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A two-phase model for the mechanical behaviour of semicrystalline polymers. Part II – Modelling of the time-dependent mechanical behaviour of an isotropic and a highly oriented HDPE grade

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ABSTRACT

This paper presents an application of the model presented in Part I for the prediction of the mechanical response of two semicrystalline polymers. This Part II particularly emphasises the capacity of the model to predict the time-dependent behaviour of semicrystalline polymers, whereas Part I illustrates the potentiality of the model to predict their multiaxial and large strains behaviour.

The two studied materials consist of an initially isotropic HDPE, studied up to the beginning of the tensile hardening, and of any highly oriented HDPE bands, so that their mesostructure state can be considered constant in the studied strains domains. This paper shows that the large strains model can be simplify to predict the mechanical behaviour of SCPs, as well isotropic as anisotropic.

The model is validated for the two studied HDPE materials under uniaxial tension on the basis of experimental data, which evidence the sensitivity to the strain rate, and the short-time and long-time viscous behaviour.

1. Introduction

A model was proposed in Part I for the prediction of the large strains mechanical behaviour of semicrystalline polymers (SCPs) (Brusselle-Dupend and Cangémi, 2008). This tridimensional model permits to describe the hardening behaviour of HDPE under several loading paths from an initial isotropic configuration.

When polymers are drawn, their mechanical properties become more important in the drawing direction than isotropic polymers. Due to their higher mechanical properties, fiber-type polymers are thus widely appreciated in industry to reinforce structures. In this context, this paper aims to show that the model presented in Part I can be simpler to predict the behaviour of oriented SCPs such as fibers.

To illustrate the capacity of the model to predict the behaviour of fiber-type SCPs, the generalised model will be particularly applied on the mechanical behaviour of a highly oriented HDPE grade manufactured by SOLVAY. The prediction of the time-dependent behaviour of SCPs, as well initially isotropic as highly oriented, will be also evidenced.

From the analysis of experimental tests performed on an isotropic and highly oriented HDPE material, the effect of the manufacturing methods on the polymers mechanical behaviour will be first emphasised. The general pragmatic approach based on a particular interpretation of the microstructure of SCPs, presented in Part I, will be then applied. Finally, the response of the mechanical model will be presented for the studied isotropic and anisotropic HDPE grade.

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2. Effect of the process conditions on the mechanical behaviour of HDPE

2.1. HDPE materials

The two polymers investigated in this study come from the same commercial grade of HDPE manufactured by SOLVAY, but differ in their process conditions. The first one, called *isotropic HDPE* (*iPE*), was processed by compression moulding in the shape of 4 mm thickness plates and cooled to room temperature, which gives rise to an initially isotropic material. The second one, called *highly oriented HDPE* (*oPE*) was obtained by a technique of orientational drawing of the first material at about 130 °C. The isotropic plates are consequently turned into bands which are oriented in the drawing direction (direction 1). They present a final thickness equal to 0.85 mm.

2.2. Experimental procedure

Mechanical tests on *iPE* and *oPE* were performed at a temperature equal to 23 °C in the SOLVAY laboratories. Experimental procedure was classical for *iPE* whereas the bands of *oPE* required some specific conditions, particularly for setting the specimens on the testing machine. Monotonic tensile tests were performed on an electromechanical tensile machine. In order to investigate the long term behaviour, dead-load type creep experiments were carried out with a creep bench operating in tensile mode. Specimens were dumbbell shaped with a gauge length of 100 mm and 10 mm (5 mm for testing on the creep bench) × 4 mm cross-section for *iPE*, whereas *oPE* bands were rectangular shaped with the same gauge length but with about 25 mm × 0.85 mm cross-section. The use of specific jaws was required to test the bands to avoid their slipping out of the jaws or their breaking on the specimen basis. In most cases, tensile tests were conducted by means of a constant crosshead speed, and the nominal longitudinal strain was measured with a high accuracy mechanical extensometer. For the bands, it was necessary to use a self-supporting extensometer because of their small thickness; a videometric extensometer was however used to capture the true longitudinal strain in the creep tests case.

