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Deformation and failure of semicrystalline polymers under dynamic tensile and biaxial impact loading

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A B S T R A C T

We propose a constitutive model to aid in the engineering design of semicrystalline polymer components that may be subjected to biaxial impact loading. To this end, we investigate the thermomechanical and failure behaviour of high density polyethylene (HDPE) under dynamic loading, both experimentally and analytically. We have carried out dynamic tensile tests at 10^1, 10^2 and 10^3 mm/s displacement rates. Digital image correlation (DIC) and infrared thermography were used to measure full 2D true strain fields and determine specimen temperature rise during tensile testing. The results were used to calibrate the constitutive parameters. To analyse the biaxial impact response, we have carried out falling weight impact (FWI) tests at a 4 m/s impact velocity. We assessed the model prediction capabilities by comparing numerical predictions with experimental results and good agreement was observed. The proposed model, which aims to achieve a compromise between prediction accuracy and formulation simplicity, shows that initial linear elastic response coupled with a temperature-dependent power-law viscoplastic flow element and a non-linear strain-hardening element are sufficient to model biaxial stress scenarios.

1. Introduction

HDPE is widely used in a variety of high impact strength demanding applications such as load-bearing biomedical implants [1], automotive fuel tanks [2], pipe protection for oil and gas transportation [3], industrial vessels and liquid food containers [4]. During service, these components may undergo accidental drop or crash loading. Thus, there is an industrial concern in predicting how these parts will perform under such impact conditions. The traditional approach when designing impact-energy absorbing components involves costly and time-consuming trial-and-error tests on actual prototypes [5]. A more recent strategy is the prediction of material response using computer-assisted finite element (FE) simulations [6]. This approach is more cost-efficient and several commercial FE codes are currently available. However, the complex non-linear elasto-viscoplastic behaviour of plastics introduces several difficulties in the experimental assessment and constitutive modelling of polymer response. Hence, these fields remain under continuous development.

A number tests are frequently used to determine the performance of polymers under impact conditions including Charpy, Izod and Falling Weight Impact (FWI). The instrumented FWI test is specifically used to measure the biaxial in-plane tensile impact resistance under out-of-plane loading conditions [7]. This test is of technological interest since it develops a stress state in the specimen which closely represents the conditions that arise when loading shell-like components such as those obtained by injection moulding, extrusion or blow moulding processes. However, to this day there are no well-established direct procedures to use FWI test results for determining material intrinsic behaviour quantitative structural design and prediction. Consequently, FWI testing is mostly used as a pass/fail test or to present comparative rankings of material impact resistance [8]. An interesting non-conventional application of the FWI is to use it for material model validation. That is, to assess how well a model can predict deformation of a material outside the conditions under which it was calibrated. An example of this approach are the investigations carried out by Duan et al. [9,10], Du Bois et al. [11], Polanco-Loria et al. [12] and Daiyan et al. [13].

Several investigations have dealt with the experimental determination of polymer phenomenological response. During tensile testing, instabilities and inhomogeneities may be developed as a result of the underlying yield properties of the material [14]. This poses difficulties in the measurement of point-wise strain: to obtain a correct determination of the intrinsic true stress–strain relation, strain must be measured on regions sufficiently small to approximate the local deformation as homogeneous. The work of G'Sell et al. [15–17] represented a major advance in the determination of thermoplastics intrinsic behaviour by the use of non-contact optical strain

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measuring techniques. At the present, inhomogeneous 3D strain fields can be measured with great accuracy by means of modern digital image correlation (DIC) techniques [18–20]. Another difficulty that may arise when testing at relatively high strain rates is material temperature increase due to heat induced by plastic deformation. Depending on specimen geometry and testing velocity the conditions can vary from isothermal to adiabatic. As a rule of thumb, in typical uniaxial testing, strain rates above 10^{-2} s^{-1} are considered to produce adiabatic heating conditions [14]. Therefore, when determining the intrinsic material response at high strain rates it is also necessary to carry out point-wise temperature measurements on the specimen [21].

Constitutive models developed for semicrystalline polymers range from phenomenological models, which typically fit true stress–strain curves using unidimensional equations [16,22], to tensor-based 3D micromechanistic and physically-inspired models. An example of the latter is the family of tridimensional models developed by several research groups [23–29] which have been refined over the years to capture several features of polymer deformation response including strain rate, temperature and pressure dependence, post-yield softening, orientation hardening and unloading and cyclic response. Nevertheless, The mathematical complexity of these models is significant and their implementation in FE codes is not straightforward [30]. Moreover, in some cases they require the non-trivial experimental determination of a large number of constitutive parameters. Relevant to the specific case of thermoplastic polymers under impact behavior is the work of Polanco et al. [12] who modelled the dynamic response of polypropylene in the three-point bending and plate impact tests using an advanced constitutive model of the aforementioned kind. Their predictions showed good agreement with experimental results. However, their study was not focused at the prediction of failure behavior.

