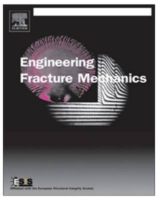
Engineering Fracture Mechanics 108 (2013) 89–97

Contents lists available at SciVerse ScienceDirect

Engineering Fracture Mechanics

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



Crack path support for deformation mechanisms in fatigue of polycarbonate

M.N. James [a,b,*], Y. Lu [a], C.J. Christopher [a], E.A. Patterson [c]

[a] *School of Marine Science & Engineering, University of Plymouth, Drake Circus, Plymouth PL4 8AA, England, United Kingdom*
[b] *Department of Mechanical Engineering, Nelson Mandela Metropolitan University, Port Elizabeth 6031, South Africa*
[c] *School of Engineering, University of Liverpool, The Quadrangle, Brownlow Hill, Liverpool L69 3GH, England, United Kingdom*

ARTICLE INFO

Keywords:
Crack path
Polycarbonate
Fractography
Deformation mechanisms
Crack growth

ABSTRACT

A significant amount of research has been directed towards characterising and predicting sub-critical crack growth mechanisms in polycarbonate (PC) materials. In particular the initiation of crazes, damage evolution and growth of fatigue cracks has attracted significant attention. It is only relatively recently that there has been clarification of the underlying physics of craze initiation and growth, and of the craze influence on crack paths. In the interpretation of mechanisms of deformation, the polymer community has perhaps not embraced the use of fractographic crack path information as fully as the metals community. This paper considers the ability of advanced imaging techniques including confocal laser scanning microscopy (CLSM), and field emission scanning electron microscopy (FESEM) to provide evidence of crack path morphology for existing models of plastic deformation and crazing in amorphous polycarbonate. It also presents the outline of a new model of crack tip stresses which takes account of craze-induced shielding mechanisms and appears able to characterise fatigue crack growth in PC.

1. Introduction

Polycarbonate (PC) is an amorphous polymer that is now widely used in structural or load-bearing applications. Along with other 'engineering' polymers such as polyoxymethylene (POM) and polytetrafluoroethylene (PTFE) it has unique characteristics of optical transparency (including birefringence, which leads to many photoelastic applications), good toughness and rigidity which confer excellent impact resistance, even at relatively high temperatures. These properties have led to many applications in product design (e.g. compact discs, power tool casings, medical devices) as well as structural uses where its impact-resistance is beneficial (e.g. aircraft windscreens, vehicle parts, hard hats and transparent lightweight armour [1]). PC has outstanding ballistic impact strength but has poor chemical resistance and can scratch easily; hard coatings, e.g. diamond-like carbon are necessary on the surface, and laminating with a second material, e.g. polymethyl methacrylate, confers superior performance [1,2].

The broad range of structural applications for PC devices has motivated much research directed at characterising and predicting sub-critical crack growth mechanisms in polycarbonate materials. In particular, the initiation of crazes, damage evolution and growth of fatigue cracks has attracted significant attention. Because of the complexity of damage mechanics and craze initiation in polymers, combined with a multiplicity of approaches, it is only relatively recently that there has been clarification of the underlying physics of craze initiation and growth, and of the craze influence on crack paths. A possible

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* Corresponding author at: School of Marine Science & Engineering, University of Plymouth, Drake Circus, Plymouth PL4 8AA, England, United Kingdom. Tel.: +44 1752586021.

E-mail address: mjames@plymouth.ac.uk (M.N. James).

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http://dx.doi.org/10.1016/j.engfracmech.2013.02.003

Nomenclature

PC	polycarbonate
CLSM	confocal laser scanning microscopy
FESEM	field emission scanning electron microscopy
SEM	scanning electron microscopy
POM	polyoxymethylenbe
PTFE	polytatrafluoroethylene
MPa	megapascal
GPa	gigapascal
3D	three-dimensional
K_F	a stress intensity factor analogous to K_I which drives forwards crack growth
K_S	an interfacial shear stress intensity factor induced by compatibility at the elastic–plastic interface
K_R	a retarding stress intensity factor which opposes crack growth and acts along the plane of the crack
Z	is the complex coordinate in the physical plane where $z = x + iyx$ and y are coordinates in a Cartesian system with the origin at the crack tip
A, B, C, D and E	unknown coefficients that need to be determined
R	stress ratio (minimum stress/maximum) in an applied fatigue cycle

additional reason for this late understanding may relate to the fact that fractography, i.e. the science of the study of fracture surfaces, has not been as widely used in the interpretation of cracking mechanisms as has been the case for metals.

The crack path through a material and the fracture surface appearance on a macro and microscale provide a complete record of cracking events provided that they can be interpreted and understood. This interpretation is generally more complex in polymers than in metals, with complexity arising from factors such as the viscoelastic constitutive behaviour, hysteretic energy loss, molecular weight effects and the different behaviour observed in the crazed region.

This paper takes a fractographic crack path approach to supporting existing models of plastic deformation and crazing in amorphous polycarbonate. Images and data obtained using advanced imaging techniques, e.g. confocal laser scanning microscopy, CLSM, and field emission scanning electron microscopy, SEM, will be presented and discussed in the context of their utility in explaining crazing and crack growth mechanisms. Finally it outlines briefly a new model of crack tip stresses which takes account of craze-induced shielding mechanisms and appears able to characterise fatigue crack growth in PC. The model has been fully detailed elsewhere [3,4].

1.1. Material and specimens

The material used in this work was 2 mm sheets of clear polycarbonate supplied as either Bayer Makrolon® GP099 or Lexan SL 2030 clear extruded polycarbonate (density 1.2 g/cm^2) in sheets 1.5 m by 1.0 m. The properties of this polycarbonate material relevant to fatigue crack growth are Poisson's ratio = 0.38, initial yield strength = 60 MPa, cyclic yield strength = 30 MPa and modulus of elasticity = 2.3 GPa. The tensile cyclic yield strength is much lower than the uniaxial yield strength, indicating that significant softening occurs under cyclic loading before any subsequent strain hardening commences. Compact tension specimens with non-standard dimensions (given in Ref. [4]) were cut from these sheets such that the crack growth direction was perpendicular to the direction of extrusion in the PC sheet. The extended width W in this non-standard specimen provides a greater length of usable fatigue crack growth for the experimental measurements. This geometry necessitates the use of a wide-range stress intensity calibration to determine K values. The equation used was the wide-range expression proposed by Srawley and Gross [5], which is referenced in the ASTM standard E-399 that deals with plane strain fracture toughness testing.

2. Crack path support for plastic deformation and crazing

Structural applications of PC often require detailed knowledge of its deformation mechanisms, and the process of crack initiation and growth under loading; in particular the formation and growth of crazes and the development of cracks in a crazed region. These issues have received very significant attention over the last 40 years, (e.g. [6–13]) with a wide variety of models being proposed to explain observed deformation and crack growth behaviour. Shear yield stress and crazing stress are the factors that determine the deformation and fracture mechanisms in amorphous polymers. Research has therefore variously focussed on constitutive laws and yielding models [6,9,10], on damage and strain energy models [12,13] and on fracture mechanics models for stress intensity [14–16]. The fracture mechanics models generally assume a Dugdale strip-yielding zone of plastic deformation as this is analogous to the observation of a crazed strip ahead of the crack tip [14,15]. Passaglia [9] has discussed this in some detail, noting that the displacement profile of the craze tip is similar to the Dugdale model with the difference that the stress distribution in the tip region of the craze is not constant, as is assumed in the Dugdale model, but has peaks in stress occurring at the craze and crack tips.