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Experimental study on characterizing damage behavior of thermoplastics

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ABSTRACT

Loading–unloading uniaxial tension tests are performed with a talc-filled and impact-modified polypropylene material. The damage parameters are calculated following two documented methods. One of these methods is based on the loading and unloading moduli, and the other is based on the volume strain. Two different approaches for obtaining the unloading modulus are studied and compared. Further tests are conducted to investigate the influence of test procedure and loading speed on the damage parameters. The SAMP-1 material model in the FE software LS-DYNA is employed with those calculated damage parameters to simulate the loading–unloading uniaxial tension tests. To validate the material model and to evaluate the applicability of the different damage characterization methods, loading–unloading 3-point bending tests are carried out and the corresponding simulation is also conducted. It is shown that the simulation with the damage parameter based on the unloading modulus calculated using the energy equivalent method is of better overall correlation with the test results.

1. Introduction

Thermoplastics are widely used for vehicle exterior and interior, among which some components such as instrument panel are related to occupant protection during crash events. It is possible to obtain reliable prediction of the mechanical response of these components with finite element method if high fidelity material properties are used as input parameters. Therefore, it is important to accurately characterize the mechanical behavior of the related materials. Although some previous studies have been carried out on characterization of thermoplastics [1–9], there are still some open questions requiring further research, such as those regarding strain-induced damage behavior.

Taking the case of pedestrian leg impact with the vehicle bumper as an example, Du Bois et al. [1] explained the significance of including a damage parameter in the material model for simulating the unloading behavior of thermoplastic materials. They used a classical damage model which associates the damage parameter with a reduction of stiffness as shown in Eq. (1) [10]. In this equation, E_0 stands for the initial Young's modulus, E_{eff} stands for the effective modulus which can be determined through an unloading test, and d is the damage parameter as a function of plastic strain.

$$E_{eff} = E_0(1 - d) \tag{1}$$

According to the equation above, the damage parameter is determined by loading–unloading uniaxial tension tests. A similar approach can be found in other literature [5,11,12]. This definition of damage has been included in the newly-developed material model SAMP-1 [8], denoted as *MAT_SAMP-1 or *MAT_187 in LS-DYNA [13]. To validate the damage parameter obtained from Eq. (1), Daiyan et al. [11] carried out the test with falling weight impacting on the plate made of modified polypropylene and simulated the loading and unloading process of these impacts with some success.

Based on microstructure evolution during deformation, another approach for characterizing damage behavior of thermoplastics was studied and reported in the literature [14,15]. An important characteristic of thermoplastics is the volume change during plastic deformation, and it has been reported by previous studies [10,14–17] that the change in volume is related to microstructure damage, including crazing or void nucleation, growth and coalescence. In the literature stated, volume change is characterized by volume strain ε_v as calculated in Eq. (2), where ε_1, ε_2 and ε_3 are the three principal strains.

$$\varepsilon_v = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \tag{2}$$

Nutini and Vitali [18] used a simple definition of the damage parameter calculated from the volume strain, which is shown in the following equation:

$$d = 1 - exp(-\varepsilon_v) \tag{3}$$

This damage parameter, expressed as a function of plastic strain, was applied in *MAT_SAMP-1 in LS-DYNA for the simulation of drop impact on a short glass fiber reinforced polypropylene box [18]. And for most of the cases studied, the correlation with test results was acceptable during the unloading stage.

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Besides the SAMP-1 model, there are some other novel constitutive models developed for thermoplastics, which also include certain damage parameters [6,12]. Ayoub et al. [12] improved the viscoelastic–viscoplastic model originally proposed by Boyce et al. [19] and Ahzi et al. [20]; the evolution of Young's modulus and the corresponding damage parameter is also calculated following an empirical function similar to Eq. (1). However, the material volume is assumed to be constant in the derivation of this model, which is invalid for some types of thermoplastics, such as the talc-filled polypropylene to be studied in this paper. Zrida et al. [6] introduced a hyper-visco-hysteresis model for polypropylene, but the good correlation was only limited at strain smaller than 6%. Since the current SAMP-1 model in LS-DYNA is relatively simple for engineering application which allows directly curve input of the related parameters and its applicability has been verified by some previous studies mentioned above [8,11,18], this model is also selected for simulating the mechanical response of the subject thermoplastic material during the loading- unloading tests in this paper.

As Eqs. (1) and (3) have been applied respectively in the SAMP-1 model for describing the damage behavior of thermoplastics, this paper aims to apply the damage parameters calculated by these two methods and compare their correlation with the test results. According to Addiego et al. [16], the volume dilatation of high-density polyethylene occurred earlier with faster strain rates during uniaxial tension tests. However, it was reported by Mohanraj et al. [15] that the volume strain of polyoxymethylene was not heavily influenced by the strain rate. It seems that the different relationship between the loading speed and the evolution of volume strain is dependent on the type of materials. And this paper also includes an experimental study on the influence of the loading speed and the test procedure on the calculated damage evolution of the subject material.

