

Fracture behaviour of brittle matrix and alumina trihydrate particulate composites

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This paper focuses onto the fracture behaviour of brittle matrix and alumina trihydrate particulate composites fabricated by hot pressing at 550-650°C. In the study of fracture mechanism, the particle size of particulate phase and volume fraction are varied. Strength, elastic modulus and density have been measured for composites. When the particles are too close to one another, the composites appear as a continuum and the crack front does not interact with the discrete particles. The fracture energy increases with the surface roughness. Larger particles result in larger cracks.

Different classes of composite materials exist, each with its own use and behaviour. The brittle behaviour is elastic to fracture and low fracture toughness. All brittle matrix materials except ceramics and highly cross-linked polymers are excluded from this. Ceramics are the most brittle of materials, exhibiting no yielding prior to fracture up to temperatures usually exceeding one-half of their melting points¹. Brittle polymers exhibit some yielding, but it is negligible compared to less brittle polymers like thermoplastics and metals. Fracture toughness is the resistance of the material to crack propagation and fracture, usually in reference to impact loading.

Polymer-particulate composites are made and most widely used for engineering applications requiring the formability of the polymer phase and properties not intrinsic to the polymer but which can be imparted by a second phase dispersion known as filler. The filler serves two functions. First, its volume displaces that of the more expensive polymers. Second, its physical and thermal properties contribute in forming useful engineering products. Polymers containing alumina trihydrate are used for high voltage insulators due to the arc quenching properties of particulate phase^{2,3}.

The purpose of this paper is to study the fracture behaviour of brittle composite particulates (alumina trihydrate) comprehensively and evaluation of their optimum strength. The framework of fracture mechanism includes: (i) relation between strength and strength controlling factors, (ii) interaction of the crack front with in-homogeneities, (iii) effect of interparticle spacing and surface roughness on

fracture energy and (iv) effect of particle size and volume fraction on strength.

Methodology

The different composites were fabricated by hot pressing the epoxy and particulate phase powder mixtures of alumina trihydrate at temperatures 550 and 650°C. The average particle size of particulate phase and volume fractions were varied. Strength, elastic modulus and density were measured for composites. Specimens were polished to observe cracks. The crack paths through the composites were also examined.

The tensile specimens were tested in tension to determine the elastic modulus experimentally. The elongation of the specimen was measured at each load of application. The tensile curves were then plotted to determine the elastic modulus⁴.

Relation between strength and strength controlling factors

The theoretical strength based on atomic cohesion models is in the range of 1/20 to 1/15 of elastic modulus of composites. But the composites have failed experimentally in the range of 1/100 to 1/250 of elastic modulus. The reason could be the presence of cracks, either the pre-existing cracks or the phenomenon leading to crack nucleation during stressing. Following the Griffith theory, the expression relating the experimental strength and strength required to form new crack, material's elastic property, and the length of the crack are derived as follows:

The rectangular sheet with elastic modulus, E is shown in Fig. 1. The load acting on the sheet is P . The tensile strength within the uncracked sheet is σ (state-I). A small slit crack of length C was first introduced prior to loading to reach state-II.

$$\begin{aligned} \text{Potential energy in the state-I} &= U_1 \\ \text{Potential energy in the state-II} &= U_2 \\ &= U_1 + U_s + U_{sc} + U_p \end{aligned} \quad \dots (1)$$

where, U_s is increase in the potential energy on account of introduction new crack surface, U_{sc} is increase in the strain energy within the sheet, U_p is the potential energy of the load owing to extension, Δx .

$$\text{Potential energy in the state-III} = U_2 + (\delta U_2 / \delta C) dC \quad \dots (2)$$

where, dC is the crack extension.

If the potential energy is not to increase during crack extension, as Griffith theory,

$$(\delta U_2 / \delta C) dC \leq 0 \quad \dots (3)$$

This expression states that the work done on the body by the applied tensile force during crack extension must be either equal or greater than the both the energy required to form new crack and the increase in strain energy within the sheet that accompanies crack extension.

$$U_{sc} = \pi \sigma^2 C^2 / 4E \quad \dots (4)$$

$$U_s = 2C\gamma \quad \dots (5)$$

where, γ , is the energy per unit area to form new crack surface.

$$U_p = -\pi^2 C^2 / 2E \quad \dots (6)$$

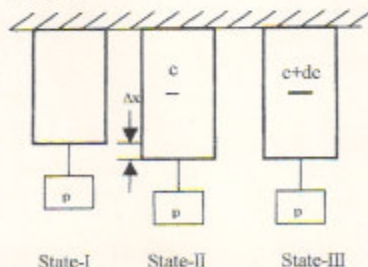


Fig. 1—Three states of a rectangular sheet subjected to tension by a load P

Substituting (4), (5) and (6) into (1) and differentiating with respect to crack length (3)

$$(\delta U_2 / \delta C) dC = [2\gamma - (\pi \sigma^2 C^2 / 2E)] dC \leq 0 \quad \dots (7)$$

The Griffith fracture equation defining the critical applied stress σ_c required to cause crack instability ($dC > 0$) is:

$$\sigma_c = (4\gamma E / \pi C)^{1/2} \quad \dots (8)$$

This equation states that the strength of sheet is not only governed by the presence of cracks but also shows that the experimental strength depends on the size of the crack, C and material properties (fracture energy, γ and the elastic modulus, E). The importance of this equation is that the strength can be analyzed in terms fracture energy, elastic modulus and crack size.

