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Application of the material inhomogeneity effect for the improvement of fracture toughness of a brittle polymer

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ABSTRACT

In a multilayered structure with a crack, a spatial change in the mechanical properties of the material strongly influences the crack driving force. This material inhomogeneity effect can be utilized to improve the fracture toughness of a given structure by inserting thin, soft interlayers into the material. The effectiveness of this procedure has been demonstrated on high-strength materials, such as metallic alloys and ceramics. It is shown in this article that the material inhomogeneity effect can be also successfully applied to polymers and that it is possible to predict the improvement in fracture toughness by a numerical analysis. First, a numerical case study based on the configurational force concept is performed on a brittle polymer matrix with interlayers made of materials with different strength and Young's modulus. After selecting the most appropriate interlayer material, a composite is fabricated, which contains a single interlayer. Fracture toughness experiments show approximately 7 times higher fracture toughness for the composite in comparison to the homogeneous matrix material. Numerical fracture mechanics tests are performed on homogeneous and composite material using the cohesive zone model for crack growth simulation. A procedure to calibrate the cohesive zone parameters is worked out, which is relatively easy for the homogeneous material, but more sophisticated for the composite material. The numerical analysis provides a tool for predicting the fracture toughness of multilayered polymer composites.

1. Introduction

It is a common practice to improve the fracture toughness and strength of a component by combining two different materials in various fashions [1–3]. Many of the naturally occurring materials, such as nacre and bone, are found to have enhanced fracture toughness and strength owing to the complex arrays of different materials [4–7]. Munch et al. [8] showed in his study that Al_2O_3, which has a fracture toughness of approximately 2.5 $MPa\sqrt{m}$, when combined with lameller Polymethylmethacrylate (PMMA), results in a fracture toughness of 15 $MPa\sqrt{m}$. The fracture toughness of multilayered components can improve by different extrinsic mechanisms, such as crack deflection and meandering, zone shielding, contact shielding, etc. [9]. However, the fracture toughness of a multi-layer system can be influenced just by the presence of material inhomogeneity. The material inhomogeneity effect arises due to a spatial variation of the mechanical property of the material. In presence of a material inhomogeneity, the crack driving force

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Nomenclature

List of symbols and abbreviations

a_o	initial crack length
b_o	initial ligament length
dl	a line element of an interface
$\mathbf{e}$	unit vector in the direction of crack extension
$\mathbf{f}$	configurational force vector
r_{pl}	plastic zone radius
t	thickness of interlayer
B	thickness of fracture mechanics specimen
B_N	net thickness of fracture mechanics specimen
C_{IF1}, C_{IF2}	material inhomogeneity due to first interface, and second interface
C_{inh}	material inhomogeneity term
E	Young's modulus
H	full length of the fracture mechanics specimen
J	J-integral
J_o	experimental J-integral
J_{exp}	experimental J-integral with crack growth correction
J_{num}	numerically evaluated J-integral
J_{tip}	near-tip J-integral or crack driving force
J_{far}	far-field J-integral
J_C	fracture initiation toughness measured in terms of J-integral
L	distance of first interface from current crack tip
P	force applied to the fracture mechanics specimen
S	span length of a single edge notched bend specimen
η	dimensionless parameter with a value of 2 for single edge notched bend specimen
δ	separation distance in cohesive elements
δ_i	separation distance at damage initiation in cohesive elements
δ_f	separation distance at failure in cohesive elements
ε_{eng}	engineering strain
$\varepsilon_{eng,pl}$	engineering plastic strain
ε_{true}	true strain
$\varepsilon_{true,pl}$	true plastic strain
v_{LL}	load line displacement
ψ	J reduction coefficient
σ_o	yield strength
σ_{eng}	engineering stress
σ_{true}	true stress
Γ	separation energy
Σ	contour along the interface between two materials
Δa	amount of crack extension
Δa_{preIL}	amount of crack extension before an interlayer
Δa_{postIL}	amount of crack extension after an interlayer
CDF	crack driving force
CPE4	bilinear plane strain quadrilateral element
CPS4	bilinear plane stress quadrilateral element
CZ	cohesive zone
ESIS	European Structural Integrity Society
FE	finite element
min	minutes
mm	millimeters
NSG	non side grooved
P1, P2	interlayer materials
Roller-1	loading roller in a single edge notched bend specimen
Roller-2	support roller in a single edge notched bend specimen
SENB	single edge notched bend specimen
SG	side grooved
TSL	traction separation law

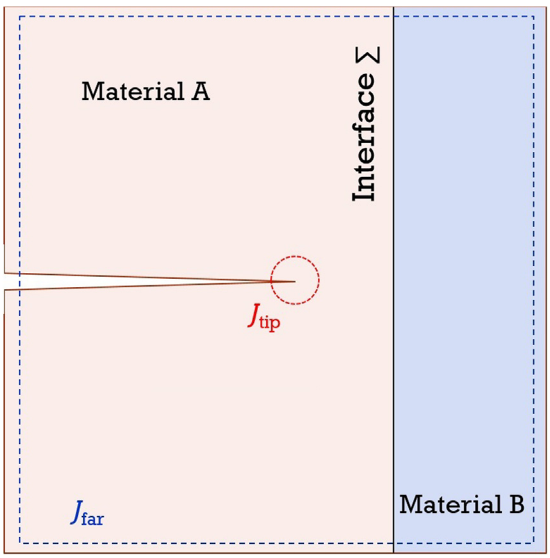

Fig. 1. Schematic representation of the material inhomogeneity, C_{inh}, in presence of an interface between Material A and Material B in front of a crack.