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Experiments and modeling of high-crystalline polyethylene yielding under different stress states

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ABSTRACT

The mechanical response of high-density polyethylene (HDPE) was examined under different stress states. The biaxial yielding of HDPE material was investigated from a series of biaxial shear/tension and shear/compression tests using butterfly-shaped specimens deformed with an Arcan apparatus equipped with a digital image correlation (DIC) system for local strain measurements. In order to investigate a wider range of stress states, notched round bar specimens with different curvature radii were also tested using a video-controlled tensile testing apparatus. More conventional mechanical loading paths (uniaxial tension/compression and simple shear tests) were also examined to provide better insights on the stress state effects. The present investigation is more particularly focused on the yield envelope determination of HDPE material. A combined DIC and analytical approach was proposed to measure the yield strengths of butterfly-shaped specimens in the region where the yielding occurs. The relevance of classical yield criteria, exhibiting dependence on both the deviatoric and hydrostatic stresses, is verified. Considering HDPE as a heterogeneous medium consisting of a percolated crystalline matrix and a discrete amorphous phase, a micromechanics-based yield locus is tested. The experimental biaxial yield data are found to support this theoretical yield criterion and thus the suggested morphological representation for high-crystalline polymers.

1. Introduction

High-density polyethylene (HDPE) is increasingly being used in engineering applications such as pipes and pressure vessels. In the scope of predicting the behavior during the in-service phase of these mechanical structures the development of constitutive models is of prime interest. This necessitates getting relevant data and basic understanding of material mechanical response under a variety of loading conditions. Over the years, a great number of studies dealt with the strain rate and temperature effects on the yielding of thermoplastics (Eyring, 1936; Argon, 1973; Brooks et al., 1998; Richeton et al., 2006), but focusing generally on a uniaxial state of stress. These previous studies led to the proposition of mathematical expressions of the yield stress in relation with its physical origins in terms of mobility of the initial molecular architecture. During the last 20 years, considerable efforts were provided to propose 3D constitutive models, dedicated to glassy or semi-crystalline thermoplastics, able to predict their strain rate and temperature dependent mechanical behavior (Boyce et al., 1988, 2000;

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Buckley and Jones, 1995; Bardenhagen et al., 1997; Chaboche, 1997; Tervoort et al., 1997; Frank and Brockman, 2001; Khan and Zhang, 2001; Drozdov and Christiansen, 2003; Colak, 2005; Zaïri et al., 2005, 2007, 2010; Pyrz and Zaïri, 2007; Richeton et al., 2007; Dusunceli and Colak, 2008; Ames et al., 2009; Anand et al., 2009; Drozdov, 2009; Regrain et al., 2009; Belbachir et al., 2010; Ayoub et al., 2010, 2011; Srivastava et al., 2010). Although able to give an acceptable representation of the mechanical response, most of 3D constitutive models do not take into account the effect of the hydrostatic stress on the yield surface, depending only on the second invariant of the deviatoric stress tensor.[1] Some studies however showed that the mechanical response of polymers is sensitive to both the deviatoric and hydrostatic stresses (Mears et al., 1969; Ward, 1971). Therefore, to fully account for its effect on the multiaxial response of thermoplastics, the hydrostatic stress must be included in any yield criterion then used to construct a 3D plastic flow model. Over the years, several criteria based on the classical plasticity theory involving the hydrostatic component of the stress tensor have been proposed to describe the yielding of various thermoplastic or thermosetting polymers; some authors used modified forms of Tresca and von Mises criteria (Bowden and Jukes, 1972; Raghava et al., 1973; Escaig, 1997; Lesser and Kody, 1997; Quinson et al., 1997; Fasce et al., 2008; Farrokh and Khan, 2010) while others used yield functions based on the Drucker–Prager criterion (Ghorbel, 2008; Epee et al., 2011). The mentioned authors used various types of experimental devices, including thin-walled tube tests for shear, compression and tension loading superimposed to hydrostatic pressure. In spite of the important number of studies dealing with the yielding of polymers, no consensus exists concerning the most appropriate way to investigate the stress state effects.

The purpose of the present work is to investigate the stress state effects on the yield response of HDPE material using complementary experimental approaches: one combining tension or compression to shear in a plane stress state and the other imposing a triaxial stress state. The biaxial yield response was measured from a series of biaxial shear/tension and shear/compression tests using butterfly-shaped specimens. The triaxial stress state effects were examined by means of tests using notched round bar specimens with different curvature radii in order to set different triaxial stress states in the median cross-section. More conventional tests using different geometries and loadings, namely uniaxial tension/compression and simple shear, were also made. The present investigation is more particularly focused on the yield envelope determination in the specimen zone where the yielding occurs. Because the average stresses and strains are different from the actual stresses and strains directly involved in the yielding zone, local measurements, using digital image correlation (DIC) for butterfly-shaped specimens and minimum diameter monitoring for notched round bar specimens, were performed. For an accurate biaxial yield envelope construction a combined DIC and analytical approach is proposed. The validity of classical yield criteria of the literature is checked by comparison with our experimental results. Considering HDPE as a heterogeneous material containing two distinguishing phases (a discrete amorphous phase embedded in a percolated crystalline matrix), the validity of a yield criterion based on the micromechanics framework is also examined.

The present paper is organized as follows. In Section 2, we present the investigated material, the different specimen geometries, the mechanical testing protocols and the experimental results. Further, various theoretical yield criteria are assessed in Section 3. Some concluding remarks are finally given in Section 4.

2. Experiments

All HDPE specimens used in this study were machined from the same pipe. Because of plastic instabilities involved in HDPE, a non-uniform state of stress and strain occurs, thus the deformation must be localized in a well-defined region of the specimen to succeed local measurements. The mechanical tests were carried out on an electromechanical Instron-5800 universal testing machine equipped with suitable testing rigs. The Instron testing machine has a capacity of 30 kN and an appropriate load-cell. In order to compare the yield response obtained from the different specimens, and thus deduce the effects of multiaxial loading, the strain rate and the temperature were fixed. The mechanical tests were achieved under an equivalent strain rate of $10^{-3}\ \mathrm{s}^{-1}$ (unless explicitly otherwise specified) and at room temperature (RT).

2.1. Material

The HDPE material retained for the present investigation was provided by the STPM CHIALI Company: density $\rho \approx 0.96$ g/cm^3, weight-average molar weight $M_w \approx 310{,}000$ g/mol and carbon black $\approx 2.5\%$. Pipes of this material with outer and inner diameters of 250 and 232 mm, respectively, were received from the manufacturer. The crystallinity ratio was determined by differential scanning calorimetry (DSC) measurements achieved at a heating rate of 10 °C/min using a Perkin-Elmer Diamond DSC. The tests were performed on specimens of 10 mg collected at three locations along the pipe thickness. The reproducibility of the measurements was verified by achieving a second run. The crystal weight fraction ϕ_{cw} was calculated as the ratio of the measured melting enthalpy ΔH_f and the theoretical melting enthalpy of a perfect polymer crystal ΔH_f^0 taken equal to 289 J/g (Wunderlich, 1980):

$$\phi_{cw} = \frac{\Delta H_f}{\Delta H_f^0} \tag{1}$$

[1] To account for hydrostatic stress effects, heuristic modifications are sometimes brought in the 3D constitutive models by the introduction of a parameter representing the ratio of yield strengths in uniaxial compression and tension.