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Influence of stress state and strain rate on the behaviour of a rubber-particle reinforced polypropylene

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ABSTRACT

This article presents an experimental investigation of a ductile rubber-modified polypropylene. The behaviour of the material is investigated by performing tension, shear and compression tests at quasi-static and dynamic strain rates. Subsequently, scanning electron microscopy is used to analyse the fracture surfaces of the tension 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. It also exhibits significant volume change, which is mainly ascribed to a cavitation process which appears during tensile deformation. Assuming matrix-particle debonding immediately after yielding, the rubber particles might play the role of initial cavities. It is further found that the flow stress level is highly dependent on the strain rate, and that the rate sensitivity seems to be slightly more pronounced in shear than in tension and compression. From the study of the fracture surfaces it appears that the fracture process is less ductile at high strain rates than under quasi-static conditions.

1. Introduction

Thermoplastics have during the last couple of decades found their use in an increasing number of applications, also involving the automotive industry. Typical examples from this field are bumpers and dashboards. Common for these components is that they have to be designed for possible crash situations. The reason why thermoplastics are so interesting for such applications is their excellent compromise between low density and mechanical properties relevant for energy absorption. On the other hand, today's main tool when designing such parts is the finite element method. Accurate numerical predictions of the response caused by e.g. an impact event require a material model that is able to represent the most important features of the thermoplastic at hand. This is a challenge in the available commercial finite element codes. Obviously, development of suitable models for thermoplastics demands good knowledge of the mechanical behaviour and preferably also the mechanisms at the meso-scale.

This paper presents results from mechanical tests on a polypropylene block copolymer, which is applied by automotive companies in bumpers and other parts. Within this field of engineering, it is common to modify the materials with rubber phases during the injection process to increase the ductility of the material when exposed to high strain rates. These rubber phases have therefore an influence on the macroscopic behaviour of the material. In particular, knowledge of the behaviour of these materials under different stress states and strain rates is required because they are applied in complex car components which may be subjected to various loading situations. Material tests reveal such information, and serve also to provide insight in relevant features to cover when a material model for thermoplastics is to be developed.

Mechanical testing of thermoplastic materials demands in general a more complex setup than what is necessary for tests on metals. One reason is the intrinsic softening effects appearing at the early stages of yielding, inducing instabilities in the specimens and subsequently a non-homogeneous deformation field [1,2]. Further, thermoplastics may exhibit volume changes when deformed [3], which can often be related to craze growth and subsequent cavitations in the amorphous phases. Besides, a strong rate dependence is often reported [4,5] which may involve thermo-mechanical effects in some cases [6,7]. In the case of rubber blended polymers,

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the presence of rubber phases has also an effect on the general behaviour of the material. Several authors have dealt with the behaviour of cavitated polymers [8,9,10], and claim that the cavitation occurring in such materials is an important dissipation process during deformation. From a microstructural point of view, cavitation is generally induced by debonding of rubber particles. The usual tool applied for investigation of this topic is scanning electron microscopy (SEM) of the fracture surfaces, visualizing the role of the particles [11,12]. However, it is more difficult to find information on the influence of the strain rate on the cavitation behaviour, and on the interrelation between microstructural evolution of the material and the observed mechanical response under different states of stress as it exists when a polymeric car component is subjected to crash.

Experimentally, the features described above call for full-field strain measuring techniques. We have used digital image correlation (DIC) in the material tests presented in this paper. A random speckled pattern is applied at the gauge area of the specimens before the test. The evolution of the speckled pattern when the material is deformed is acquired by a digital camera. Subsequently, the DIC software uses the camera pictures to determine the displacement field and thereafter to calculate the deformation gradient field and the in-plane strain field with reference to the original configuration [13].

