlar-49 fiber was calculated for each of the matrix materials. The results are shown in Table VI. This calculation involved the use of the experimentally determined interfacial bond strength. The results indicate that the fiber aspect ratio for the fibers used to make the experimental composites[23] was from 4 to 27 times longer than the critical aspect ratio. This means that the composites should have failed by fiber fracture. However, Blumentritt[24,25] reported that these composites failed primarily by fiber pull-out with little fiber fracture even though very good fiber orientation was obtained. This indicates that these composites contained defects. Incomplete wetting of the fibers and microvoids act to decrease the effective length of the fiber and promote debonding.[26] Also, stress concentrations at fiber ends or points of fiber contact initiate cracks which can propagate along the fibers and lead to fiber pull-out.

The results of single-filament pull-out tests performed on water treated and sized Kevlar-49 with several of the matrix materials are shown in Table VII. A comparison of the results of the unfinished Kevlar-49 and the water treated Kevlar-49 shows that the interfacial bond strength and the frictional

TABLE VII
Interfacial Bond Strengths and Frictional Shear Strengths

Matrix material	Interfacial bond strength, psi	Frictional shear strength, psi
Water-Treated Kevlar-49		
Ionomer	1540	154
Polyethylene	1820	220
Poly(methyl methacrylate)	2150	425
Sized Kevlar-49		
Ionomer	1340	168
Polycarbonate	5600	380
Poly(methyl methacrylate)	7800	450

shear strength are greater for the water-treated Kevlar-49. The greatest increase was for the ionomer matrix. A comparison of the surface of an unfinished Kevlar-49 fiber with one which has been water treated shows that the treated fiber is much rougher. The unfinished fiber is very smooth. Figures 6a and 6b are photomicrographs of unfinished Kevlar-49 and water-treated Kevlar-49, respectively. The rougher fiber could lead to mechanical wedging, which would explain the increase in interfacial bond strength and frictional

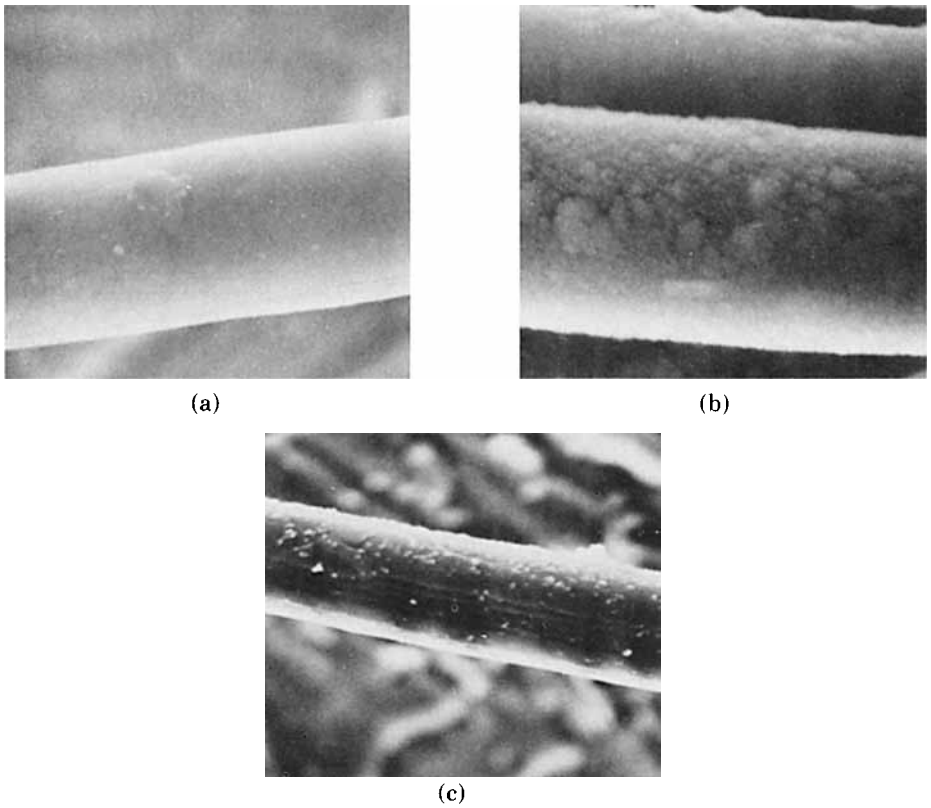


Fig. 6. Surface of Kevlar-49 fiber: (a) unfinished; (b) water treated; (c) sized. Fiber diameter is approximately 12 microns.

shear strength. The results of the single-filament pull-out test indicate that stronger composites can be made with fibers having rough surfaces assuming the failure mechanism is fiber pull-out.

A comparison of the results of Kevlar-49 with no surface finish and sized Kevlar-49 shows that sized Kevlar-49 has a greater interfacial bond strength and frictional shear strength. There was a dramatic increase in the interfacial bond strength for PMMA and PC. The increase in bond strength might be partly due to an increase in the roughness of the surface. Figure 6c illustrates the roughness of the sized Kevlar-49 fiber. The increase in bond strength might also be explained by improved wetting of the fiber. The results indicate that stronger composites can be made with sized Kevlar-49 when fiber pull-out is the failure mechanism. It is important to note, however, that it was not possible to disperse the cut fiber bundles so that bulk composites of sized Kevlar-49 did not possess very good tensile properties.

CONCLUSIONS

The properties of the fiber–matrix interface were measured by a single-filament pull-out test. This test involved pulling a partially embedded fiber out of a film of matrix material. Two stress levels, interfacial bond strength and frictional shear strength, were measured by this technique. The interfacial bond strength is the peak stress at which adhesive forces between the fiber and matrix are overcome. The frictional shear strength is the stress level which follows the peak value and represents the slippage between the fiber and matrix material. This single-filament pull-out test was used to quantify the adhesion of different fiber preparations to each of the matrix materials. Sized Kevlar-49 had the greatest interfacial bond strength and frictional shear strength values for each of the matrix materials. Water-treated Kevlar-49 exhibited adhesive values below those of the sized fiber, while the fiber with no finish exhibited the weakest interfacial properties. Some of the increase in bond strength of the sized and water-treated Kevlar-49 was attributed to the increased roughness of the fiber.

The tensile strength of discontinuous fiber-reinforced thermoplastic bulk composites correlated well with the frictional shear strength measured in the single-filament pull-out test. This suggested that the frictional shear strength is the controlling parameter in composite strength. This is in support of Outwater's theory of fiber pull-out in composite failure. However, critical fiber length determinations indicated that the failure mechanism should be fiber fracture rather than fiber pull-out. Fracture by fiber pull-out implies that the effective fiber length was reduced, possibly by incomplete wetting of the fibers or by stress concentrations at fiber ends and points of fiber contact.

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