Plastic damage characterisation using visible, infrared and incoherent light transport optical techniques.

Stéphane André, Norbert Renault, Christophe Baravian, Christian Cunat

Nancy Université
LEMTA – UMR CNRS 7563
2, av. de la forêt de Haye – BP160, F-54504 VANDOEUVRE Cedex
stephane.andre@ensem.inpl-nancy.fr

Abstract :

Three experimental non intrusive techniques are used simultaneously for the metrological monitoring of the deformation of a material in a tensile load machine. The first technique is a video-extensometer (Videotraction®) based on the tracing of markers carried out through an image treatment processing. The second technique relies on the use of an infrared camera that records the temperature field evolution during the whole experiment, used to get some information about the power dissipated within the sample as a function of strain. Finally an incoherent steady-light transport (ISLT) technique is combined with the two previous ones. It provides information about the damaging processes occurring within the sample during deformation. The objective of the paper is to describe the techniques and illustrate their synergetic working for thermo-structural analysis during damage process. Applications are made with the tensile test applied to a High Density PolyEthylene (HDPE) specimen.

Résumé :

Trois techniques expérimentales sont utilisées simultanément pour le suivi dynamique de la déformation d’un matériau lors d’un étirage mécanique. La première technique est un vidéo-extensomètre (Videotraction®) basé sur une analyse d’image de marqueurs à la surface de l’échantillon. La seconde technique utilise une caméra infrarouge permettant l’acquisition du champ thermique et donnant par approche inverse une information sur la puissance dissipée lors de l’expérience de traction. La troisième technique est basée sur le transport incohérent stationnaire de lumière utilisé pour le suivi de l’endommagement. Nous décrivons ici les différentes techniques et montrons leur complémentarité pour la caractérisation de l’endommagement d’un Polyéthylène Haute Densité lors d’une expérience de traction mécanique.

Key-words : Plastic; Damage; Tensile Test; Thermo-mechanics

1 Introduction

The knowledge of the mechanical behavior of polymers is a very challenging research area nowadays. Their use is always spreading in industry and requires the development by the scientific community of reliable and predictive behavior models accounting for various phenomena (thermomechanical couplings, fatigue phenomena, damaging processes, physical and chemical ageing…) which are directly related to the microscopic structure evolutions of the polymers. Understanding the physical nature of strained states and the kinetics that enables material deformations is the main task. It requires considering the various involved scales (micro, meso, macro) for the construction of appropriated physical models. Therefore an experimental system that allows for *in situ* monitoring of coupled physical variables at various scales is highly desirable.

It is the object of the paper to present such a metrological platform. It is based on the association of three compatible optical techniques in order to monitor the evolution of various variables during a whole mechanical test. It is the nature of these variables that makes the experimental richness of this platform. These variables are :

(i) the stress and the strain measured thanks to the video-extensometer. This technique will be described in section 2. It provides the classical macroscopic observables of 'engineering' nature.

(ii) the volumic heat sources developed by the matter as a result of thermomechanical couplings between state variables (thermoelasticity), between state and internal variables (cold-work), and of internal mechanisms activity only (dissipation). They are naturally a consequence of the mechanical solicitation imposed on the material. As will be explained in section 3, the problem here is mainly of mathematical order : reconstructing the source term of the heat balance equation from the temperature fields acquired with an IR camera. This second technique provides also a macroscopic observable but which reflects the activity of internal mechanisms at a lower scale and therefore can contribute to a better understanding of them. It furthermore allows to check if developed behavior's law are consistent with both the dynamical and thermal observed response to an input excitation through well designed thermomechanical couplings.

(iii) microscopic variables characterizing damaging or deformation processes, namely the concentration and anisotropy of some structures or defects that are responsible for the microstructure evolution. To get some rapid idea on the technique, the reader may imagine that it is like if an X-ray equipment (SAXS or WAXS) was mounted onto a tensile machine for instance. Images are produced (and analyzed) from the spatial intensity repartition of some energetic signal impinging on the specimen as a result of interactions with the matter. Of course the scale at which objects or properties can be analyzed depend on the wavelength of the excitation signal. In our case, it is visible light. Therefore it offers an access to physical processes occurring at a scale ranging from 50 nm to 50 µm, typically. The essential difference with an X-ray equipment is that the present technique is very light, very easy to implement in the environment of a mechanical testing machine and does not induce or suffer from perturbations resulting from the two other optical techniques of the platform, and gives a significant signal on timescales of a few milliseconds. This technique applies to any sufficiently diffusing materials and does not apply to black or metallic samples. This technique is well suited for polymers and will be presented in section 4.

