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Rate-dependent phenomenological model for self-reinforced polymers

J.I. Múgica *, L. Aretxabaleta, I. Ulacia, J. Aurrekoetxea

Mechanics and Industrial Manufacturing Department, Mondragon Goi Eskola Politeknikoa, Mondragon Unibertsitatea, Loramendi 4, 20500 Mondragón, Guipúzcoa, Spain

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ABSTRACT

The visco-elastoplastic nature of self-reinforced polymers (SRPs) implies that their mechanical behaviour depends on strain rate. Such dependence, when significant, must be taken into account in order to predict the impact response of these materials. In this paper, the strain rate dependence of the mechanical behaviour of a self-reinforced polypropylene (SRPP) and a self-reinforced poly(ethylene terephthalate) (SRPET) is determined and constitutively modelled. To do this, stress–strain curves corresponding to constant strain rates are deduced for each material by using a characterization method presented and validated in previous works. The strain rate dependence of the stress–strain response is quantified based on the 'strain rate sensitivity coefficient', defined by G'Sell and Jonas for their material model for semi-crystalline polymers. Such dependence is found to be higher in the SRPET than in the SRPP and, moreover, in both materials it depends on strain. Finally, a modified phenomenological constitutive model based on the G'Sell–Jonas one is proposed. The results show that the modified model improves the prediction of the original model reproducing accurately the rate-dependent behaviour of both SRPs.

1. Introduction

SRPs (also referred to as single polymer composites or all-polymer composites) are composite materials whose main feature is that the reinforcement and the matrix belong to the same polymer family (e.g. polypropylene, polyethylene, etc.) [1]. The macromolecules in the fibre-reinforcement, which are highly oriented, provide the composite with higher strength and stiffness than those of the bulk polymeric material [2,3]. There are different consolidation techniques to manufacture SRPs, e.g. hot compaction [4], film stacking [5], injection moulding [6], filament winding [7], wet powder [8] or solution impregnation [9]. The recyclability is one of the main advantages of all-polymer composites. Moreover, SRPs have also demonstrated other interesting properties for the automotive sector, such as improved impact resistance when compared to thermosetting composites [10] and capability of being thermoformed [11]. Currently, different kinds of products made of SRP have already come out to the market, always related with impact applications, such as armour, luggage and sport equipment [2]. Moreover, SRP thin plates can be combined with metal sheets to obtain fibre metal laminates (FML) offering higher specific impact resistance even than that of the plain composite [12–14].

Finite element analysis (FEA) can be used to predict the response of components under complex structural loads, including impact. However, in the case of intermediate strain rates (10–100 s^{-1}), the lack of standard test methods for measuring the material data required by the FEAs limits obtaining reliable results. Currently, there is a test procedure, employed by many authors, which enables to perform tensile tests at constant strain rates using conventional tensile machines. In them, the piston rod and the specimen are not directly coupled, unlike the quasi-static tensile test machines. By having slack in the connection between drive and specimen clamp, the desired velocity can be achieved and the energy of the system is transferred to the specimen. An alternative method to determine the stress–strain response for different strain rates (so called iso-strain rate stress–strain curves) of polymers was proposed by Aretxabaleta et al. [15]. This method requires performing tensile impact tests. They used this method with a isotactic polypropylene to determine the curves corresponding to strain rates between 15 s^{-1} and 100 s^{-1}, associated to low-velocity impacts [15]. From these data, the corresponding parameters of the so called G'Sell–Jonas constitutive model for semi-crystalline polymers were deduced and biaxial-bending impact tests were simulated with reasonable accuracy [16], validating the method as an alternative to characterize polymers at different strain rates.

The G'Sell–Jonas model is a phenomenological model which considers the strain rate effect [17]. It has been successfully used in many research works to predict mechanical behaviour of different polymers, e.g. poly(vinyl chloride) (PVC) and high-density polyethylene (HDPE) [17], polypropylene [16] or polyether ether ketone [18]. Also, modified models based on the G'Sell–Jonas one

* Corresponding author.

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have been proposed, which take into account strain instabilities causing softening [19] or transformation from isotropic to adiabatic behaviour affecting strain rate dependence [20,21]. However, none of these proposals considers a strain rate dependence varying with strain, when this phenomenon was identified in some of the above materials.

Studies previously conducted on SRPs principally deal with the development of a energetically optimal manufacturing process for them or their capability of dissipating impact energy as plain composite or when combined with metal sheets as FMLs. While it is true that the strain rate and temperature dependence of some of their mechanical properties have previously been object of study, there is no previous work to date on the tensile mechanical response depending on the strain rate and its modelling [22].

In this work, the strain rate dependence of the mechanical behaviour of a self-reinforced polypropylene (SRPP) and a self-reinforced poly(ethylene terephthalate) (SRPET) is determined and constitutively modelled. To this end, firstly, iso-strain rate stress–strain curves of the materials are deduced based on the method proposed by Aretxabaleta et al. [15] and, secondly, a modified G'Sell–Jonas constitutive model is proposed to predict the rate-dependent mechanical response of these materials.

