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The SEĖ method for determination of behaviour laws for strain rate dependent material: Application to polymer material

F. Lauro*, B. Bennani, D. Morin, A.F. Epee

Laboratory of Industrial and Human Automation Control, Mechanical Engineering and Computer Sciences, LAMIH – UMR CNRS 8530, University of Valenciennes, Le Mont Houy, 59313 Valenciennes Cedex 9, France

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ABSTRACT

The need to model fracture in crashworthiness by means of finite element codes is a real challenge for research. Before implementing fracture criteria, an excellent knowledge of the stress and strain states in the material just before the crack appearance is the first condition necessary to ensure the model development. At present, most of the material behaviour laws, for example for steel, are only defined until the maximum force when necking occurs. For polymers, the early occurrence of the diffuse necking leads to an experimental technique in which the speed loading is controlled in real time to maintain a constant strain rate during the test. This technique is not however used, due to technical limitations, for high strain rate behaviour laws. In this paper, the authors propose to use the heterogeneity of the displacement field on the surface of the tensile specimen as an initial condition to identify behaviour laws. The method developed uses the information in all the surface zone of the specimen by using digital image correlation. Stresses, strains and strain rates are then obtained to build a surface behaviour called the SEĖ surface. By cutting it, the experimental behaviour laws for a range of large strains and strain rates are then defined for model identification.

1. Introduction

Polymers are increasingly being used in the field of transportation (automotive, aeronautics, …). Car manufacturers in particular appreciate the lightness of these materials with respect to the European norm of 2008. In the past, they were mainly used inside the car but, over the last fifteen years, polymers have also been used for structural parts of cars like bumpers, wings, etc. In addition, some safety norms, especially for pedestrian impacts or driver/passenger safety, have led car manufacturers to study the behaviour of polymers in more detail in the case of multiaxial loading for a wide range of plastic strain rates and temperatures.

Unfortunately, polymers are known to be sensitive to both strain rates and loading conditions. Moreover, the early presence of necking leads to a non-uniform plastic strain field on a classical tensile test specimen. Consequently, the determination of the uniaxial true stress–strain curve is really difficult to perform. This problematic is increased in the case of a specimen with a rectangular cross section for which the classical hypothesis of Bridgman can't be applied [1].

Nevertheless, the determination of the true stress–strain curve becomes essential when large plastic deformations and large plastic strain rates are considered, in particular to perform ductile damage or fracture analysis. The first difficulty of this determination is the heterogeneity of the plastic strain field and the stress field in the cross section of the specimen after the occurrence of necking. In this case, the stress could be determined by $\sigma = \lim_{\Delta S \to 0} (\Delta F / \Delta S)$ where ΔF is the force increment on the tensile specimen and ΔS the section variation associated to it. Until now, these values have been difficult to obtain during a tensile test and this has led to the calculation of an average stress. To improve results, Bridgman [1] uses a correction technique which takes the radial and hoop stresses into account in the calculation of the nominal stress for a round bar specimen. This technique is difficult to extend to rectangular cross-section specimens because of the stress state which cannot be calculated easily with a non-axisymmetric specimen. Consequently, Ling et al. [2] proposes a weighted-average method for determining uniaxial true tensile stress versus strain relation after necking for strip shaped samples. The true stress–strain function after the onset of necking is corrected by the weighted-average function which is determined by using lower and upper bounds of the true stress–strain curves. The parameters of this function are identified by means of an optimisation process which correlates the force displacement curves obtained by the

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* Corresponding author.
E-mail address: franck.lauro@univ-valenciennes.fr (F. Lauro).

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Nomenclature

ε	Total strain tensor
ε_{ii}	Strain in direction i
$\dot{\varepsilon}_{ii}$	Strain rate in direction i
ΔF	Force increment
F	Force
f, g	Displacement functions
ΔS	Section variation
S_0	Initial section
s	True stress
s_{ii}	Stress in direction i
Δt	Time increment
$\overline{u}$	Displacement field
$\overline{x}$	Position

simulation of a tensile test and an experimental one. This technique is also used for damage models identification [3] but the solution depends on both the optimisation algorithm and the amount of experimental data.