Finally section 5 will show how these three techniques operate in the framework of a tensile test performed on a polymer specimen with a MTS810 Load Frame. The kind of results that can be obtained and their evident richness will be shown and discussed.

2 Videotraction system

This technique (G'sell,1992) relies on the videomonitoring of markers previously inscribed on the specimen (Fig. 1a,b) on its front face. In full field optical techniques dedicated to strain measurement, the natural granularity of the surface (it's roughness) may be used to compute relative displacements of identified geometrical points. Here, artificial spots are inscribed (with an ordinary fine pen for example) but as a consequence, their number is limited. Usually, seven markers are plotted in the form of a cross (Fig. 1b,c) : five dots along the tensile axis and three along the direction perpendicular to it (one marker has a central position and thus is in common to both directions). The image analysis consists in a simple computation of the midpoints of the spots (around 200 pixels) whose relative distance can be updated from one acquisition to the other. It allows then to compute the longitudinal ε_{11} and transverse ε_{22} strain. The natural assumption that the third component of the strain tensor ε_{33} is equal to ε_{22} can be made. This assumption can be checked by extending the method to additional spots placed on the lateral surface of the specimen. The dimensional variation of the transverse section is then obtained experimentally and joined to the measurement of the force applied on the sample (through the force cell of the machine), gives the true stress acting on it. The main difficulty of the technique lies in a precise location of the markers where necking will occur, in order to ensure the measurement of an intrinsic property of the matter and not of a property of the matter combined to some structure effect (by structure, we mean the geometrical shape of the specimen). Enhanced precision is reached with an interpolation applied to the four measured strain in the tensile axis (Fig. 1c). This allows to localize precisely where the maximum strain is obtained as the central dot can never be perfectly located *a priori*, i.e. before the experiment reveals it through necking.

Two advantages of this technique are of prime importance for the objective of integrating other instruments. The first one is that it needs only a CCD camera (I2S, with a resolution of 575x560 px) at a certain distance of the sample. The camera is mounted on the top of a telescopic drive which allows to follow the movement of the observed zone. The image treatment is very rapid and a software program can carry out in real time, the data acquisition, the image analysis and *in fine* the command of both the MTS machine and the telescopic drive. This allows for well controlled desired loading paths.

The technique produces the true stress versus true strain curve as can be seen in Figure 4a (upper curve).

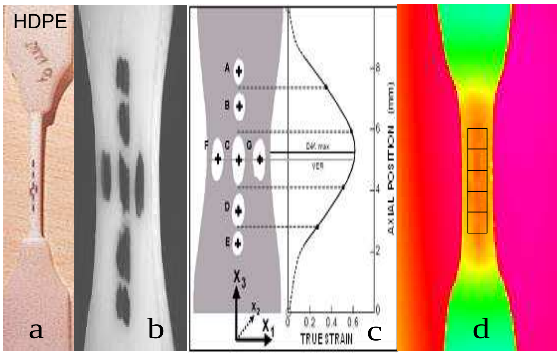

FIG. 1 : a) Deformed sample, b) deformed markers viewed by the CCD camera, c) Principle of the videoextensometer, d) infrared image on the opposite face.

3 Heat power source measurement system

As said in the introduction, the metrological system does not rely on the equipment in itself (an infrared imager of highest quality as possible in terms of frequency rate and digitisation range) but rather on the mathematical treatment that is performed on the thermal fields acquired during the experiment (Fig. 1d). About the experimental component, it is only important to mention that the infrared camera is also mounted on a telescopic drive enslaved to the videotraction's drive. In this way, the measurements are performed at the same location where the mechanical measurements are taken. This allows to be in a Lagrangian reference frame. The IR camera looks at the surface opposite to the surface where the markers are inscribed.

Infrared detection has been employed and is used more and more for thermomechanical applications (Hartley et al, 1987; Chrysochoos and Belmahjoub, 1992; Krapez et al, 2000). Many scientists have worked on the problem of analysing temperature fields in order to reconstruct the heat power (Coles and Murio, 2001) but the problem is obviously not closed yet. This is an ill-posed mathematical inverse problem (i.e. the solution of inverse problems is very sensitive to infinitesimal perturbations on the observed signal). It is not the purpose here to present the inversion process that has been used and which will be described elsewhere. In two words, it is based on an adjoint formulation for the estimator (Wong et al., 1990), which is completed by a penalization term to provide some appropriate regularization. Temperatures measured on the edges of the images are used as boundary conditions. On Fig. 4a (Lower curve, right y-axis) is shown the thermomechanical signal identified from the inversion process for HDPE sample under tensile test at constant rate.

