Engineering Fracture Mechanics 126 (2014) 166–177

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Experimental procedure to characterize the mode I dynamic fracture toughness of advanced epoxy resins

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ARTICLE INFO

Article history:
Received 20 December 2013
Received in revised form 18 April 2014
Accepted 26 May 2014
Available online 8 June 2014

Keywords:
Dynamic fracture mechanics
Stress intensity factor
Toughened epoxy resin
Experimental strain analysis
Fast crack growth

ABSTRACT

This research aimed at developing an experimental procedure to characterize the dynamic fracture toughness of a fast running crack in advanced epoxies enriched with thermoplastic particles and demonstrating quasi-brittle fracture. A strain gauge method was defined to determine the dynamic stress intensity factor K_{ID} for the mode I crack opening with various crack speeds. This strain gauge measurement was associated with high speed cinematography on a three point bending test dedicated to the fracture of notched specimens made of the Hexply®M21 epoxy resin. Results demonstrate that the crack propagation speed has a large influence on the dynamic fracture toughness of advanced epoxy resins.

1. Introduction

Impact loadings on laminated composite materials may damage the interlaminar phase up to initiate, even rapidly propagate the delamination process. This large decohesion critically compromises the integrity of the light weight composite structures. The material constituting the interlaminar phase must ensure overall cohesion and resist crack propagation. In this framework, thermoset epoxy resins are incorporated in most Carbon Fiber Reinforced Polymers (CFRPs) since they present good mechanical properties while exhibiting a satisfactory damage tolerance. Moreover, epoxy resins are classically reinforced with thermoplastic inclusions that improve not only their fracture toughness [1] but also the delamination resistance of the laminated CFRPs [2]. Advanced epoxy resins considered in this research are highly cross-linked thermoset polymers, enriched with embedded thermoplastic nodules (Fig. 1) and demonstrating quasi-brittle fracture. As a combination of various glassy polymers, fracture in these modified epoxies involves a competition between crazing and shear yielding [3]. Crazing is a process of plastic deformation that is an important source of fracture toughness for thermoplastics [4]. The extension of crack surface by crazing in the thermoplastics involves successively alignment [5], stretching and breakdown of the molecular chains [6]. On the other hand, the crazing process is of moderate importance for highly cross-linked thermoset materials which rather develop localized shear yielding [7]. These two fracture mechanisms are strain rate dependent [7] which affects the toughness of glassy polymers when dynamic conditions prevail. For example, experimental studies on polymethylmethacrylate (PMMA) actually reported that the loading rate influences the fracture toughness of crack initiation [8,9]. Some authors also observed a strong variation of the fracture toughness and an increase in the crack surface roughness

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http://dx.doi.org/10.1016/j.engfracmech.2014.05.010
0013-7944/

Nomenclature

$a,\ \dot{a}$	crack length (mm) and crack velocity (m s^{-1})
$A_0 \cdot f_0(\dot{a}, \theta, \alpha)$	singular term of the asymptotic strain description (MPa)
$A_1 \cdot f_1(\dot{a}, \theta, \alpha)$	non-singular term of the asymptotic strain description (MPa)
$A_2 \cdot f_2(\dot{a}, \alpha)$	term of the asymptotic strain description independent of the crack tip position (MPa)
$c_1,\ c_2$	dilatational and shear wave speed in the material (m s^{-1})
d_{x_1}	distance from the strain gauge to the notched edge of the specimen (mm)
d_{y_1}	distance from the strain gauge to the crack path (mm)
E	Young modulus (MPa)
E_{frac}	apparent modulus calculated from the fracture parameters (MPa)
E_{stiff}	apparent modulus deduced from the specimen stiffness (MPa)
$f(a/w),\ \Phi(a/w)$	dimensionless correction factors used for the standard analysis
$F_c,\ U_c$	critical load (N) and associated critical displacement (µm)
G_{IC}	critical energy release rate (J m^{-2})
h	specimen thickness (mm)
K_{IC}	mode I critical stress intensity factor (MPa $\sqrt{m}$)
K_{ID}	mode I dynamic stress intensity factor (MPa $\sqrt{m}$)
k_{ns}	ratio of the non-singular coefficient A_1 on the singular coefficient A_0 (m^{-1})
l	specimen length (mm)
L	distance between the lower supports (mm)
p	pins diameter (mm)
$r,\ \theta$	polar coordinate system to describe the strain gauge position in the $(x_1,\ y_1)$ system
$r_i,\ \theta_i$	polar coordinate system to describe the point $(x_1, y_1 = \lambda_i r \sin(\theta))$
r_p	plastic zone radius (mm)
S	specimen stiffness (N m^{-1})
t	time (µs)
w	specimen width (mm)
$x_1,\ y_1$	coordinate system relative to the crack tip
$x_2,\ y_2$	coordinate system relative to the strain gauge
α	angle between the strain gauge measuring direction and the crack direction
β	dimensionless coefficient function of the crack velocity
$\Delta t^p_{x/10}$	time between the rise of strain at $x/10$ of the peak strain and the peak strain (µs)
ϵ_g	asymptotic strain recorded by the gauge (def)
ϵ_g^p	maximum asymptotic strain value recorded by the gauge (peak strain) (def)
κ	dimensionless coefficient depending on the Poisson's ratio
$\lambda_1,\ \lambda_2$	dimensionless coefficients function of the crack velocity
μ	shear modulus (MPa)
ν	Poisson's ratio
ρ	material density (kg m^{-3})

Abbreviations

CFRP	composite fiber reinforced polymer
DCB	Double Cantilever Beam
PMMA	polymethylmethacrylate
SENB	Single Edge Notched Bending specimen

of PMMA with the crack propagation speed $\dot{a}$ [10,11]. As a consequence, the fracture toughness of toughened epoxy resins is expected to be sensitive to dynamic parameters such as the loading rate or the crack propagation speed $\dot{a}$.

For a mode I crack opening, the material fracture toughness is characterized by the critical stress intensity factor K_{IC} defined by Irwin [12] to describe the asymptotic crack tip stress field at the initiation time. The critical stress intensity factor K_{IC} is classically determined by a three point bending quasi-static test on a notched specimen according to the ISO 13586:2000(F) standard [13]. This parameter is assigned to quasi-static loadings and then is inappropriate to characterize the mechanical behavior of epoxy resins in case of impact. The dynamic stress intensity factor K_{ID} is preferred to model dynamic crack opening and fast propagation stages [14]. Kanchanomai et al. [15] identified the dynamic stress intensity factor K_{ID} at the onset of propagation in epoxy specimens using the ISO 13586:2000(F) standard [13] with dynamic loadings. In this study, a decrease in the epoxy initiation toughness was observed as the loading rate moves from quasi-static to dynamic. This experimental method is justified for dynamic loading rates assuming that a state of equilibrium exists in the specimen while the crack does not propagate. Conversely, dynamic effects associated with fast crack propagation imply a very transient state of stress in the specimen. Thus the ISO 13586:2000(F) standard [13] analysis is clearly unsuitable to