Polymer Testing 29 (2010) 793–802

Contents lists available at ScienceDirect

Polymer Testing

journal homepage: www.elsevier.com/locate/polytest

Material Behaviour

Mechanical response and microstructure investigation of a mineral and rubber modified polypropylene

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ARTICLE INFO

Article history:
Received 13 April 2010
Accepted 1 July 2010

Keywords:
Thermoplastics
Mechanical tests
Split-Hopkinson bar
Dilation
Voids
Scanning electron microscopy

ABSTRACT

The paper presents an experimental investigation of a semi-ductile rubber-modified polypropylene reinforced by mineral particles. The behaviour of the material is investigated by performing tension, shear and compression tests at quasi-static and dynamic strain rates, applying digital image correlation for full-field strain measurements. Subsequently, scanning electron microscopy is used to analyse the fracture surfaces of the tension and compression test samples, and to relate the observed mechanical response to the evolution of the microstructure. The experimental study shows that the material is highly pressure and strain rate sensitive, and that the rate sensitivity seems to be more pronounced with increasing pressure from tension via shear to compression. It also exhibits significant volume change, which is mainly ascribed to a cavitation process appearing during tensile deformation. Assuming matrix-mineral particle debonding immediately after yielding and self cavitation of rubber particles, both kinds of particles might be the source of initial cavities. From the study of the fracture surfaces in tension it appears that the fracture process is less ductile at high strain rates than under quasi-static conditions, while the micrographs taken of compression samples show that the size of the cavities is much smaller than in tension.

1. Introduction

Thermoplastics have been more and more used in the automotive industry during the last couple of decades. The reason why these materials are so interesting is their excellent compromise between mechanical properties and low density. The demand of cost reduction during the development of lightweight structures requires increased use of numerical design tools such as the finite element method. A prerequisite for accurate modelling, however, is a better understanding of the behaviour of polymers.

The material we introduce in this paper is a rubber modified polypropylene (PP) reinforced with mineral inclusions. One application is as impact energy absorbant in the bumper part of cars. The effect of both the mineral and rubber inclusions on the behaviour of the polymers is well known [1,2]. An important benefit is to increase the toughness and the impact resistance of the original material. These particles have, therefore, influence on the macroscopic behaviour. Because the material is manufactured for application in complex car components, it can be subjected to various loadings and strain rates. It appears necessary to have good knowledge of the material under different states of stress and strain rates, coupled with

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doi:10.1016/j.polymertesting.2010.07.001

comprehension of the microscopic underlying mechanisms which lead to the observed macroscopic response. Such information constitutes also the first step of the development of a model for thermoplastics relevant to crash applications.

Experimental characterisation of thermoplastics is a complex topic. This is due, on one hand, to strong instabilities initiated during the tests leading to localisation phenomena and non-homogeneous strain fields [3,4]. On the other hand, significant volume changes are often reported which can be linked to growth of crazes and cavitation processes in the amorphous phase [5]. Full field measurement techniques are, therefore, required. During the tests, a camera monitors the evolution of a speckled pattern applied to the gauge section of the specimens before each test. A Digital image correlation (DIC) software is then used to acquire the displacement field from the pictures and, afterwards, to calculate the deformation gradient and the in-plane strain field.

In addition to the possible change of volume, polymers are also known to exhibit other properties different from some other classes of materials. One example is a significant rate sensitivity [6–11]. Another is that the flow stress is dependent on hydrostatic pressure [5,8,9].

To investigate these issues for the PP at hand, we performed compression, tension and shear tests on the material at several strain rates from 5×10^{-3} to 500 s^{-1}. The highest strain rate corresponds approximately to what is experienced by a car component when crashed. The possible anisotropy of the material was also evaluated because it was delivered as injection moulded plates of small thickness.

The mineral particles have a strong influence on the macroscopic behaviour of the material [12]. They play a key role in the cavitation process often reported to occur in these materials, as the cavities are initiated around the particles, which debond at the early stages of deformation. Bartczak et al. [12] and Bai et al. [13] claim that the cavitation process is also the most predominant dissipative process in this kind of material. We performed scanning electron microscope (SEM) analyses after some of the tension and compression tests to provide an understanding of how the macroscopic behaviour is related to the deformation mechanisms, and to the evolution of the cavities in particular. SEM is a common tool to analyse the microstructure of polymers [14]. Although several authors have pointed out already the role of cavities on the macroscopic behaviour of mineral reinforced polymers, it is still difficult to find data providing information about the void evolution with the strain rate and under the different states of stress which may exist in car components subjected to a crash.

The paper is organised as follows: Section 2 provides a description of the material and experimental procedures used. The experimental results from the mechanical tests are given in Section 3, while Section 4 presents the SEM observations. A discussion, which emphasises the most interesting findings, is provided in Section 5. The paper closes with the concluding remarks in Section 6.

2. Material and experimental methods

2.1. Material description

The material investigated is a block copolymer which contains 78%wt of PP and 22%wt of EPR rubber phase (50% ethylene 50% propylene). Mineral inclusions were added during the injection process. They represent 20% of the total weight.

The material was injection moulded into plates of 3 mm thickness. During the process, residual stresses were avoided by keeping the temperature of the mold and the flow constant. The subsequent cooling was slow enough to ensure that the temperature could be considered homogeneous in the plate during the whole process. Thus, the plates were supposed to have homogeneous material properties. This issue was checked in the tension loading mode, see Section 3.1.

2.2. Experimental setup for mechanical tests

To characterise the behaviour of the material for crash applications, mechanical tests were carried out in tension, compression and shear at several strain rates. During the tests, a camera monitored the evolution of the speckled pattern applied on the surface of the specimens. The strain field was thereafter calculated using a digital image correlation (DIC) technique. Fig. 1 defines the geometry of the three types of samples.

We used a modified ISO527b specimen in tension, see Fig. 1a. A small geometrical imperfection having a circular curvature with depth 0.25 mm and length 15 mm was machined close to the centre of the specimen. Such modifications are often reported [5,15]. A servo-hydraulic machine was used to cover strain rates ranging from 5×10^{-3} to 10 s^{-1}. For both force and picture acquisition, the sampling frequency was 10 Hz at 5×10^{-3} s^{-1} while it was 4 kHz at 10 s^{-1}.

The compression sample was designed to avoid buckling. The dimensions shown in Fig. 1b are small because we were limited by the thickness of the plate (3 mm). For the quasi-static strain rate of 5×10^{-2} s^{-1}, a servo-hydraulic testing machine was used, whereas a direct-impact Hopkinson bar [16] was employed at the highest strain rate level of 400 s^{-1} s^{-1}. In this particular Hopkinson bar setup, only the transmission bar is used and the striker directly impacts the specimen. The wave separation technique [17] was then used to calculate the dynamic stress and strain. In compression, the sampling rate of force and camera acquisition was 10 Hz at the strain rate of 5×10^{-2} s^{-1}. At 400 s^{-1}, the sampling rate of the force acquisition was 10 kHz, while it was 30 kHz for the digital camera.

For the shear state of stress, we used the geometry defined in Fig. 1c. Inspired by the work of Klepaczko et al. [18], it is a double shear specimen having small notches machined to initiate the shear deformation. A servo-hydraulic machine was used in the quasi-static shear tests at a shear strain rate of 2×10^{-2} s^{-1}. To obtain an elevated shear strain rate of 300 s^{-1}, a purpose-made setup was designed to adapt the shear specimens into the compression direct-impact Hopkinson bar. At 2×10^{-2} s^{-1}, the