International Journal of Impact Engineering 76 (2015) 1–8

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Damage at high strain rates in semi-crystalline polymers

R. Balieu [a,*], F. Lauro [b], B. Bennani [b], G. Haugou [b], F. Chaari [b], T. Matsumoto [c], E. Mottola [c]

[a] Division of Highway and Railway Engineering, KTH Royal Institute of Technology, SE-10044 Stockholm, Sweden
[b] Laboratory of Industrial and Human Automation Control, Mechanical Engineering and Computer Sciences, LAMIH-UMR CNRS 8201, University of Valenciennes, Le Mont Houy, Bat. CISIT, 59313 Valenciennes Cedex 9, France
[c] TOYOTA MOTOR EUROPE, B-1140 Brussels, Belgium

ARTICLE INFO

Article history:
Received 28 April 2014
Received in revised form
31 July 2014
Accepted 25 August 2014
Available online 16 September 2014

Keywords:
Damage
Digital image correlation
Microtomograph
Semi-crystalline polymers
High strain rates

ABSTRACT

A specific damage characterization method using Digital Image Correlation for semi-crystalline polymers is proposed for a wide range of strain rates. This damage measurement is an extension of the SEĖ method [16] which was developed to characterize the behaviour laws at constant strain rates of polymeric materials. This procedure is compared to the well-known damage characterization by loss of stiffness technique under quasi-static loading. In addition, an in-situ tensile test, carried out in a microtomograph, is used to observe the cavitation phenomenon in real time. The different ways used to evaluate the damage evolution are compared and the proposed technique is also suitable for measuring the ductile damage observed in semi-crystalline polymers under dynamic loading.

1. Introduction

Semi-crystalline polymers have a complex behaviour which depends on several parameters, such as temperature, pressure and strain rate, and they are often accompanied by volume change during their viscoplastic deformations [1,2]. This complex behaviour has led to the development of several material models in which these parameters are taken into account to describe the deformation process until failure. Ahzi et al. [3] and Ayoub et al. [4,5] proposed physical constitutive models for semi-crystalline polymers where the intermolecular resistance is treated in a composite framework. In these models, the crystalline and amorphous phases are considered as two separate resistances. Following this microstructure, some multi-scale constitutive models have also been developed to capture their viscoelastic, viscoplastic behaviour [6,7]. Finally, models based on the continuum mechanics and overstress approach have also been developed in static [8,9] and furthermore, extended by taking the degree of crystallinity into account [10]. These models were also proposed for dynamic applications as they are easier to implement into finite element codes as they accurately describe the large deformation process of polymers [2,11–13].

Nevertheless, all these models need material parameters which are sometimes difficult to identify due to their nature or the early necking stage in the deformation process. As a consequence, specific methods have been developed to obtain information after necking by using constant strain rate control with a video-controlled system [14,15] or by using full-field data from digital correlation measurement from heterogeneous displacement fields [16]. With the first method the speed loading is controlled according to real time deformation and then limited to quasi-static tests. The second method was then developed to overcome this problem and applied to dynamic tensile tests. They both give very good results to obtain stress-strain relations at constant strain rate. However, the damage measurement is still a challenge on a large strain rate range. G'sell [17] first proposes an extension of his method, by measuring a volume variation with seven spots painted on the tensile specimen to follow the deformation in the plane and considering transverse isotropy for the thickness direction [18]. Once again, this method is limited to quasi-static cases and the significant volume considered could lead to a mean damage value. The classical loss of stiffness technique could also be used by measuring the Young modulus variation with loading–unloading curves but it is also limited to quasi-static conditions [19]. Finally, inverse approaches could be used to identify parameters of damage models, nevertheless they are always based on macroscopic mechanical data which induces less accuracy [20,21]. In this paper, the SEĖ method [16], which was first developed for the polymer

* Corresponding author. Tel.: +46 8 790 8710.
E-mail address: balieu@kth.se (R. Balieu).

http://dx.doi.org/10.1016/j.ijimpeng.2014.08.013
0734-743X/

behaviour identification on a large strain rate range, is extended to the damage measurement on a large strain rate range. This method is applied to a polypropylene filled with 20% wt of mainly talc particles called Hostacom by LyondellBasell, for various strain rates and on small volumes all along the tensile test specimen. To validate this approach, the method is first applied under quasi static loadings and compared with the loss of stiffness technique. Tensile tests inside a microtomograph are also performed to complete the validation. As good results are obtained by comparing these various techniques, the SEĖ method for damage measurement is then applied to dynamic tensile tests carried out on a hydraulic jack and Hopkinsonâ€™s bars. The results obtained for this semi-crystalline polymer filled with mineral particles highlight the independence of the damage evolution to the strain rates.

