Engineering Fracture Mechanics 115 (2014) 270–283

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

Damage and fracture mechanisms of polyoxymethylene: Multiscale experimental study and finite element modeling

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A R T I C L E I N F O

Article history:
Received 11 February 2013
Received in revised form 9 October 2013
Accepted 9 November 2013
Available online 20 November 2013

Keywords:
Semi-crystalline polymer
Polyoxymethylene (POM)
Damage
Local approach of fracture
Tomography
Finite element

A B S T R A C T

This work deals with the deformation and damage of a semi-crystalline polymer (polyoxymethylene) into which a metallic screw is screwed. The micro-mechanisms were investigated by using the Synchrotron Radiation Tomography technique. Penny shaped damage/crazes were revealed. The maximum damage location was found to be dependent on the initial notch root radius of the specimen. The X-ray laminography technique highlighted the extent of the damaged/crazed volume within a flat CT specimen. Thanks to an understanding of these micro-mechanisms, the local approach of fracture was applied to model the screw penetration operation. To this end, a dedicated damage based constitutive model was implemented in a FE code. After calibration of the material parameters, the FE simulations were able to describe the net stress versus opening displacement curves, as well as the evolution of void volume fraction distribution along the remaining section, as a function of increasing load.

1. Introduction

The increasing use of polymers for structures which, in the past would have been made of metal, requires investigations concerning the machining of such materials. When the definite design and fixture of the material cannot be reached by manufacturing processes such as injection or molding, tooling/cutting/screwing of the material might be necessary. The present work deals with screwing into a polymeric material by using a metallic screw for automotive industry fixation. For the polymer, the screwing process was considered to be split into four stages:

- Stage 1: initiation of the groove formation by a scratching process.
- Stage 2: radial indentation of the polymeric material until the maximum depth of the thread was reached.
- Stage 3: permanent regime consisting of friction between metal/polymer.
- Stage 4: tightening the assembly, which induced opening stresses in the wedge crack created by the previous stages.

The study started with careful observations of the final microstructure at the end of the stage 3, that is, without tightening. To this end, a longitudinal cut around a thread was carried out. The surface was then carefully polished and a Au–Pd coating applied before microstructure examination using Scanning Electron Microscopy (SEM). Fig. 1 shows the observations and summarizes the essential of the analysis. The polymer matter ahead of the thread exhibited the same features as those observed near a blunted crack tip. Indeed, it seems that the thread tip of the screw was not in contact with the polymer

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0013-7944/$ - see front matter
http://dx.doi.org/10.1016/j.engfracmech.2013.11.011

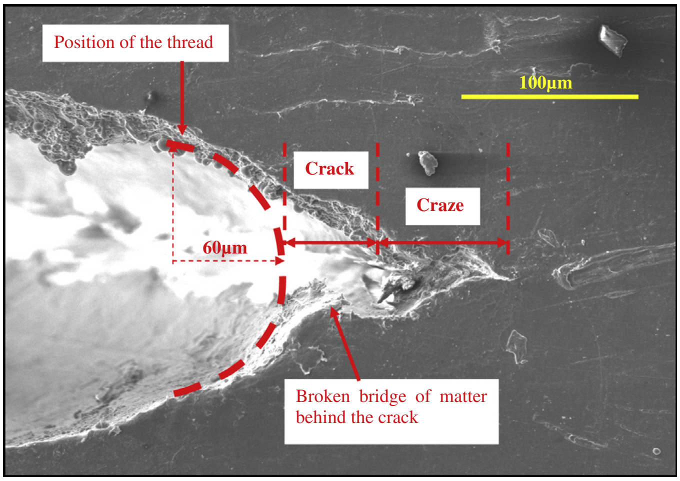

Fig. 1. SEM observation of the microstructure in the vicinity of the thread after the screwing process.

forming the crack tip. This configuration can be contrasted to what Williams et al. [1] considered as a "crack tip touching" condition. Moreover, the presence of a crack prolonged by a crazed zone has been reported in many papers devoted to the fracture mechanisms and mechanics in polymers [2]. The bridging matter behind the crack has also been underlined by Ben Hadj Hammouda et al. [3] when describing the slow crack growth mechanisms in Medium Density PolyEthylene.

On the other hand, a growing recent interest has developed relating fracture mechanics concepts to the machining/tooling/cutting processes [4–6]. The idea here is then to consider that the act of screwing falls into the tooling/cutting processes. However, instead of applying the global approach of fracture (K_{IC}, G_{IC}, J_{IC}), the novelty of the present work consists in the use of the local approach of fracture to model the phenomena appearing during the screwing process. This task requires using laboratory specimens to reproduce the damage and failure micro-mechanisms leading to the damage shown in Fig. 1. This objective is detailed in the first part of the paper including the choice of the material and the design of the specimen to be investigated as well as the use of X-ray tomography to inspect the damage development within the sample. The experimental data are then described according to two categories:

– the global parameters, essentially based on the load and the (opening) displacement measured during the test, accessible at the macroscopic scale;
– the local parameters, obtained from X-ray tomography and assumed to highlight the micro-mechanisms involved in deformation, damage and fracture due to the observed changes in the microstructure.

Finite Element (FE) modeling plays a major role in the local approach of fracture. For this study a damage based constitutive model was implemented into an in-house FE code. The particular precautions taken for meshing the various specimens are discussed. Finally, the numerical simulation results are discussed.

2. Experimental procedure

2.1. Material and specimens

The polymer under investigation was a polyoxymethylene (POM) used in the automotive industry for assembling processes. This work was dedicated to understanding real engineering components for which thicknesses were less than 2 mm. The boss which is the POM material intended to receive the metallic screw is illustrated in Fig. 2a. Several trials were carried out to produce standard specimens [7,8] with POM by injection molding. The samples obtained, being generally over 4 mm thick, exhibited significant porosity in the center due to the manufacturing process. To overcome this difficulty and to better fit in with the aims of the study, samples were extracted from the boss (Fig. 2a). POM is a semi-crystalline polymer, with a degree of crystallinity of about 40%, measured by Differential Scanning Calorimetry (DSC). The glass transition temperature was estimated at −60 °C by using the Dynamic Mechanical Thermal Analysis (DMTA) technique. Observations of the initial spherulitic microstructure with cryofractured or microtomed samples, by SEM showed a skin-core effect due to manufacturing process. Nano-indentation tests were carried out to measure the evolution of the Young's modulus through the 2 mm thickness of the boss. The maximum and minimum values being within a scatter of 11%, this skin-core effect was not considered to be significant in this study. Nevertheless, it can be noted that the mean diameter of the spherulites in the core was estimated at 50 µm and this texture is considered to control the fracture mechanism.