The use of advanced constitutive models can also be coupled with failure models formulated on a continuum level [31]. This means that the microstructural features of the fracture process are omitted and are only accounted in an averaged sense, over a “smoothed” continuum element [32]. This approach has been recently considered as an alternative to more complex fracture mechanics formulations, especially in practical engineering analysis. Failure models of this kind often involve strain or stress based failure criteria and is more conveniently used together with FE analysis. A damage equation that is function of stress or strain tensor components is evaluated at each material element in the FE mesh. When the equation satisfies the failure condition, the element is considered as damaged and is either removed from the mesh or degraded. Reasonably accurate results in the application of this technique to engineering polymers have been reported in Refs. [33–35].

Despite the numerous advances in polymer mechanics, its application to failure prediction of parts subjected to multiaxial impact loading conditions is still rare in the literature. Thus, the objective of the present investigation is the validation of a constitutive model for HDPE that aims to achieve a compromise between prediction accuracy and formulation simplicity. We analyse experimentally HDPE intrinsic stress–strain behaviour at moderately high strain rates (in the 10^{-1} to 10^{2} s^{-1} range) and we use these data for model calibration. Then, we assess the model prediction capabilities by contrasting simulations with experiments with the aim of validating this modelling approach as feasible predictive tool applicable in design.

2. Constitutive model

The constitutive model is based on the kinematic finite strain framework of previous models for thermoplastic polymers proposed by Bergström et al. [28,30]. The model consists of an arrangement of 3 separate elements: a linear elastic spring acts in series with a viscoplastic dashpot (network A), and a non-linear Langevin spring acts in parallel to both (network B). The linear spring represents the initial elastic response. The dashpot represents pressure and temperature dependent viscoplastic flow. The Langevin spring models the orientation hardening response at large deformations.

Fig. 1 shows a schematic rheological representation of the constitutive model. Since networks A and B act in parallel, the total Cauchy stress tensor **T** is given by:

$$\mathbf{T} = \mathbf{T}_A + \mathbf{T}_B \tag{1}$$

The deformation gradient $\mathbf{F} \equiv \partial \mathbf{x}/\partial \mathbf{X}$, which relates the position of a material point in the reference configuration, **X**, to the current configuration, **x**, is given by:

$$\mathbf{F} = \mathbf{F}_A = \mathbf{F}_B \tag{2}$$

In addition, the deformation gradient in network A, $\mathbf{F}_A$, may be multiplicatively decomposed into elastic and plastic components [36]:

$$\mathbf{F}_A = \mathbf{F}_A^e \mathbf{F}_A^p \tag{3}$$

where the relaxed configuration, $\mathbf{F}_A^p$, represents an intermediate state that is obtained by elastically unloading the material to a stress-free state.

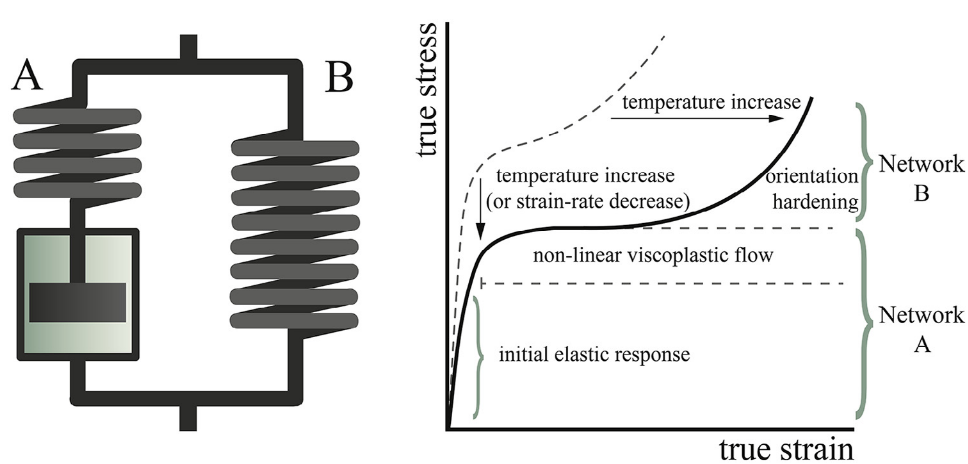

Fig. 1. 1D rheological representation of the constitutive model.