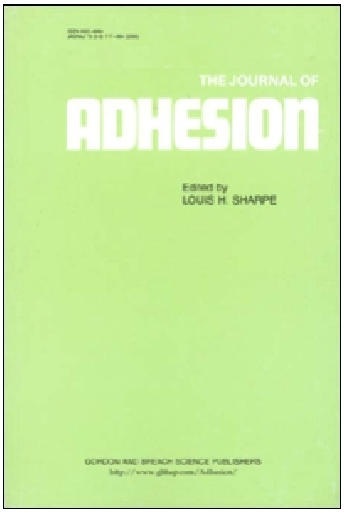

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Preliminary Examination of the Thermophysical Bond of Insert-molded Poly(Carbonate)/ C Fiber Composites*

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The adhesive strength of a thermophysical bond between two polymers has been examined using fracture mechanics. Bimaterial composite specimens were constructed by injecting C fiber poly(etheretherketone) (PEEK) into a mold containing one-half of a pre-molded poly(carbonate) (PC) dogbone. The resulting specimens were notched at the interface and tested in tension. Adhesion of the two materials was reasonably good, as demonstrated by fracture surfaces that showed a mixture of PC and C fiber PEEK fragments. Interfacial fracture energy of the composite was approximately 1.5 kJ/m^2.

Keywords: Insert-mold; over-mold; bimaterial; composite; adhesion; fracture energy

INTRODUCTION

Although fracture toughness of poly(etheretherketone) (PEEK) composites has been widely discussed in the literature [1 – 7], PEEK composites constructed by insert molding with other engineering polymers have received less attention. Insert molding often involves molding a higher performance polymer, such as PEEK, on to a less expensive one. This approach provides an economical method of producing

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higher performance products at a reduced cost [8,9]. In some cases, it is a good alternative to polymer blends.

An important feature in many insert-molded products is good adhesion between the materials. In this study, the adhesive strength of the interface between polycarbonate (PC) and C fiber PEEK has been examined using fracture mechanics. Composite tensile specimens were constructed by injecting C fiber PEEK into a mold containing one-half of a pre-molded PC dogbone. The molten C fiber PEEK locally melts the interface of the PC to form a physical bond. (The inverse did not work, given the constrains of normal manufacturing practices associated with injection molding.) The resulting series composite specimens were notched at the interface and tested in tension. The results for the composite are compared with the materials of construction.

ANALYSIS

General Mechanics

Tensile stresses, σ, were calculated using elongation force, F, divided by the underformed cross-sectional area, A [10, 11],

$$\sigma = F/A. \qquad (1)$$

Tensile strains, ε were determined from sample elongation, ΔL, and its initial length, L,

$$\varepsilon = \Delta L/L. \qquad (2)$$

Tensile moduli, E, were computed as stress, σ, over strain, ε, where strains were small and the materials were linearly elastic ($\varepsilon < 0.01$),

$$E = \sigma/\varepsilon. \qquad (3)$$

Strains at early times, t, were used to estimate strain rate, ε',

$$\varepsilon' = \varepsilon/t. \qquad (4)$$

Mechanics of Composite Specimens

Figure 1 shows the central portion of monolithic (a) and series composite (b) specimens. For the series composite (Fig. 1b), the two

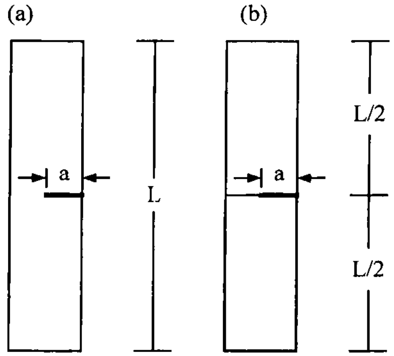

FIGURE 1 The central portion of tensile specimens (ASTM D638 Type I dogbone) with a single edge notch of length a. (a) monolithic specimen. (b) bimaterial composite comprised of two materials with different tensile moduli, E_1 and E_2, where $E_1 < E_2$. With the use of an extensometer, $L = 50\,\text{mm}$. The specimen width and thickness were 13 mm and 3.2 mm, respectively.

materials have different tensile moduli (E_1 and E_2), where $E_1 < E_2$. Each segment has the same cross-sectional area, A, and the same fractional length, $L/2$.

