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LARGE FRACTURE TOUGHNESS BORON-EPOXY COMPOSITES*

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Abstract

The high tensile strengths of strong interfacial bonding may be combined with the large fracture toughness of weak interfacial bonding in brittle fiber/brittle matrix composites by intermittently coating the filaments before layup so as to have random alternate weak and strong regions. Appropriate coating materials enable Cook-Gordon Mode I interfacial debonding to take place, which produces very long pull-out lengths with an associated large contribution to toughness. Unidirectional boron-epoxy composites (volume fraction ~0.2) have been so made which have toughnesses greater than 200 kJ/m^2 (as opposed to about 40 kJ/m^2 with no coating) while retaining rule of mixtures tensile strengths (~650 MN/m^2). Similar trends have been observed for crossply layups.

Introduction

In conventional brittle fiber/brittle filament composites, when the interfacial bond between filament and matrix is strong, fracture is often caused by rapid matrix cracks which break through all filaments in their paths. The toughness of such composites is low because, in general, the critical transfer length associated with strong interfacial bonding is small, which limits the various components of the total toughness—the 'surfaces' component, Piggott-Fitz-Randolph stress redistribution and Cottrell-Kelly pull-out (see, for example, ref. 1). The critical length is given by $l_{crit} = \sigma_f d/2\tau$, where σ_f is the filament strength, d the filament diameter, and τ the interfacial shear strength. A general increase of l_{crit} by lowering the filament-matrix shear bond will increase the toughness, but weak interfaces throughout the composite reduce the tensile strength quite significantly.

Recent work (2,3) has shown that "intermittent bonding" allows high toughness to be obtained in brittle filament/brittle matrix composites without significant loss of tensile strength. Filaments are arranged to have alternate bands of high and low shear stress (and low and high toughness) by interrupted coating along the filaments with appropriate substances. The strong regions ensure that the filament strength is picked up; randomly positioned weak areas effectively blunt cracks by the Cook-Gordon mechanism (4) which in turn produces long pull-out lengths with an associated large contribution to toughness. Unidirectional boron-epoxy composites of volume fraction 0.20-0.25 have been made in this way; they have fracture toughnesses of over 200 kJ/m^{-2}, and they retain rule of mixtures tensile strengths (~650 MN/m^{-2}). At the volume fractions used, that apparently represents K_{1c} values greater than 100 $MN/m^{-3/2}$

Two different coating materials have been investigated (2,3), viz: silicone vacuum grease (SVG) and polyurethane varnish (PUV). Both appear to produce similar interfacial shear strengths in the coated regions, since the tensile strength variations with coating geometry are indistinguishable. Their effects on toughness, however, are significantly different: SVG produces only a modest increase in toughness (up to say 60 kJ/m^{-2} as opposed to some 40 kJ/m^{-2} when uncoated), whereas PUV coatings give the previously quoted values of over 200 kJ/m^{-2}. The difference is explained in terms of the occurrence of Cook-Gordon debonding with PUV, but its absence in SVG systems. Thus it seems that interfacial toughness, rather than the commonly considered interfacial shear strength, may be an important parameter controlling overall composite toughness. The relationships between interfacial toughnesses, in various debonding modes, and interfacial strengths are not clear.

This present paper reports the results of recent experiments with cross-ply layups rather than unidirectional composites. The absolute values of strength and toughness are of course lower, but in general terms the same trends are observed, with markedly improved toughness at high percentage PUV coatings.

Experiments and Results

Tensile strength and toughness specimens were made from layers of intermittently bonded, epoxy composite tape, manufactured on a drum apparatus with a device for coating the filaments, before lay up,(3) with various coating/uncoating sequences. The tape (similar to Avco Rigidite, Prepreg tape) consisted of a 250 μm monolayer of B/W filaments in EPON 828 epoxy, backed, for ease of handling, on 760 mm wide nylon scrim cloth about 50 μm thick. Tensile specimens consisted of 5 layers of tape, arranged in the following orientation sequence 0°/+45°/0/-45°/0, where 0° is the pulling direction. The specimens had a gauge section of some 60 mm x 6 mm x 1 mm. The toughness

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specimens were 7 layer flat coupon specimens (about 76 mm x 76 mm) with long starter cracks, akin to ASTM compact tension specimens (5) in profile. To prevent the composite arms above the crack from shearing off under load, an additional layer of tape was added to each side of the specimen, with filaments parallel to the crack. The central cores of the specimens thus consisted of 5 oriented filament layers in the path of the crack, where, within the limitations of the specimen and tape preparation method, the coated and uncoated layers occurred randomly relative to each filament. The starter crack in these edge crack specimens was made with a profiled diamond slitting wheel. Toughness was measured for increments of crack area, *using Gurney's segmental area technique* (6).

