

Experimental and numerical study of polypropylene behavior using an hyper-visco-hysteresis constitutive law

M. Zrida^b, H. Laurent^{a,*}, G. Rio^a, S. Pimbert^a, V. Grolleau^a, N. Masmoudi^b, C. Bradai^b

^a Université Européenne de Bretagne, Laboratoire d'Ingénierie des MATériaux de Bretagne (LIMATB - EG2M), Université de Bretagne Sud, BP 92116, 56321 Lorient cedex, France

^b Laboratoire des Systèmes ÉlectroMécaniques (LASEM-EPMM), Ecole Nationale d'Ingénieurs de Sfax, Route de Soukra Km 3.5 B.P. 1173, 3038, SFAX, Tunisia

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ABSTRACT

The aim of this paper is to study the mechanical behavior of three copolymer polypropylene (PP) and to use a non usual phenomenological three-dimensional hyper-visco-hysteresis (HVH) model. This model is introduced in the finite element computation software, called *HEREZH++* [1]. This behavior law is particularly adapted to model cyclic loading, loading/unloading and complex loading (non-radial). Experimental tests of monotonic tension, cyclic loading–unloading and relaxation tests at various strain rates and variable levels of strain are carried out on three grades of PP molded specimens. The results obtained from these tests enabled us to identify the HVH model parameters by a least squares minimization method. The constitutive model seems to be adequateness to describe the stress–strain evolution of the studied polymers under various mechanical loadings such as the loading–unloading and the torsion tests.

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1. Introduction

The increasing use of semi-crystalline polymeric materials in the production-manufacture of light-weight structures has led to renewed interest in the behavior of these polymers under various loading and impact conditions. During the design process, the structural components of thermoplastic materials are generally subjected to a lifetime analyses to ensure that their characteristics will be as reliable and as predictable as those of metallic materials. To accurately predict the responses of these polymeric materials, their complex mechanical behavior has to be modeled in order to account for the nonlinear strain rate dependency, nonlinear unloading, pressure sensitive yielding, hysteresis, cyclic softening and significant recovery at zero stress [2].

Many studies have been published during the last two decades on behavioral laws governing polymer materials. Because of the structural complexity of these materials, several models are being developed and used. These models are of two kinds: phenomenologic [3–6] and micro-mechanical models [7–9]. The phases

present in the micro-structure of polymers, especially semi-crystalline ones, are the main reason why their mechanical behavior is so complex. Several studies have shown the existence of hyper-elastic and viscous contributions to the behavior of polymers [10,11]. The behavior of the amorphous phase, having a rubbery aspect above the glassy transition temperature T_g , has been assumed to be similar to viscoplastic [12], viscoelastic [13] or elastoviscoplastic behavior [14]; whereas the crystalline phase corresponds only to elastoplastic behavior. For this reason, most phenomenologic mechanical models involve the assumption that the behavior of polymers is elastoviscoplastic [3,4,6,7,15,16]. Among these models, we can quote the G'Sell model [3,17] and the model based on overstress principle [2,10,18,19]. The two latter models have proved to be accurate in the case of polymers showing an elastoviscoplastic behavior.

The present study focuses first on the experimental analysis of the mechanical responses of semi-crystalline polymers (three different copolymer polypropylene grades) belonging to the polyolefin family. Secondly, an unusual phenomenologic hyper-visco-hysteresis (HVH) model will be used to predict the effects of these conditions on the evolution of the elastoviscoplastic response of semi-crystalline polymers. A behavioral law of this kind was

* Corresponding author. Tel.: +33 2 97 87 45 75; fax: +33 2 97 87 45 72.

E-mail address: herve.laurent@univ-ubs.fr (H. Laurent).

originally developed by P. Guélin [20,21] and improved by D. Favier [22] and P. Pégion [23]. It has been used to simulate the behavior of some metal alloys [24,25], shape memory alloys [26] and elastomers [27]. However, this law has not been used so far to model the behavior of polymers. The present model is based on cumulative stress contributions. Based on previous studies, the additive stress can be said to involve three main contributions, which are known as the hyperelastic, viscous and hysteresis contributions.

With a view to accurately describing the evolution of the behavior of the polymer, many experiments were first performed at room temperature. Tensile tests were carried out at various strain rates along different loading paths involving simple loading, relaxation and loading–unloading conditions. Comparisons were then made between the experimental results and the HVH model predictions obtained.

The aim of the present study was therefore as follows:

- (1) To compare the mechanical behavior of three grades of polypropylene copolymers.
- (2) To test the application of the hyper-visco-hysteresis (HVH) model to polymers and find adjustable parameters for use in various tests.
- (3) To check whether this model can take changes in the PP grades into account.
- (4) To apply the constitutive model to a complex case such as the torsion test.