When load is applied, this composite sample deforms with the same average stress in each component. However, because the materials differ in stiffness, the individual components do not deform to the same extent. The stiffer material deforms less while softer material deforms more. As a result, the apparent stiffness of the composite specimen depends on the moduli of the individual components, E_1 and E_2, as [12–19]

$$E = 2E_1E_2/(E_1 + E_2). \tag{5}$$

Fracture Mechanics

The adhesive strength of the interface and the component materials were determined using tensile specimens with a single edge notch, Figure 1. The fracture energies, G, were calculated from the notch length, a, and mechanical response of notched specimens [20, 21],

$$G = 2.5\pi aU, \tag{6}$$

where U is the strain energy density to break (or area under the stress–strain curve). U was computed by integrating the stress–strain curve to the breaking strain, ε_b, from $\varepsilon = 0$ to $\varepsilon = \varepsilon_b$,

$$U = \sigma(\varepsilon)d\varepsilon. \tag{7}$$

If specimens broke at small strains with a linear stress–strain response, approximate values of fracture energy were estimated from breaking stress, σ_b,

$$G^* = 1.25\pi a\sigma_b^2/E. \tag{8}$$

EXPERIMENTAL

Materials

The materials of construction were PC and a C fiber PEEK compound that contained < 20% C fiber.

Sample Preparation

Both monolithic and composite specimens were molded. Composite samples were fabricated by first molding PC dogbones (ASTM D638 Type I) and then cutting them in half with a bandsaw. Half pieces of the pre-molded PC were inserted back into the dogbone mold and C fiber PEEK was injected, without any surface preparation. The bonding surface of several pre-molded PC specimens was polished with abrasive paper, but this treatment did not affect the strength of adhesion.

Dogbones were notched at their midpoint for fracture energy measurements. For the composite specimens, this corresponded to placing the notch at the interface. Figure 1 shows the notch orientation. First, a scroll saw with 0.64 mm, coarse-tooth blade at approximately 900 strokes per minute was used to cut within 0.5 mm of the desired depth. Then, a universal style utility blade was mounted in an INSTRON® 5582 test machine to cut the final 0.5 mm. A specimen was placed in the tensile tester and the blade was brought into contact with the edge near the notch. A pressure reading of less than 1 N was used to signify contact and then the gauge length was reset. After resetting gauge length and centering the partially-cut notch under the blade, the machine was started. The blade moved downward at 2 mm/min until the preprogrammed notch length was reached. Notch length, a, was varied between 1 mm and 4 mm. Composite specimens where the notch was not at the immediate interface or grew during preparation/handling were not used.

Mechanical Testing

Samples were tested in tension using an INSTRON® 5582 test machine equipped with a 100 kN static load cell and extensometer (ASTM D638). Testing was performed at room temperature, 23°C. Samples were fixtured using rigid clamps with a gage length of 115 mm. The extensometer was attached such that $L = 50$ mm and samples were elongated at 2 mm/min. Strain rate was estimated directly from plots of strain *versus* time to be $\varepsilon' = 2 \times 10^{-4}\,s^{-1}$, Eq. (4).

Five samples of each type were tested for yield stress, yield strain, breaking stress and breaking strain. Moduli and strain energy densities were determined from stress–strain curves. For notched samples, notch size, breaking stresses, moduli, and/or strain energy densities were used to calculate fracture energies. Averages and standard deviations were calculated for each specimen type.

