Journal of the Mechanics and Physics of Solids 61 (2013) 1407–1420

Contents lists available at SciVerse ScienceDirect

Journal of the Mechanics and Physics of Solids

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

Identification of a cohesive zone model from digital images at the micron-scale

Julien Réthoré [a],*, Rafael Estevez [b]

[a] Université de Lyon/INSA Lyon/CNRS/LaMCoS, 20 Avenue des Sciences, F-69621 Villeurbanne Cedex, France
[b] SIMaP UMR 5266, Université de Grenoble/CNRS/Grenoble-INP/UJF, 1130 rue de la Piscine, B.P. 75, F-38402 St Martin d'Hères cedex, France

ARTICLE INFO

Article history:
Received 19 November 2012
Received in revised form
25 January 2013
Accepted 28 January 2013
Available online 11 February 2013

Keywords:
Crack tip fields
Cohesive model
DIC
Inverse problem
Identification

ABSTRACT

We present a new methodology for the identification of a zone cohesive model that describes material failure. The material under consideration fails by crazing. The study is conducted at the micron scale in order to capture and analyze the fracture mechanism. The crack tip displacement fields are measured optically by Digital Image Correlation. The local stress intensity factors (mode *I* and *II*) and the location of the equivalent elastic crack tip are calculated during the loading. The variation of the location of the equivalent crack tip is used to track the initiation and growth of the process zone, up to the onset of crack propagation. These experimental measurements are used to define the appropriate parameters in a cohesive zone model. The methodology addresses the onset of crazing, the traction–separation profile and the maximum opening corresponding to the local nucleation of a crack. The cohesive parameters that are derived from the experimental data are consistent with results available in the literature. In addition, the model enables the characterization of the normal and tangential mode of the cohesive model.

1. Introduction

The description of fracture mechanisms by cohesive zone models (Barenblatt, 1962) has been a subject of increased interest in the micromechanics community since the pioneering work of Needleman (1987) and Xu and Needleman (1994). This approach enables a local description of the fracture mechanics that can be physically motivated. The fracture mechanisms is represented by a traction-opening relationship that mimics the failure process. Cohesive zone models are typically characterized by a maximum traction $T_{\max}$ at the onset of decohesion and a critical opening δ^{cr} that corresponds to the nucleation of a crack locally. In metals and ceramics, the opening δ^{cr} is on the order of nanometers (Gall et al., 2000; Abraham, 2001; Yamakov et al., 2006; Kubair et al., 2009) resulting in an extension of the cohesive process zone by tens of δ^{cr} (Rice, 1980). These dimensions are smaller than one micrometer and are not accessible by direct optical observation techniques. The use of electronic microscopes could be an alternative, but the sample size required to observe a failure process make them difficult to handle.

In polymer fracture, crazing is the mechanism responsible for failure, a process that is well documented and characterized for amorphous, glassy polymers (Kramer, 1983; Kramer and Berger, 1990). The typical dimensions involved in crazing allow an analysis by optical interferometry and extensive work by Döll and coworkers (Döll, 1983; Döll and Könczöl, 1990) have established that the critical opening is 2–10 μm, resulting in a length for the cohesive process zone of some tens of micrometers. Such dimensions allow for an optical analysis of the crack tip displacement fields: by interferometry as reported by Döll, but also by means of recently developed Digital Image Correlation (DIC) techniques.

---

* Corresponding author. Tel.: +33 472 438787.
E-mail addresses: julien.rethore@insa-lyon.fr (J. Réthoré), Rafael.Estevez@simap.grenoble-inp.fr (R. Estevez).

0022-5096/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jmps.2013.01.011

Experimental techniques based on DIC for the analysis of the displacement fields are currently expanding due to the improvements in the optical devices and monitoring setups. The methods initiated with the extraction of continuous regular fields (*e.g.*, Sutton et al., 1986; Sun et al., 2005; Besnard et al., 2006) but recent developments using discontinuous enrichment for the displacement decomposition, addressed problems with a singularities like shear bands (Réthoré et al., 2007b) and the analysis of a crack tip field (Réthoré et al., 2007a; Grégoire et al., 2009; Nguyen et al., 2011; Poissant and Barthelat, 2010). Since the earliest development of the DIC technique, fracture mechanics has been a topic of investigation (*e.g.*, McNeill et al., 1987; Abanto-Bueno and Lambros, 2002; Réthoré et al., 2005; Roux and Hild, 2006). However, the aim has usually been to extract stress intensity factors, whereas research for extracting adhesive or cohesive properties of an interface or a failure in a material has only been addressed more recently (Abanto-Bueno and Lambros, 2005; Fedele et al., 2009; Shen and Paulino, 2011; Fuchs and Major, 2011). Theoretical developments had already been proposed in Hong and Kim (2003) for evaluating a cohesive law from elastic far-fields. In the papers mentioned above, the observational scale is far too large compared to the resolution of DIC in order to capture the local state of the material during the crazing phase. Herein, the optical setup is adapted to the scale of the cohesive zone and sub-micron resolution images of the sample surface are acquired. From these images, a direct identification strategy of a cohesive zone law for Poly(Methyl Methacrylate) (PMMA) is established.