Interaction of the crack front with in-homogeneities

Fig. 2 shows the interaction of the crack front and in-homogeneities. During fracture, steps are formed perpendicular to the moving crack front. Each in-homogeneity momentarily pinned the crack front and the crack front bowed between the pair of pinning positions prior to breaking away. The interaction has established when the crack front wraps around each inhomogeneity. The important observation is that the crack front increases its length as it bows between each pair of pinning positions.

The schematic representation of crack front interaction with an array of equally spaced pinning positions is shown in Fig. 3. Prior to stressing, the crack front is straight. Upon the application a tensile stress, the crack front begins to move between each pair of pinning positions forming new fracture surface

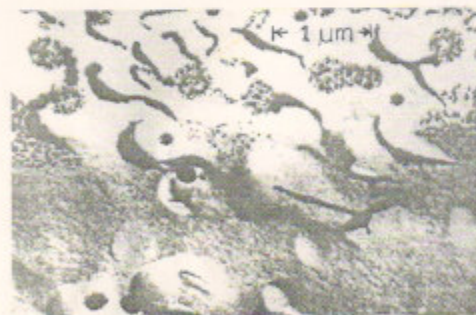


Fig. 2—Fracture surface of epoxy matrix and alumina trihydrate particulate composite

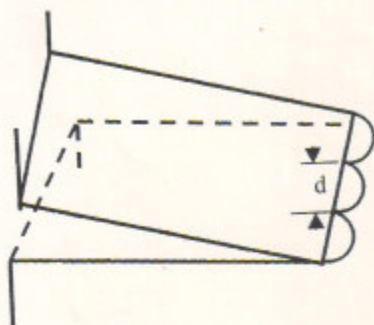


Fig. 3—Schematic representation of the interaction of a crack front with a linear array of dispersed inhomogeneities, equally spaced by a distance d

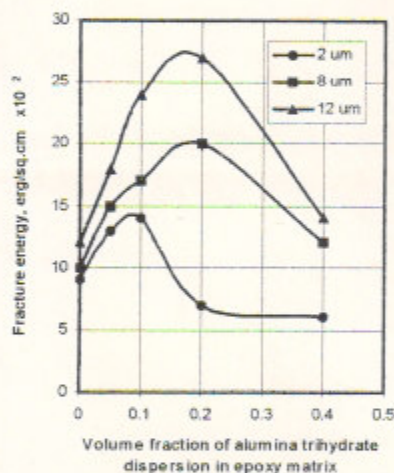


Fig. 4—Effect of interparticle spacing and surface roughness on the fracture energy

area and its increasing length. To accomplish this, work must be done by the applied forces both to form the newly fractured surfaces and to create the increased crack front length.

Effect of interparticle spacing and surface roughness on the fracture energy

The mean distance between alumina trihydrate particles was varied by fabricating different composites containing one by three average particle size dispersions (viz., either 2, 8 and 12 μm dispersions) and one of three volume fractions of (viz., either 0.05, 0.20 and 0.30) of these fractions.

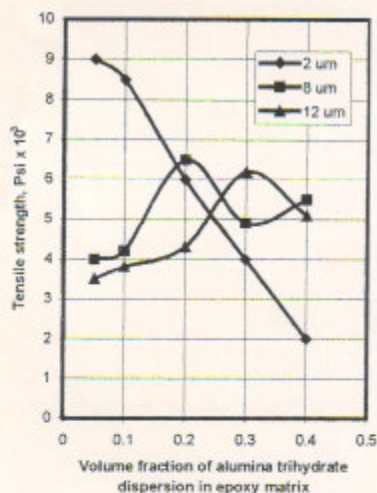


Fig. 5—Effect of particle size and volume fraction on the strength

The results of this investigation are illustrated in Fig. 4. The largest particle size dispersion has the greatest effect. The decrease in the fracture energy from the maximum is caused by an ineffective interaction when the particles became closely spaced. When the particles were too close to one another, the composite appeared as a continuum and the crack front did not interact with the discrete particles. The intercept values of the curves with the y-axis give the effects of surface roughness on the fracture energy. The fracture energy increases with the surface roughness.

Effect of particle size and volume fraction on the strength

The effect of particle size and volume fraction is shown in Fig. 5. In comparing the product γE for these composites with that of the matrix, each of the three series exhibits a maximum with respect to volume fraction. These maxima occur at 0.05, 0.30 and 0.20 volume fractions for the 2, 8 and 12 μm series, respectively. For the 2 μm series, γE decreases from that of the matrix value at volume fractions > 0.15 . For the other two series, γE is significantly larger than that of the matrix value at all volume fractions and is largest for the 12 μm series relative to the 8 μm series. At volume fractions < 0.10 , the smallest particle size dispersion results in the optimum strength, and at volume fractions > 0.10 optimum strengths can be obtained for either of the

larger particle size dispersions at the volume fractions where γE exhibits maximum values.

Conclusions

The strength of brittle composites can be analyzed with the three controlling factors, viz., the fracture energy, elastic modulus and crack size. The interaction has established when the crack front wraps around each inhomogeneity. The decrease in the fracture energy is caused by an ineffective interaction when the particles became closely spaced. When the particles are too close to one another, the composite appears as a continuum and the crack front does not interact with the discrete particles. The fracture energy increases with the surface roughness. Although larger particle size dispersions result in

larger fracture energies, they also are more effective crack precursors and form larger cracks.

Since an increased fracture energy and an increased crack size are competitive strength controlling factors, a compromise must be made with regard to the particle size to obtain the optimum composite strength at a given volume fraction.

References

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