RESULTS AND DISCUSSION

Unnotched Samples

Table I shows the tensile properties of unnotched specimens. Properties for PC and C fiber PEEK agreed well with literature values [22, 23]. Unnotched PC elongated about 6% before yielding with

TABLE I Tensile properties of unnotched specimens[a]

Material	σ_y (*MPa*)	ε_y (*mm/mm*)	σ_b (*MPa*)	ε_b (*mm/mm*)	E (*GPa*)
PC	60 ± 1	0.062 ± 0.001	66 ± 1	1.04 ± 0.01	2.3 ± 0.1
C fiber PEEK	NY	NY	129 ± 1	0.018 ± 0.001	12.0 ± 0.4
PC/C fiber PEEK	NY	NY	46 ± 8	0.013 ± 0.004	3.9 ± 0.2
PC/PC	NY	NY	33 ± 14	0.017 ± 0.009	2.5 ± 0.1

[a] NY = no yield. Error values are standard deviations based on five specimens.

considerable necking; failure occurred at 104% elongation with a breaking stress of 66 MPa. C fiber PEEK elongated 1.8% before breaking at 129 MPa. It did not yield. For PC/C fiber PEEK composites, stress increased linearly with elongation; samples broke without yielding, $\sigma_b = 46$ MPa and $\varepsilon_b = 1.3\%$. Failure occurred abruptly in the vicinity of the interface, with the advancing crack propagating randomly from one material to the other.

The modulus of the PC/C fiber PEEK composite was intermediate to the moduli of the materials of construction. A value calculated from Eq. (5), $E = 3.8$ GPa, using moduli measured from the individual materials agreed well with the measured value.

It is well known that interfaces can act as flaws or stress raisers. To demonstrate the effects of the interface on specimen strength, PC/PC composites samples were molded and tested. Results are included in Table I. Although modulus of the PC/PC composite was equal to that of monolithic PC, the presence of the interface greatly reduced its strength. The overmolded PC/PC composite failed suddenly in the vicinity of the interface without yielding at 2% elongation, resulting in a 50% reduction in breaking stress.

Stress–Strain Behavior of Notched Samples

Figure 2 shows a typical result for notched PC/C fiber PEEK composites. The stress–strain response was linear. Crack propagation was analogous to unnotched specimens. Consequently, the fracture

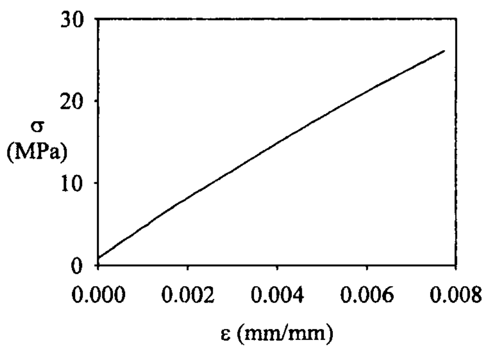

FIGURE 2 Stress *versus* strain for PC/C fiber PEEK composite with a 2 mm notch.

surfaces from any given PC/C fiber PEEK composite were a mixture of PC and C fiber PEEK. On several occasions fragments were ejected as specimens broke. Monolithic C fiber PEEK exhibited similar behavior.

Notched PC behaved differently. As notched PC samples were elongated, the material adjacent to the notch yielded and necked down. Stresses continued to climb slightly as the notch or crack began to grow. A 5% deviation in the compliance from an equivalent unnotched specimen was used to designate the initiation crack growth in notched PC specimens [24].

Effect of Notch Size

In all cases, larger notches gave lower breaking stresses and breaking strains. Because the stress–strain behavior of monolithic C fiber PEEK and the PC/C fiber PEEK composite were more-or-less linear, it was possible to construct plots of breaking stress *versus* the inverse half power of the notch size ($a^{-1/2}$), shown in Figures 3 and 4. The points are experimental data. The solid lines represent linear regression that has been forced through the origin. Using the slope of these lines and the tensile moduli of unnotched samples in conjunction with Eq. (8), fracture energies were determined to be $G^* = 2.0\,kJ/m^2$ for monolithic C fiber PEEK and the $G^* = 1.2\,kJ/m^2$ for PC/C fiber PEEK composite.

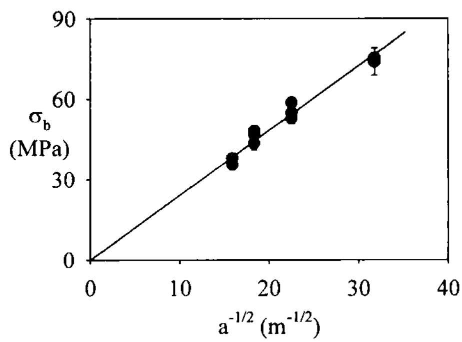

FIGURE 3 Breaking stress, σ_b, as a function of notch size, a, for monolithic C fiber PEEK. Error bars represent standard deviations based on five specimens.