2. Experimental methods

A talc-filled and impact-modified polypropylene is chosen as the subject material in this paper. Loading–unloading uniaxial tension tests are performed on a universal test machine to obtain the damage parameters summarized in Eqs. (1)–(3). The tension specimen, as shown in Fig. 1, is modified based on the standard ASTM D638 [21] and cut off from a flat plaque. The gage section of the specimen is 5 mm long and 3 mm thick.

Fig. 2 shows the setup of the loading–unloading uniaxial tension tests. A ZWICK/ROELL020 universal test machine is used with an integrated load cell of a loading capacity of 20 kN. The two-dimensional digital image correlation (DIC) method is applied for strain measurement. The camera and the illuminator shown in Fig. 2 are used to obtain photos for the DIC calculation, which is performed with the commercial software Vic-2D. The acquisition rate of the camera is 15 Hz.

It is to be noted that the strain data presented in the following sections are calculated as the average results inside the whole gage section shown in Fig. 1, which is on the frontal surface of the specimen. It has been verified that the deformation inside the gage section on the frontal and the side surfaces is the same for this specific specimen design with the subject material [22]. Therefore, for the uniaxial tension specimen with a rectangular cross-section area in Fig. 1, the true stress σ_{true} can be calculated as shown in Eq. (4), where F is the load being applied, A_0 is the initial cross-section area, and $\varepsilon_{transverse,eng}$ is the engineering strain in the transverse direction.

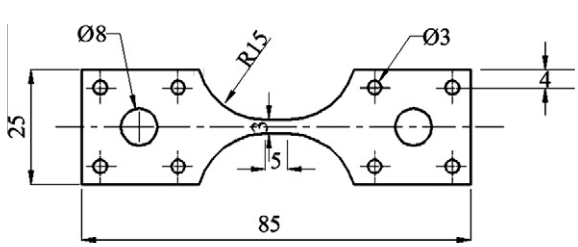

Fig. 1. Design of uniaxial tension specimen.

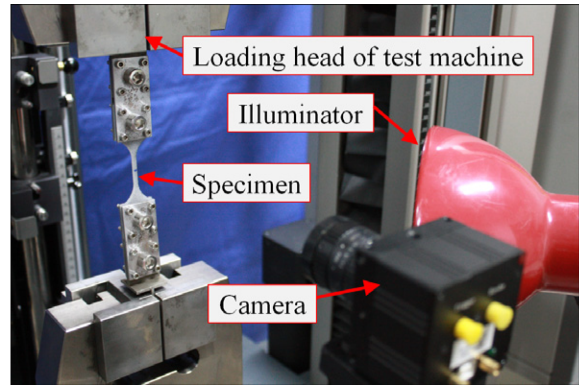

Fig. 2. Setup of uniaxial tension test.

$$\sigma_{true} = F/[A_0 \cdot (1 + \varepsilon_{transverse,eng})^2] \quad (4)$$

For each tension test, the loading and unloading stages are carried out at the same speed. The results at the loading speeds of 0.5 mm/min and 5 mm/min respectively are compared to study the impact of the strain rate on the damage behavior. Furthermore, two different test procedures are performed at the loading speed of 0.5 mm/min: in one procedure, only one specimen is continuously and cyclically loaded and unloaded at various elongations as shown in Fig. 3; in the other, each specimen is loaded and then unloaded at a predetermined elongation only once as shown in Fig. 4, and therefore, a group of specimens is necessary for constructing the damage parameter at various targeted plastic strains. For simplification, the former procedure is named Procedure S and the latter one is named Procedure G in this paper. Procedure S was applied by Zrida et al. [6] and Ayoub et al. [12] in their experimental study on mechanical behavior of polypropylene and high-density polyethylene respectively. Daiyan et al. [11] applied Procedure G in their study on mineral and elastomer modified polypropylene. Results of tests following these two procedures with the same subject material are compared in this paper to study whether loading history exerts influence on the damage evolution calculated with either Eq. (1) or Eq. (3). Experiments designed for

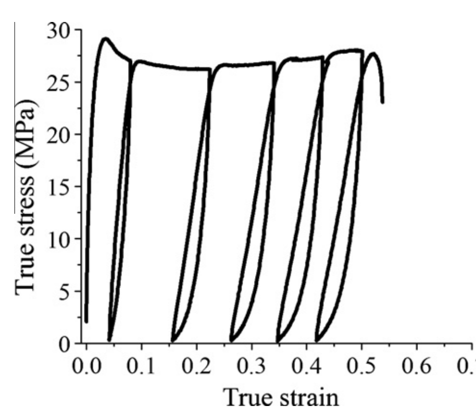

Fig. 3. Sample of true stress–true strain curve obtained following Procedure S.