In the current paper, mechanical tests in tension, shear and compression are performed to investigate the effect of stress state on the response of the material. The material was delivered as injection-moulded plates, and the possible anisotropy of the mechanical properties is therefore also evaluated. The tests are carried out at different strain rates between 10−3 and, where the higher level corresponds approximately to the strain rate experienced by an automotive part in a crash situation. SEM analyses of the fracture surface were also carried out, as this enables an evaluation of the microstructural mechanisms, which is a key to understand the mechanical properties of the material at a macroscopic level. The main contribution of the paper is to describe the mechanical behaviour of a rubber-modified polypropylene copolymer under different stress states and strain rates relevant for structural impact applications. Full-field measuring techniques were employed in the strain calculations, and the observed macroscopic behaviour was partly explained by microscopic investigations.

The paper is organised as follows. Section 2 provides an overview of the experimental programme, involving procedures for tension, compression and shear tests at different rates as well as SEM analysis. The results from the mechanical tests and SEM study are presented in Sections 3 and 4, respectively, while Section 5 provides a discussion of the findings. The concluding remarks in Section 6 close the paper.

2. Material and methods

2.1. Material description

The material investigated in this paper is a (PP-EPR) impact block copolymer, consisting of a polypropylene (PP) matrix and ethylene–propylene rubber (EPR) particles. The fractions are respectively 78 and 22 wt%. The degree of crystallinity of the PP phase has been estimated to 50%. The EPR particles consist of 50% propylene and 50% ethylene. Because the matrix and particles are not miscible, the EPR phase can be considered as rubber inclusions into a PP matrix. Mineral inclusions are also present in low quantity (0.5%). The material has good mechanical properties for crash applications and exhibits a very high ductility.

The material was injection-moulded into plates of 3 mm thickness. Both the temperature of the mould and the flow were kept constant during the process to avoid residual stresses. 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

Mechanical tests were carried out in tension, compression and shear at several strain rates at room temperature to establish the mechanical behaviour relevant for crash situations. Most of the tests were monitored with a digital camera, providing pictures for a subsequent determination of the strain field applying digital image correlation (DIC).

In tension, modified ISO527b specimens were used for all strain rates, see Fig. 1a. A small imperfection was machined at both sides of the specimen and near the centre of its gauge section to localise

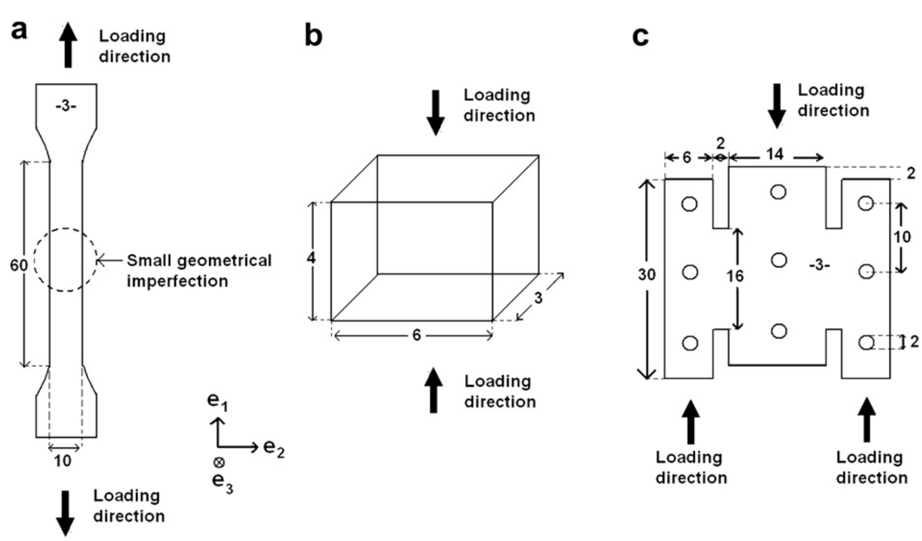

Fig. 1. Geometry of the specimens used to characterise the material: (a) tension specimen, (b) compression specimen, and (c) shear specimen. Note that the scale differs between the three parts of the figure.