4 Incoherent Steady Light Transport system

Of course the challenge here is that the additional optical technique does not produce any parasitic phenomenon and on the contrary operates in synergy with the previous components. This technique is based on incoherent light transport. It consists in a laser diode (635nm) focused ($50\mu m^2$ area) on the back surface at the center of the observed IR image which is also the centre position of the cross markers (Fig. 2). The power of the diode (635nm, much smaller than the minimum wavelength detected by the IR camera) is of the order of 0.1mW, so there is no local heat induced by the diode. A CCD camera (1024^2 pixels, 12 bits) acquires the backscattered image (3x3mm^2) far from the laser diode impact (Fig. 2).

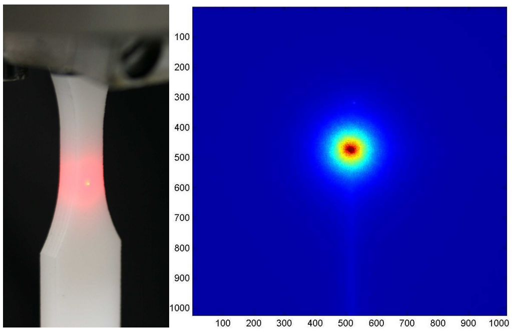

FIG 2 : ISLT Technique. Excitation of the HDPE polymer with the laser (left) and image (3x3mm^2) digitized by the CCD camera (right) in false color logarithmic representation

From the backscattered image, we perform two treatments. The first treatment consists in looking at the spatial intensity decrease from the laser impact. For this, we find the centre of the image, and then perform an angular integration at different radial positions from there. This image corresponds to multiply scattered photons inside the medium, leaving it in the backward direction. It has been shown recently that most of these photons are incoherent and that the collected intensity from them can be very well modelled by the radiative transfer model in diffusion approximation (Baravian et al, 2005; Caton et al, 2006). For the present case, this diffusion approximation is developed considering the medium as non-absorbent and semi-infinite, leading to an analytical expression for the backscattered intensity. The only open parameter in this model is the transport length (ℓ_{TR}), corresponding to the average diffusion path of photons in the medium (Figure 4b).

5 Example of results on HDPE

On Fig. 4a, the upper curve corresponds to the true stress vs true strain curve and one recognizes the typical behavior of HDPE with three typical phases: At small strain range, a quasi-elastic large increase in stress, then a plateau corresponding to some flowing or plastic regime of deformation and finally a hardening phase. The lower curve presents the experimental thermomechanical signal extracted through the inversion process from a thermographic sequence of images like in Fig. 1d. One can observe from the different levels of noise between both mechanical and thermomechanical curves, all the difference that exists between a directly measured signal and the one produced by an inversion process applied on measurements. The thermal processes accompanying deformation can be analyzed from this signal and four distinct behaviors can be observed. At early stages (quasi instantaneously), the heat power appears to be negative as a result of the endothermic reversible process of the well-known thermoelastic coupling. The magnitude of this power decrease corresponds to a thermoelastic coefficient of 16.10^{-5} K^{-1}, as expected for HDPE. Then mechanical processes become exothermic. The heat power rapidly turns to a positive value (viscoelastic regime ?) and then holds a constant value which characterizes the plastic-flowing regime (the plateau observed on figure 4a). In the hardening phase, a strong increase in the dissipated heat reveals additional processes occurring in the matter or that the material has changed. The experimentalist can observe by looking at the sample that its color changes during the experiment. Starting from a whitish color (see the left picture on Fig. 2), the region where high deformation occurs turns to intense white (Fig. 1a). This is one the purpose of the ISLT technique to quantify this property. At the beginning of the experiment, the photons transport length ℓ_{TR} has a typical value of 2 mm corresponding to the turbidity of the undamaged PEHD. At the end of the tensile experiment, the transport length is typically in the order of 0.2 mm, so it diminishes by one order of magnitude due to craze development (Figure 4b).