Based on the same approach as Bridgman, Zhang et al. [4] proposes an extensive three-dimensional numerical study on the diffuse necking with tensile specimen with a rectangular cross section. An approximate relation is established between the area reduction of the minimum cross section and the measured thickness reduction. A method is then proposed to determine the true stress-logarithmic strain relation from the load thickness reduction curve. This technique is also extended to anisotropic material by observing the width reduction of the tensile specimen in addition [5]. A technique is developed by G'sell et al. [6] for the purpose of polymer materials. An experimental set up dedicated to the analysis of the displacement fields on a tensile test is built to take the volume variation into account. The damage process in polymer material is so important that it modifies the volume of the tensile specimen and in this way the total strain. This cannot be introduced in the correction technique based on the Bridgman hypothesis. G'sell then uses a specific experimental technique coupled with the calculation of the plastic strain in the three principal directions. The displacement in the direction of the tension is used to control the speed of the machine in real time. For that, a tensile test with a seven spots specimen is carried out and the spots displacements are followed by a camera. (Fig. 1)

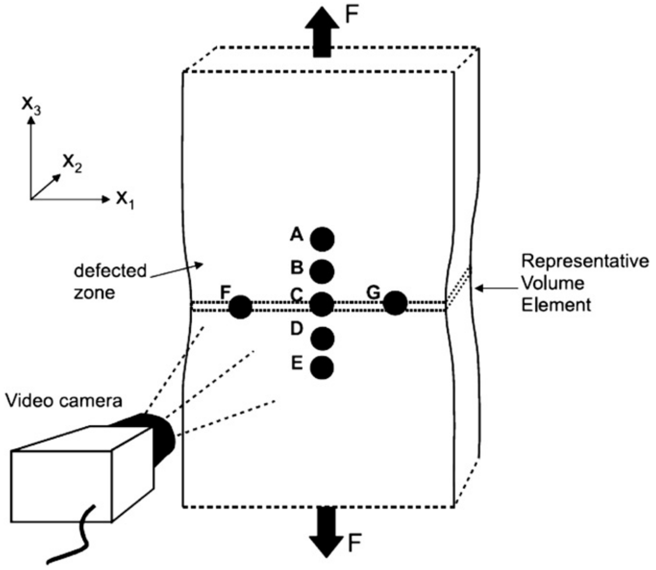

Fig. 1. Configuration of the seven markers in the video-controlled tensile testing system [6].

The axial strain is then calculated with a Lagrangian formalism between each spot in the axis AE and interpolated by a polynomial equation along the entire specimen in order to become the true strain. The transverse strain is calculated using the same approach with the spots placed on the horizontal axis FG. Finally, the strain in the thickness is obtained by an incompressible or transverse isotropic hypothesis. The true stress can then be calculated with using the same hypothesis and the volume variation simply obtained by $(\varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33})$. This technique is very interesting and well adapted for polymers under static loading. As the true strain is calculated during the tensile test in real time, the speed of the tensile grips is controlled throughout the test to keep a constant strain rate which will determine the true stress–strain curves. Nevertheless, this technique could not be used for higher strain rates, such as in crash simulations, due to the limitation of the real time controlling.

Recently, Parsons et al. [11] present an experimental investigation of the large strain tensile behaviour of polycarbonate using digital image correlation. The true stress–strain relation is obtained by direct measurement of the displacement field and by calculation of an average stress over the specimen section. The local strain rates are not important enough (less than 0.05 s^{-1}) to change the true global stress–strain relation and the experimental data is consequently validated under these conditions.

2. SEĖ method (sigma, epsilon, epsilon dot) for determination of material behaviour laws

Classical experimental frameworks used to observe and identify material behaviour for dynamic applications suffer from two main weaknesses:

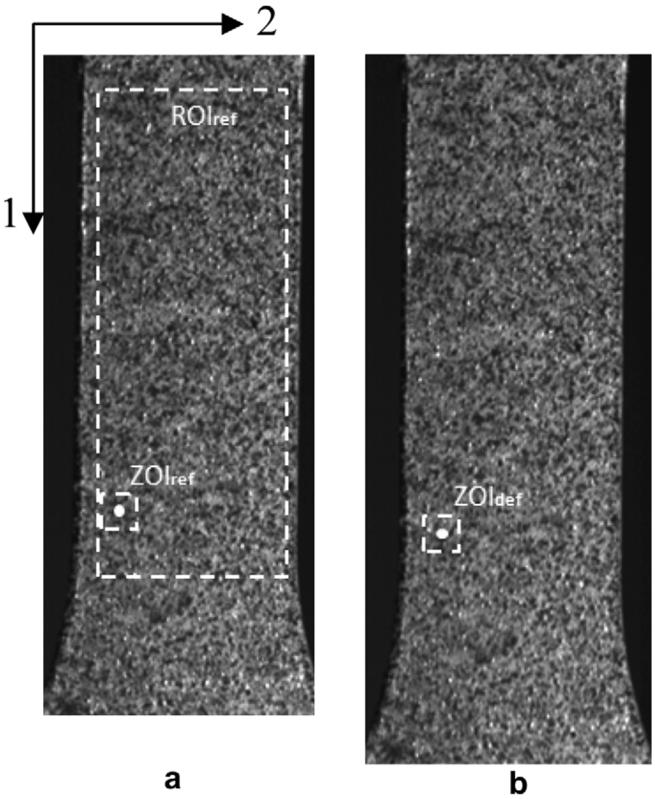

Fig. 2. ROI and ZOI on a flat specimen for (a) the reference picture and (b) the deformed one.