2. Damage at low strain rates

2.1. Strain field measurements by Digital Image Correlation

The SEĖ method was developed to identify the behaviour laws at constant strain rates for a large strain rate range (quasi-static to dynamic) from uniaxial constant speed tests. In this method, the Digital Image Correlation (DIC) measurement is used to identify the true stress–strain relationships of the material associated with the true strain rates (not constant) of each speed loading. It results in a true behaviour surface in the space of true strain, true stress, true strain rate. By cutting this behaviour surface at the desired strain rate, the behaviour laws at constant strain rate are therefore obtained 16. Due to the heterogeneity of the deformation along the length of the specimen, the strain and strain rate are not constant in the whole specimen. The displacement field measurements (achieved by DIC) are carried out in the Region of Interest (ROI), which is the length gauge of the tensile specimen, on each Zone of Interest (ZOI) included in the ROI (Fig. 1(a)). Various strains and strain rates measured in each ZOI are consequently obtained. The Henky in-plane strain tensor $\underset{\sim}{e}$ is deduced from the displacement fields of the ZOI. In the SEÊ method, a hypothesis about the material behaviour (incompressibility, transverse isotropy, …) has to be made to obtain the thickness strain in order to calculate the tensile stress in each ZOI by taking into account the force applied also on each ZOI. To achieve it, the resultant force is equally divided on each ZOI which have the same dimension (initially) and afterwards divided by the current section area of the ZOI (measured by DIC). Uniaxial quasi-static tensile tests on flat specimens at 1 mm/min are carried out with, two cameras in front of the specimen to follow the displacement field, and one for the measurement of the thickness variation. This procedure is used to measure the volume variation during the tests. The Henky longitudinal, transversal and thickness strains are presented in Fig. 1(b).

A transverse isotropy is observed during the tensile test as the transversal ($\mathbf{e}_{xx}$)and thickness strains ($\mathbf{e}_{zz}$) are very close, as shown in Fig. 1(b). Fig. 2 shows the true volumetric strain evolution (i.e. tr($\underset{\sim}{e}$)) versus the true longitudinal strain evolution during the test. With this measurement technique, the non-isochoric viscoplastic deformation is clearly captured.

2.2. Damage measurements with the SEĖ method

Damage, as well as the viscoplastic deformation, is an irreversible process which evolves during the deformation. Furthermore, the deformation of mineral filled semi-crystalline polymers induces decohesion at the charge–matrix interface. In this case, the viscoplastic response of the material is accompanied by damage in the form of nucleation, growth and coalescence of cavities. Low and high magnifications SEM micrograph of the fracture surface of mineral filled polypropylene, after a tensile loading at 1 mm/min, are shown in Fig. 3(a) and (b). A ductile fracture is observed with filament structures. The fibrillation observed is due to the cavitation phenomenon which occurs in the material. Nucleation of cavities around the mineral fillers is observed as well as growth of voids in the matrice part of the polymer.

In the Continuum Damage Mechanics approach, the damage variable D is defined by the surface density of micro-voids and micro-cracks lying on a plane cutting the Representative Volume Element (RVE) of real cross sectional area S. The RVE, introduced in mechanics of continuous media, represents a volume where all properties are represented by homogenized variables. For the plan with normal $\overrightarrow{n}$, the damage variable is given by

$$D_{(\overrightarrow{n})} = \frac{S_D}{S}, \tag{1}$$

where S_D is the effective cross sectional area which corresponds to the intersection of all micro-cracks and micro-voids lying in S. For an isotropic damage, the damage variable $D_{(\overrightarrow{n})}$ does not depend on the normal $\overrightarrow{n}$. This variable is therefore a scalar [22] such as

$$D = \frac{S_D}{S}. \tag{2}$$

By using the strain measures obtained by DIC, the true stress, which takes the reduction of the real cross-sectional area into account for each ZOI, is therefore calculated assuming the compressibility (transverse isotropy) $\sigma_{yy_i}^{\text{com}}$ or the incompressibility hypothesis $\sigma_{yy_i}^{\text{com}}$, such as

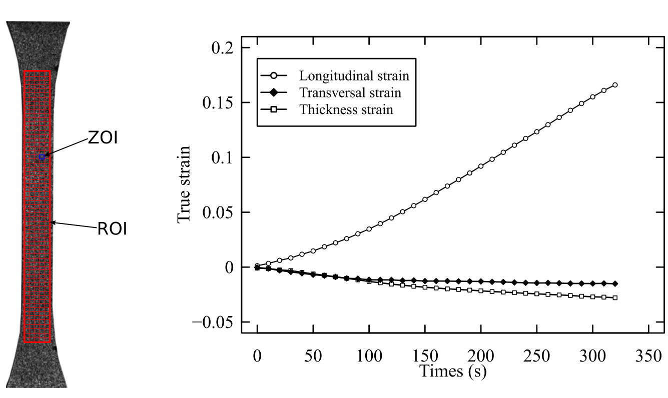

Fig. 1. Representation of the ROI divided in ZOI on the tensile specimen (a). Comparison of the true (Hencky) longitudinal ($\mathbf{e}_{xx}$), transversal $\mathbf{e}_{yy}$ and thickness $\mathbf{e}_{zz}$ strains for the tensile test at 1 mm/min (b).

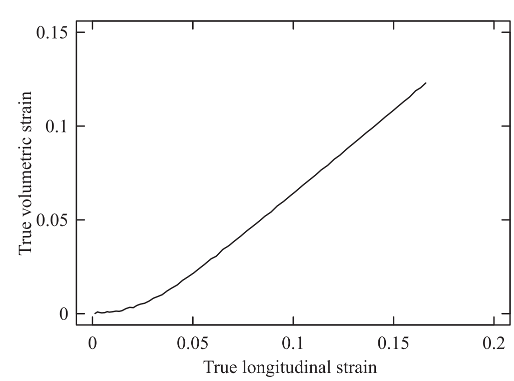

Fig. 2. True volumetric strain measured by DIC for the tensile test at 1 mm/min.