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Effect of filler geometry on fracture mechanisms in glass particle filled epoxy composites

A.L. Yesgat, R. Kitey *

Department of Aerospace Engineering, Indian Institute of Technology Kanpur, 208016, India

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ABSTRACT

Quasi-static experiments are conducted on epoxy systems, embedded with milled-fibers and spherical glass particles, to study the effect of filler shape and volume fraction on the flexural and fracture characteristics of polymer composites. While the flexural modulus and fracture toughness of composites monotonically increase with filler volume fraction, the values are consistently higher for the milled-fiber case. On the contrary better flexural strength is achieved by reinforcing spherical particles. Besides reinforcement dependent toughening mechanisms the effect of process zone evolution in the form of filler/matrix debonding is evident from the fracture surface micrographs. Due to instantaneous fracture in spherical particle composites the process zone is restricted to a narrow strip in the vicinity of the initial crack front whereas the slow stepwise crack growth in slender filler case let the process zone evolve in pockets over the entire fracture surface. In general crack deflection process is dominant in spherical particle composites whereas fiber bridging in slender filler case is followed by fiber pull-out, fiber fracture and matrix cracking. Computational study of crack–inclusion interaction indicates that the crack-leg bridging has extensive influence on fracture parameters when compared to the crack-tip shielding. The fracture parameters get exponentially magnified with the crack-tip approaching the inclusion if spaced at less than a characteristic distance. The skewed orientation of slender fillers induces mode-mixity at microscopic scale which in turn improves macroscopic fracture behavior of composites.

1. Introduction

Rigid filler reinforced polymer composites have evolved into versatile engineering materials due to their ability of attaining application oriented thermo-mechanical, adhesive and dielectric properties. Because of easy processibility and resistance to corrosion and moisture ingression they are becoming integral part of semiconductor and MEMS devices [1], aerospace and structural components [2] and bio-mechanical systems [1]. In general the reinforced composite properties are tailored by varying shape, size, volume fraction, surface morphology and adhesion characteristics of secondary phase fillers. Particularly, the failure properties such as tensile strength and fracture toughness are significantly influenced due to the material discontinuities at the filler–matrix interface.

Most studies on mechanical characterization of filler composites are conducted either by reinforcing regular shaped (mostly spherical) particles [3–7] or by embedding randomly shaped fillers [8–11] into the matrix material. By

* Corresponding author. Tel.: +91 512 259 7060.
E-mail addresses: yesgat@iitk.ac.in (A.L. Yesgat), kitey@iitk.ac.in (R. Kitey).

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Nomenclature

V_f	filler volume fraction
V_f^*	filler volume fraction (measured)
V_m	matrix volume fraction
V_v	void volume fraction
ρ_f	density of filler material
ρ_m	density of matrix material
ρ_{ct}	theoretical density of composite
ρ_{ce}	experimental density of composite
m	slope of load vs. displacement curve
E_f	flexural modulus
σ_f	flexural stress
σ_{fu}	flexural strength
ε	flexural strain
S	beam geometry: Span
W	beam geometry: Width
B	beam geometry: Thickness
P	symmetrically applied load to SENB specimen
δ	midspan deflection of beam
a	crack length
ξ	a/W ratio
K_I	stress intensity factor in mode-I
K_{Ic}	mode-I fracture toughness
K_{II}	stress intensity factor in mode-II
K_{Ieff}	effective stress intensity factor (mixed-mode)
$(K_I)_{ep}$	stress intensity factor of neat epoxy
J	J-integral
Ψ	mode-mixity
r	distance from the crack-tip
θ	angle from the crack orientation
θ_c	prospective direction of crack propagation
σ_{yy}	crack opening stress ahead of crack-tip
σ_{xy}	shear stress ahead of crack-tip
$\sigma_{\theta\theta}$	tangential stress around the crack-tip
d	distance of inclusion from the crack-tip
β	orientation of inclusion from the crack direction
D_{eq}	equivalent inclusion diameter

experimentally analyzing micron and submicron silica reinforced epoxy systems (up to 0.35% volume fraction), Adachi et al. [3] showed that the elastic modulus of composite was marginally affected by the filler size but the fracture toughness was reported to be increasing with increasing filler volume fraction (V_f) and decreasing filler size. Spanoudakis and Young [4] used glass particles up to 62 μm diameters to reinforce the epoxy and demonstrated that the elastic modulus and fracture toughness of the composites increased with increasing V_f but the increasing particle size adversely affected the elastic and fracture parameters. They suggested that the fracture characteristics in the presence of fillers were improved due to crack-tip blunting mechanism. Jajam et al. [5] reported that the epoxy system, when embedded with nano silica particles at low volume fractions, exhibited better fracture characteristics when compared to the micron size fillers under quasi-static loading conditions, however, the reverse effect was observed for the dynamic loading case. They also suggested that the elastic properties of the composites were relatively uninfluenced by the particle size. By reinforcing glass particles of sizes up to 200 μm into the epoxy, Kitey and Tippur [6] reported that the weakly bonded fillers were better in enhancing dynamic fracture properties of composites when compared to the strongly bonded ones but the elastic properties remained unaffected by the filler size or filler matrix adhesion strength. They suggested that for an optimal particle size the maximum fracture toughness was achieved. By using silica, alumina and silicon carbide fillers of sizes up to 300 μm, Moloney et al. [7] showed that the elastic modulus and fracture toughness of epoxy composites increased with increasing filler volume fraction but they were not influenced by the filler size. They also reported higher fracture toughness values for the composites prepared with untreated fillers when compared to the silane treated ones.