This paper is organized as follows. In Sections 2 and 3, the three grades of PP and mechanical tests are introduced. Section 4 presents the theory on which the HVH model is based and the three stress contributions. Material parameters identification of the HVH model is carried out for several experimental tests in Section 5. Finally, to compare the experimental results with the numerical results obtained by performing HVH simulations, cyclic, two tensile-relaxation and torsion tests are presented, which show the accuracy of the model.

2. Materials

The three heterophasic copolymer polypropylene (PP) of commercially available grades used in this study were supplied by the company Total-Petrochemicals in Belgium:

- *PPC3650*: a “reference” grade with a melt flow index (MFI) of 2 g/10 min containing no nucleating agent,
- *PPC7712*: a PP with a MFI of 13 g/10 min, obtained by degrading the reference grade with a nucleating agent,
- *PPC9712*: a PP obtained under the same conditions as *PPC7712* but giving a MFI of 25 g/10 min.

The specifications of these materials are listed in Table 1. The molecular weights and the use of talc as a nucleating agent at a concentration of less than 1% were the only differences between

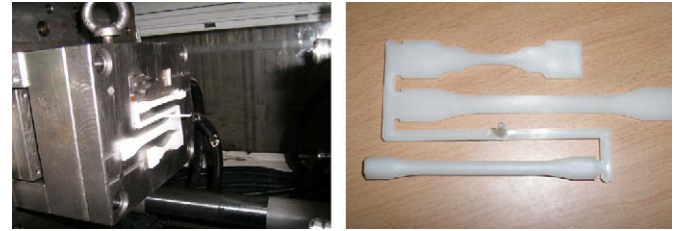


Fig. 1. Injection-molding machine and the specimens obtained.

Table 2

Injection process parameters with the three grades of PP.

Mould temperature	10 ± 3 °C
Speed of injection	30 mm/s
Pressure of preservation	200 bar
Preservation time	4 s
Cooling time	15 s

these three grades. The ethylene content was the same in all three cases. Among the three grades, the *PPC7712* seems to be the most promising: it combines good fluidity and mechanical properties. It is characterized by an excellent impact resistance and allows faster processing through early demoulding.

The specimens of the three grades of material were molded using an injection-molding machine on a specially designed three-imprint mould (Fig. 1). Some of the parameters of the injection process of the three grades are given in Table 2. The percentage crystallinity of the specimen was determined by performing Differential Scanning Calorimetry (DSC) using a melting enthalpy of with 100% crystalline polypropylene [28].

Polarized optical microscopic observations were carried out on the three grades. The resulting micrographs are given in Fig. 2, which shows that they had a spherulitic morphology. This figure shows that the size of the spherulites obtained in the case of *PPC7712* and *PPC9712* was smaller than in the case of *PPC3650*. The nucleating effects of talc can be clearly seen here: it induced an increase in the PP crystallization rates in the case of both *PPC7712* and *PPC9712*.

3. Experimental procedure used in mechanical tests

Several mechanical tests were performed using different loading paths: standard tensile, relaxation, uniaxial cyclic tests and torsion tests. These tests were performed at room temperature.

All the samples were deformed using an universal testing machine INSTRON-5560 equipped with an extensometer having a gauge length of 10 mm and an elongation of ±1 mm in the active region of the samples. The tensile force was measured using a standard of 5 kN load cell. In keeping with ISO 527-2, the dimensions of the specimens were $L_0 = 80 \text{ mm}$, $w = 10 \text{ mm}$ and $h = 4 \text{ mm}$ (see Fig. 3).

Table 1

Thermo-mechanical characteristics of the three PP grades (at 20 °C).

	Method	PPC3650	PPC7712	PPC9712
Melt flow index MFI(g/10 min)	ISO 1133	2	13	25
Molecular weight M_w (g/mol)	Supplier data	419952	229527	268866
Melting temperature (°C)	ASTM E 1269-01	164.9	165.4	165.1
Crystallization temperature (°C)	ASTM E 1269-01	113.7	121.2	121
Glass transition temperature (°C)	ASTM E 1269-01	-38	-44	-50
Crystallinity ratio χ_c (%)	[28]	36.8	34.2	34.1
Tensile modulus (MPa)	ISO 527-2	1320	1280	1250
Yield stress (MPa)	ISO 527-2	20	19	19
Charpy impact strength (notched) (kJ/m ²)	ISO 179	7.5	7	6

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