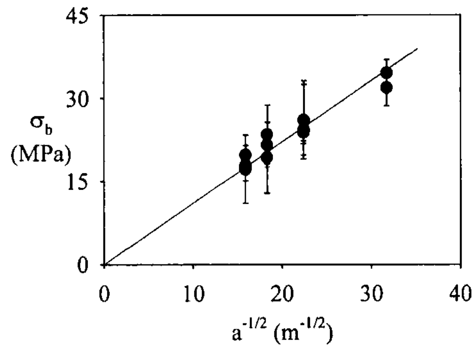

FIGURE 4 Breaking stress, σ_b, as a function of notch size, a, for the PC/C fiber PEEK composite. Error bars are standard deviations from five specimens.

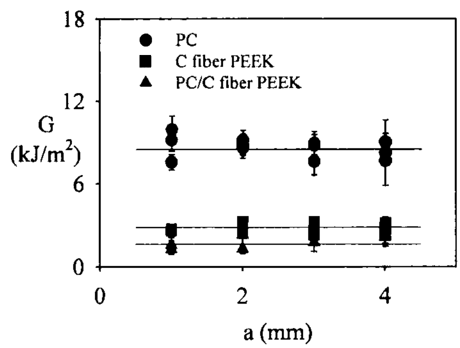

FIGURE 5 Fracture energy, G *versus* notch size, a. Error bars are standard deviations from five specimens.

The non-linear fracture behavior of PC required a more general analysis. Strain energy densities were determined by integrating stress–strain curves up to the point of crack initiation, Eq. (7), and then computing fracture energies (G) with Eq. (6). Figure 5 shows G values for PC with various notch lengths along with results for monolithic C fiber PEEK and the PC/C fiber PEEK composite. G values for PC were independent of notch length, $G = 8.5\,kJ/m^2$.

Fracture energies are summarized in Table II for the materials of construction as well as their series composite. G values for PC and monolithic C fiber PEEK were in general agreement with those reported by other investigators [1, 2, 7, 25]. PC is a material known for its toughness. Thus, a fracture energy that is much greater than C

TABLE II Fracture energies at room temperature[a]

Material	G (kJ/m^2)	G' (kJ/m^2)
PC	8.5 ± 0.9	–
C fiber PEEK	2.8 ± 0.3	2.0 ± 0.2
PC/C fiber PEEK	1.6 ± 0.6	1.2 ± 0.5
PC/PC	3.1 ± 1.5	2.2 ± 0.4

[a] Error values are standard deviations based on five specimens.

fiber PEEK was expected. Although the fracture behavior of the PC/C fiber PEEK composite was similar to monolithic C fiber PEEK, its fracture energy was less than the values measured for the materials of construction. This was due, in part, to presence of the interface, which acts as a stress raiser. Nevertheless, the fracture energy of the PC/C fiber PEEK composite was comparable with amorphous commodity polymers such as PS or PMMA [18].

Results from the notched PC/PC composite further demonstrate the effect of an interface, Table II. Unlike the monolithic PC specimens, PC/PC composite failed catastrophically without yielding, giving a much lower fracture energy.

The larger variation observed in the breaking stresses, breaking strains, and fracture energies of the composite samples probably arose from a variety of sources: variation in the shape of the interface, notch location relative to the slightly variable interface (for the notched specimens), as well as sample and extensometer placement. (Unlike the monolithic specimens, the mechanical response of the composite specimens, particularly where $E_1 \neq E_2$ is sensitive to clamp and extensometer position.)

CONCLUSIONS

It is possible to create a bimaterial composite by injecting C fiber PEEK into a mold that contains a PC insert. When tested in tension, the resulting composite failed at or near the interface. Fracture surfaces showed a mixture of PC and C fiber PEEK, suggesting good adhesion. Even though the fracture energy of the composite was less than the values for the materials of construction, it was comparable with the cohesive strength of amorphous commodity polymers.

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