2.3. Experimental results

Except for the experimental data provided by the videometric methods, stresses and strains data recorded during experimental tests do not reflect the intrinsic properties of the material because they do not take the evolution of the cross-section into account. For these tests, true stress and true strain were consequently calculated as follows from the measured values of force (F) and engineering strain (ε_0) coming from conventional tests:

$$\sigma = \frac{F}{S_0}\frac{S_0}{S} = \frac{\sigma_0}{(1-\nu\varepsilon_0)^2}, \tag{1}$$

$$\varepsilon = \int_{l_0}^{l} \frac{\mathrm{d}l}{l} = \ln(1+\varepsilon_0), \tag{2}$$

where S_0, l_0 and S, l are, respectively, the initial and current cross-section and gauge length of the specimen. σ_0 is the engineering stress (or the nominal stress σ_{nom}) obtained from F/S_0. In (1), ν corresponds to Poisson's ratio. Its value can be evaluated from volume strain–true strain curves obtained from Videotraction® technique (G'Sell et al., 2002) in the small strains domain on the assumption that elastic volume strain ($\varepsilon_{\mathrm{vol}}^{(e)}$) theoretically expresses according to

$$\varepsilon_{\mathrm{vol}}^{(e)} = (1-2\nu)\frac{\sigma_{11}}{E}. \tag{3}$$

Poisson's ratio was only evaluated with this method in the case of *iPE* and arbitrarily chosen for *oPE*. Fig. 1 shows that *iPE* presents a ν value equal to about 0.38, which is close to the value of 0.4 usually known for polyolefines. A value of ν equal to 0.3 was considered for *oPE*.

2.3.1. Monotonic tensile behaviour of HDPE

Figs. 2 and 3 depict the monotonic tensile behaviour of the two HDPE materials evidenced with several experimental methods. Note that, except for the tests performed with a videometric method, strain rates indicated in these figures were deduced from the recorded engineering strain *vs* time. The most striking feature is the strengthening and gradual hardening behaviour of *oPE* which lead the bands to a sudden break at about 10×10^{-2} in the drawing direction (Fig. 3a). This kind of behaviour contrasts with the classical ductile behaviour of *iPE* (Fig. 2a). The HDPE bands present a strong anisotropy, associated with crystals chains unfolding caused by oriented efforts during drawing. According to the only test performed in the transverse direction (direction 2), a quasi instantaneous break characterises the transverse behaviour of the material, which thus seems to be semibrittle-type (Fig. 3b). In the drawing direction (or direction 1), the change of the initial spherulitic morphology into a fiber-type structure during orientational drawing results in an important increase of the stiffness and a markedly decrease of the strain at break. Two stages can be really identified on the stress–strain curves in direction 1 of the bands: after a slight hook de-

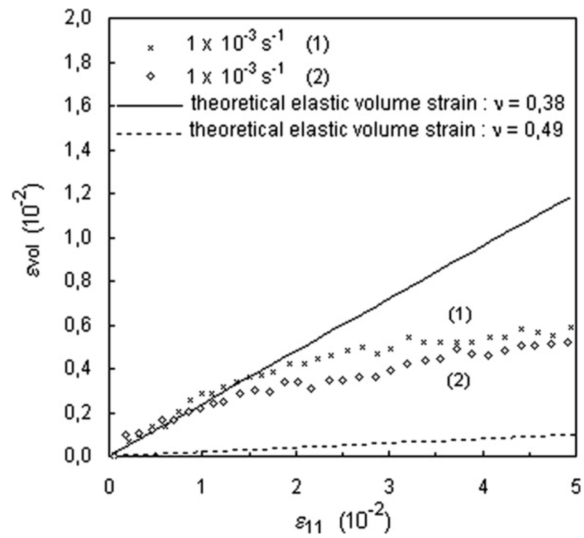

Fig. 1. Evaluation of *iPE* Poisson's ratio from experimental tensile results obtained with Videotraction® method.