Fracture in glassy polymers is governed by the competition between shear yielding and crazing. Shear yielding corresponds to the development of localized plasticity due to softening upon yielding. The magnitude of the shear bands is limited by a progressive re-hardening that takes place during continued deformation. Crazing is also a mechanism of localized plasticity, but at a smaller scale. It involves three characteristic stages: (i) initiation at a local critical stress state, (ii) craze thickening with the formation of craze fibrils up to (iii) craze fibril breakdown corresponding to the local nucleation of a crack. In the literature, these three stages are addressed separately with studies devoted to craze initiation (Sternstein et al., 1968; Sternstein and Myers, 1973; Oxborough and Bowden, 1973; Argon and Hannoosh, 1977), the formation of craze fibrils (Kramer, 1983; Kramer and Berger, 1990) and the craze opening profile measured by optical interferometry (Döll, 1983; Döll and Könczöl, 1990). In particular, Döll and coworkers reported the maximum craze opening for various glassy polymers. The prediction of the cohesive process zone obtained with the Dugdale model (1960) is in good agreement with those observations. However, a reduced domain in terms of loading conditions is explored in Döll and coworkers' experiments and they are restricted to steady state crack growth under a constant load.

Kramer (1983) and Kramer and Berger (1990) pointed out that crazing, and in particular, the fibrillation stage involves some plasticity. Based on Kramer's work, a rate-dependent cohesive zone model was proposed by Tijssens et al. (2000) and Estevez et al. (2000) that accounts for some plasticity and the three characteristic stages of crazing. Rate-dependence of the failure process has been experimentally demonstrated for PMMA by Saad-Gouider et al. (2006). In this study, the loading rates corresponded to a time to rupture that varied from one second and to several hours and a rate of the stress intensity factor ranging between $1\times10^{-5}\ \mathrm{MPa}\sqrt{\mathrm{m}}/\mathrm{s}$ and $1\ \mathrm{MPa}\sqrt{\mathrm{m}}/\mathrm{s}$. Saad-Gouider et al. (2006) have shown experimentally that under mode I, the energy release rate in PMMA is rate-dependent, and its bulk plasticity is negligible. This observation confirms the need for a rate-dependent cohesive zone model as formulated by Tijssens et al. (2000), that results in a rate-dependent Dugdale model (1960) for monotonic loadings. The calibration presented by Saad-Gouider et al. (2006) focused on the identification of the parameters involved in the description for craze initiation and craze thickening. The value of the critical opening, δ^{cr}, was taken from Döll (1983) and Döll and Könczöl (1990). Although tractable, the extraction of cohesive zone model parameters requires (i) specific experiments to characterize craze initiation, (ii) numerous fracture tests at different loading rates for craze widening and related fibrillation, and (iii) optical interferometry of wedge cracks to measure the craze critical opening, δ^{cr}.

In the present study, an identification of a cohesive zone model for crazing from the analysis of the displacement fields measured by DIC in the vicinity of the crack tip is presented. The material under consideration is a PMMA identical to that investigated by Saad-Gouider et al. (2006). We demonstrate that the proposed analysis provides an estimation of (i) the craze stress at the onset of crazing, (ii) the traction-opening profile during craze widening and (iii) the critical opening corresponding to craze fibril breakdown and onset of crack propagation. These parameters and profile are derived from a single test. The experiment is also simple and provides complementary information to that reported in Kausch (1983, 1990) which focused on specific features of crazing.

The paper is organized as follows. First, the experimental setup and the fracture test from which the crack tip fields are analyzed by DIC is described. In a second section, the background for the analysis of the crack tip displacement fields is presented. Next, stress intensity factor calculations, the monitoring of the crack tip position and related process zone during loading are described. These terms are used to derive an identification protocol for the traction–displacement relationship of the cohesive zone model that is based on the DIC data. The results from the proposed identification protocol are then discussed from a materials science perspective and the novelty of the present strategy is pointed out with respect to available literature.

The following notation is adopted. Tensors are denoted by bold-face symbols. Implicit summation is considered over repeated Latin indices. The summation convention is *not* used for repeated Greek indices.

2. Experimental setup

A commercial PMMA (Perspex) in the form of 10 mm thick plates, stored for more than three months under standard room conditions in order to avoid any ageing effects has been used in this study. This is the same material used