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Effect of particle size distribution on debonding energy and crack resistance of polymer composites

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ABSTRACT

Crack resistance of particle reinforced polymers is affected by the size distribution of particles. Particle debonding is a major dissipation mechanism that contributes itself and triggers other mechanisms such as matrix shear bands or plastic void growth. Assuming the specific debonding energy at the particle/matrix interface as independent of particle size together with the debonding criterion that depends on the particle size leads to analytical expressions that depend on the parameters of the particle size distribution function as well on the debonding probability function. But numerical results show nearly constant crack resistance by changing mean particle size. Using instead a debonding criterion with the supposition that debonding stress does not depend on particle size reveals that smaller particles increase facture toughness. The increase is significant for composites with particle size distribution functions that show small standard deviations. However, should the debonding energy at the interface be proportional to the particle diameter then the crack resistance remains constant by changing particle size for both debonding criteria.

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1. Introduction

Throughout the last decades the subject of improving the mechanical properties of particle filled polymers received large attention and a bulk of publications exists. A survey about this development was given by Fu et al. [1]. The particle size plays a decisive role among the structural and mechanical properties of the components and at the interface that influence the crack resistance, see, for example, Singh et al. [2]. Depending on the used particle or matrix materials crack resistance may increase or decrease with changing particle size distribution parameters. The variation of composite fracture toughness with particle volume fraction for different particle sizes is shown in Fig. 1 for an aluminium–polyester composite. Modelling of crack resistance for composites with particles of mean size was proposed for example by Evans et al. [3], Huang and Kinloch [4], Hsieh et al. [5], Williams [6] and Refs. [7,8]. Evans and Faber [9] developed a basic model for fracture toughness calculation considering particle size distribution, but basic equations are contradictory in the used approximations concerning the particle size dependence.

In the present paper the crack resistance of particle composites caused by particle/matrix debonding was modelled. As in real composites the particle size distribution is considered. The sequence of analysis consists of the presentation of basic equations for crack resistance calculation, followed by the description of the stress field in front of a crack. The size of the dissipation zone was calculated on the basis of linear elastic fracture mechanics. The volume specific debonding energy is calculated as a function of the position in front of a crack for different debonding stress criteria. Subsequent integration over the particle size distribution and the dissipation zone size provides the contribution of particle debonding to the crack resistance of the composite. The analysis of the particle debonding mechanism will be aimed to understand the direct contribution to crack resistance and as a trigger for subsequent mechanisms as, for example, plastic void growth.

2. Crack resistance, fracture toughness

To initiate the propagation of an existing crack, energy must be available. The composite energy release rate G (available from the change of the elastic energy and the applied load for an increment of crack growth) must at least be equal to the energy necessary R_c (crack resistance) to initiate crack propagation. This is expressed usually as: $G \geqslant G_c = R_c$ with G_c as fracture toughness of the composite (all these quantities as energy per unit area of crack growth). The fracture processes act in different zones: there are processes immediately near the crack surfaces, which is termed as process zone. The second group are the more extended structural processes, as for example particle/matrix debonding, which takes place in the debonding zone. These zones are illustrated in Fig. 2. This kind of subdivision of the region in front of the crack can be