Tensile strength and fracture toughness for the PUV coated crossply specimens are plotted in Figures 1 and 2 against C, the percentage coating. $C = \ell_c/(\ell_c + \ell_{uc})$ where ℓ_c is the coated length, ℓ_{uc} the uncoated length and $(\ell_c + \ell_{uc})$ the repeat distance of the coating pattern along the filaments.

Discussion

The promising results obtained earlier for unidirectional filaments have been duplicated in crossply layups. The absolute values of strength and toughness are less, of course, for the same volume fraction of filaments. Even so, quite respectable strengths and toughnesses are still obtained (300~400 MN/m^2 and 100~200 kJ/m^2 at the higher percentage coatings) coupled with less anisotropy.

A significant contributor to total toughness is the pull-out work performed by those filaments bridging the crack face after passage of the main crack front. Such filaments, broken at distances removed from the main crack plane, can stabilize cracking in specimens that have bad geometric stability factors (7) and which would normally be unstable (e.g the single edge notch (SEN) tensile specimen). Testpieces with filaments bridging the crack faces will not return to the origin upon unloading because of geometric interference (i.e the filaments would have to be pushed back up the holes down which they had been pulled). Usually, when unloading lines do not go back to the origin, it is an indication of generalised yielding at regions remote from the crack tip (cf. the difficulties of testing metals, such as low carbon steels, which have large toughness-to-yield-strength ratios). A means of establishing whether gross irreversibilities away from the crack tip have occurred in filamentary composites is to cut through the fibers bridging the crack faces and beyond into virgin material ahead of the crack tip. If the crack then closes up, it may be assumed that the cause of remaining open was simply geometric interference on the part of the filaments, akin to a residual elastic opening moment at the crack tip. Such an investigation of displacement reversibility is important, since all fracture mechanics is predicated on this fact.

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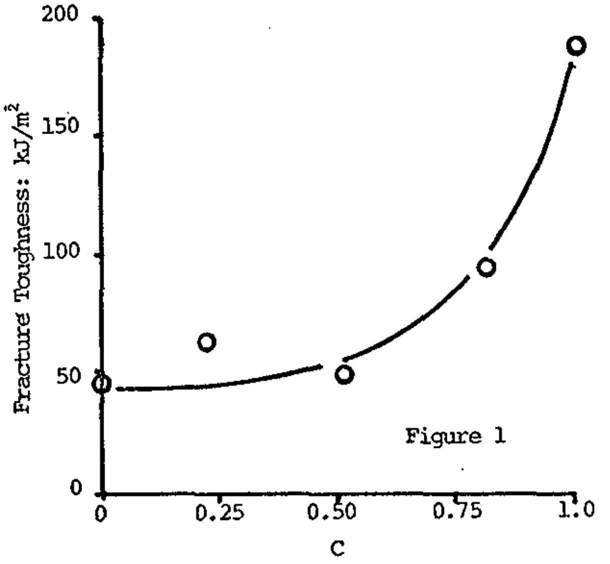

Figure 1

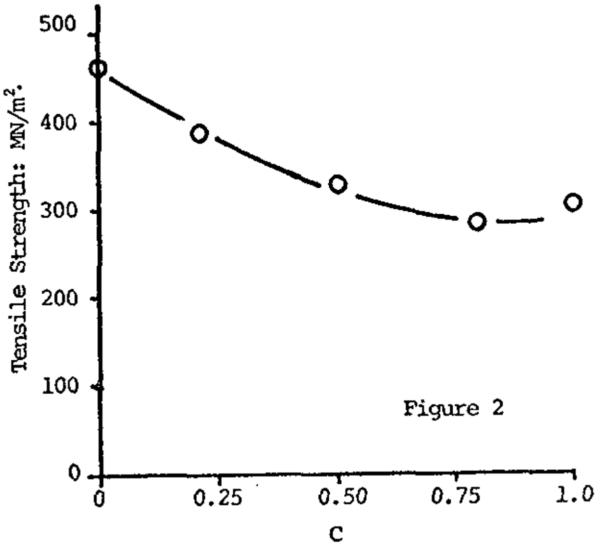

Figure 2