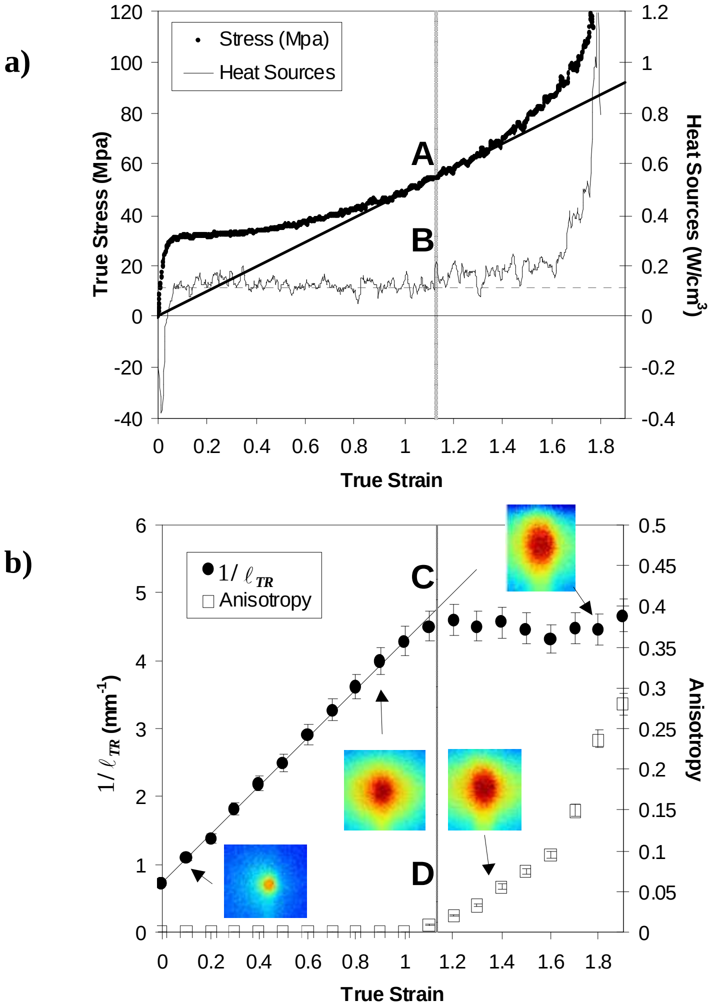

FIG. 4: Experimental signals obtained with the three techniques on the same tensile test at a deformation rate of 10^{-2} s^{-1}. a) True Stress and heat Sources. b) Incoherent light transport.

Fig. 4b shows the ISLT parameters evolution as a function of deformation. We observe a linear increase of the inverse of the transport length in the first 100 seconds of the experiment, corresponding to a strain value close to one. Then, the transport length remains approximately constant until the end of the experiment. The second accessible parameter from image analysis is the anisotropy of the scattering objects (the crazes).

When a global anisotropy appears in the medium, the incoherent light transport also presents a global anisotropy in a perpendicular direction. This anisotropy is determined at a distance of $2\,\ell_{TR} \pm \ell_{TR}/5$ from the image center. It is defined by the half amplitude of the angular variation at this distance divided by the average angular intensity value, to produce a dimensionless quantity. Fig. 4b shows also the behavior of this parameter. It can be seen that anisotropy remains null until a strain value of 1 (corresponding to a freezing of the transport length). At this typical value of deformation, anisotropy appears and increases until the end of the applied strain.

The linear increase in transport length at the beginning of the experiment can be interpreted as an increase in craze density. When the transport length remains constant after a deformation of approximately 1, crazes remain constant in both number and average size, but start to be gradually deformed as the strain increases. The relevance of such a combination of techniques is evident with this concluding remark : Point A on curve 1 situates a characteristic point on the mechanical curve where the stress locally behaves linearly with the imposed strain (the straight line starting from the origin). This point precisely corresponds to the minimum of the material function, to a strong resumption in the dissipated heat power (Point B) and to a behavior modification of the deformation mechanisms at the microstructural scale (Points C and D).

6 Conclusions

An experimental platform allowing for in situ multiple measurements of the macro and microscopic variables involved in a thermomechanical test has been presented. It is based on three optical techniques working in synergy. It is as versatile as possible to authorize its implementation in the environment of mechanical testing machines. It is used here in the framewok of a tensile test of a polymer and the richness of the information is demonstrated. It could be very helpful for engineers or scientists to check the validity of new modelings of behavior's law, integrating various rheological behaviors like viscoelasticity, plasticity, hyper elasticity but also damaging or fatigue processes.

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