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Nomenclature

A_d	debonded particle surface
A_{ij}^k, B_{ij}^k, C_{ij}^k	stress concentration factors, $k = (p, m)$, $i = (x, y, z)$
B	material parameter as defined in Eq. (5.7)
d_p	particle diameter and mean particle diameter if no size distribution
$d_{p,j}$	particle diameter of the class j
$d_{p,\min}$, $d_{p,\max}$	minimum and maximum particle diameter, respectively
E_c	composite modulus
E_p	particle modulus
E_m	matrix modulus
f_n	normalized particle size distribution function
G	energy release rate (energy per unit area of crack)
G_c	critical energy release rate of the composite
h_j	relative frequency of particles of the diameter class j
m	parameter of the debonding probability distribution
N_j	number of particles with the diameter $d_{p,j}$
N_p	total number of particles
n_j	particle volume density of diameter class j
n_p	total particle volume density
P_d	probability of debonding at the particle/matrix interface
r, θ, ϕ	spherical coordinates of the particle
R_c, R_m	crack resistance of composite and matrix (energy per unit area of crack)
R_c^0	composite crack resistance for mean particle size, stress debonding criterion
$R_{c,en}^0$	composite crack resistance for mean particle size, energy debonding criterion
R_d^0	specific debonding energy for mean particle size, stress debonding criterion
$R_{d,en}^0$	specific debonding energy for mean particle size, energy debonding criterion
R_{dz}	specific dissipation zone energy (energy per unit area of crack)
R_{pz}	specific process zone energy (energy per unit area of crack)
S_f	surface parameter as defined in Eq. (5.4)
v	particle volume fraction
v_j	particle volume fraction of the diameter class j
V	total volume of particles
V_f	volume parameter as defined in Eq. (3.2)
W_d	debonding energy of one particle
β	shape factor of dissipation zone
γ_d	specific fracture surface energy of fibre/matrix interface (specific debonding energy)
κ	stress concentration factor
η_d	energy density of the debonding mechanism (energy per volume)
ν_m, ν_p	Poisson's ratio of matrix and particle, respectively
ρ, ϕ	radial and angular coordinates of the particle centres with the origin at the crack tip
ρ_d	half width of dissipation zone for debonding
$\sigma_{c,ij}$	composite stress components, $i = (x, y, z)$
$\sigma_{c,d}$	composite stress ($\sigma_{c,zz}$) for particle/matrix debonding
σ_d	debonding stress (radial stress component) at fibre/matrix interface, stress criterion
σ_d^γ	debonding stress (radial stress component)at fibre/matrix interface, energy criterion
σ_0	mean debonding strength, parameter of Weibull distribution
ω_d	slope of the function: $\gamma_d = \omega_d d_p$

traced back to the works by Evans and Faber [9]. In the following only the debonding process is taken into account, for other possible mechanisms the same general procedure can be used. The total crack resistance can be calculated by the separate contributions of the mechanisms in the process zone and debonding within the dissipation zone, as:

$$R_c = R_{pz} + R_{dz} = R_{pz} + R_d = R_{pz} + 2\int_0^{\rho_d} \eta_d(\rho)d\rho \quad \text{or}$$
$$R_c = R_{pz} + 2\eta_d\rho_d \tag{2.1}$$

where R_{pz} and R_{dz} are the specific fracture energies of the process and dissipation zone, respectively (as energy per unit area of crack), η_d is the volume density of debonding energy, ρ is the distance from the crack tip and ρ_d is the width of the debonding zone. For the special case that η_d is independent of the distance, ρ, to the crack tip the integral can be carried out directly (second equation of Eq. (2.1)). For the calculation of the width of debonding zone, ρ_d, the approximation for the plastic zone of homogeneous materials, as used for example by Wetzel et al. [10], is extended for the compos-

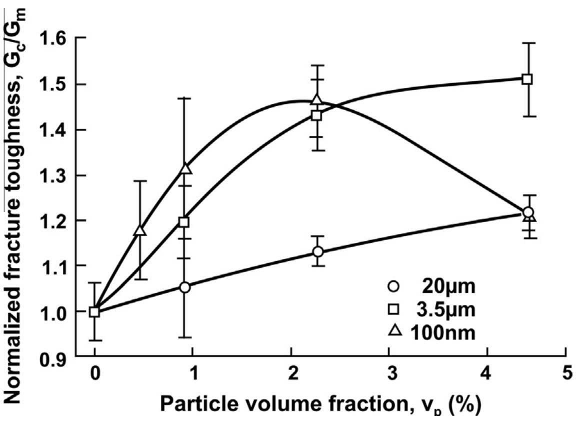

Fig. 1. Normalized fracture toughness of aluminium–polyester composites plotted against particle volume fraction for various particle sizes. Adapted from [2].

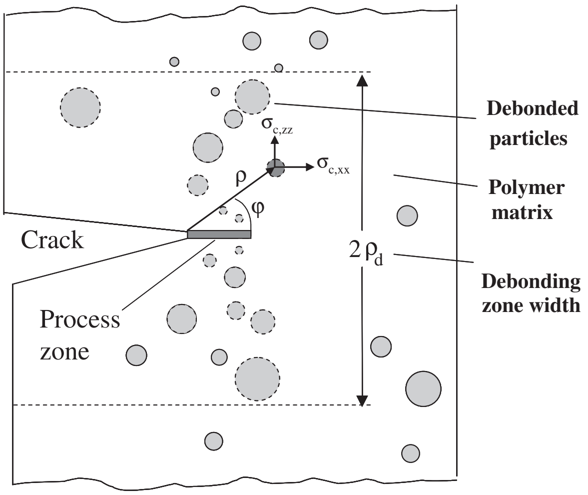

Fig. 2. Debonding and process zones in front of a crack; radius of debonding zone ρ_d, particle size distribution.

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