2. Materials and experimental procedure

2.1. Materials

The materials used are two different SRPs, one based on polypropylene (SRPP) and another one based on polyethylene terephthalate (SRPET). These composite materials consist of a thermoplastic fibre 0°/90° woven reinforcement embedded in a thermoplastic matrix. The SRPP was supplied by Propex™ and the SRPET was supplied by Comfil™, respectively known by the trade name of Curv® and Comfil®. Both materials present a non-linear visco-elastic initial phase with a tangent modulus of 4.12 GPa and 5 GPa in the SRPP and the SRPET, respectively [2,3].

2.2. Low-velocity tensile impact tests

Tensile impact samples of geometry according to ISO 8256:2004 were cut by water jet from 1 mm thick SRPP and 1.1 mm thick SRPET plates. Tensile impact tests were performed at different impact energies, varying the impact velocity, using a 1.093 kg weight pendulum impact tester (Ceast 9050). The velocities used varied from 0.5 to 3.5 m/s (0.2 m/s steps). 3 samples were submitted at each condition in order to analyse their reproducibility.

Sample are fixed between the mobile (30 g weight) and fixed grips of the tensile impact tool (Fig. 1). When the pendulum reaches the lowest point, it hits the mobile grip and a tensile force are transmitted to the sample. This force are measured at the fixed grip by a piezoelectric sensor. If the sample mass (<1 g) and the mobile grip mass (30 g) is neglected and assuming that the hammer never loses the contact with the fixed grip during the impact, the velocity history of the latter coincides with that of the former [15]. This implies that the fixed grip reaches the impact velocity instantaneously. Accordingly, the velocity history of the hammer can be deduced by means of

$$v(t)_{\text{integrated}} = v_0 - \frac{1}{m_{\text{imp}}} \int_0^{t_c} f(t)dt \tag{1}$$

where v_0 is the initial impact velocity, deducible based on the drop height, m_{imp} is the mass of the hammer and $f(t)$ is the force registered during the impact. With this approach, the velocity, obtained by integration, can considerably differ from the real one depending principally on the impact velocity, but also the contact stiffness and restitution coefficient [23]. In the present work, a more accurate measuring method is used and compared to the traditionally used method. It is based on measure and register the velocity history with a non-contacting laser vibrometer (Polytec OFV-505). As illustrated in Fig. 1, the laser beam is focused on the mobile grip.

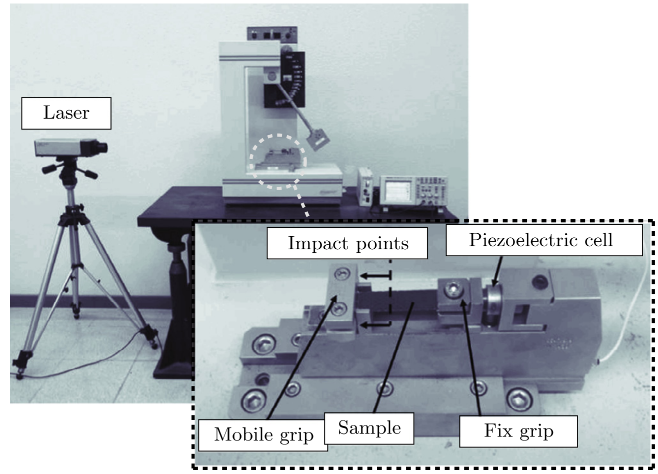

Fig. 1. Testing and measuring device consisting of the tensile impact machine and the laser vibrometer. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3. Data processing

The characterization method proposed by Aretxabaleta et al. [15] was used with both materials. It allows to obtain iso-strain rate stress–strain curves from tensile impact test of different impact velocities. The method consists in determining discrete stress–strain pairs of points corresponding to specific strain rates from the data of the different impact velocity impacts. For this, it is necessary to obtain the strain rate history, as well as the stress and strain responses. On the one hand, the displacement of the pendulum at the impact point, $x_{\text{laser}}(t)$, are obtained integrating numerically the velocity–time data, $v_{\text{laser}}(t)$;

$$x_{\text{laser}}(t) = x_0 + \int_0^{t_c} v_{\text{laser}}(t)\mathrm{d}t \tag{2}$$

where x_0 is the displacement at the time of impact (in this case, 0). Then, the strain–time data are determined from the displacement–time data and the initial length of the samples, $l_0 = 25$ mm by means of

$$\varepsilon(t) = \ln\left(1 + \frac{x(t)}{l_0}\right) \tag{3}$$

and the strain rate–time data are calculated by deriving numerically Eq. (3).

On the other hand, also knowing the force–time data and the initial section of each sample, the stress–time response is determined according to

$$\sigma(t) = \frac{F(t)}{S_0}(1 + \varepsilon(t)) \tag{4}$$

which assumes volume preservation. Fig. 2 schematizes the procedure to determine stress–strain pairs for a specific strain rate. It can be distinguished the strain rate, stress and strain histories of the three impact tests of different impact velocities, v_1, v_2 and v_3, from the lowest to the highest. The interpretation of the strain rate history curve, equal in shape to that of the velocity, is the following. Initially, it is zero since the mobile grip and, hence, the sample, are immobile. When the contact takes place, its value starts to