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Test Method

Mechanical characterization of thin injection-moulded polypropylene specimens under large in-plane shear deformations

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ABSTRACT

The methodology to extract in-plane shear properties has been standardised for polymer-based composite materials. However, no standards have been designed to extract reliable test data that can be used to calibrate material models in numerical simulations for non-fibre reinforced polymers. The quality of the results from three widely used experimental techniques was examined in this study for mineral-filled polypropylene in terms of shear strain distribution, out-of-plane deformations and shear stress-strain curves with the aid of the digital image correlation method. The V-Notched Rail test (ASTM D7078) exhibited ultimate fracture of the specimen, but valid shear strain was only obtained for small deformations. For relatively large strains, more reliable shear test data were obtained from a modified version of ASTM B831: a standard test designed for aluminium but modified and implemented for polymers. Although out-of-plane deformations were avoided using aluminium holders, large variability was found in the strain distribution along the shear path. In contrast, the modified Wyoming Iosipescu test (ASTM D5379) exhibited the most robust shear stress-strain results due to consistent shear strain uniformity and low variability during the entire duration of the test.

1. Introduction

In recent decades, the use of polymer materials in the design of safety components for vehicles has increased due to their combination of modulus, yield stress and high toughness [1]. When their structural response is analysed using finite element codes, an accurate constitutive equation is required. Due to the significant stress anisotropy, plasticity laws based on the von Mises theory are no longer suitable to describe the phenomenology of inelastic polymer deformations [2]. Therefore, additional mechanical tests to the classical uniaxial tensile test are required to calibrate advanced material models (e.g. SAMP-1) which introduced shear test data to characterise non-linear plasticity [3].

Since it is very difficult to induce a "pure shear" stress state for large deformations in thin sheet components due to unwanted effects, such as out-of-plane deformations, significant effort has been applied in the design of tests to ensure the testing section is "shear dominated" in order to extract reliable material shear data. Numerous specimen geometries and testing fixtures have been proposed to characterise the shear response of polymers; such as the simple shear test [4], Iosipescu shear test [5–7], V-notched rail shear test [8–10], and the two-rail [11] and three-rail shear tests [12]. Several methodologies have been adopted in standards to measure the shear strength and modulus of polymer composites reinforced by high-modulus fibres. However, no standards are designed to extract the shear behaviour of thin sheets of solid polymers under large deformations. Several studies have been attempted to apply currently available testing methods to injection moulded polymers to find out which testing method can be applied to plastics subjected to large shear deformations. Daiyan et al. [13] conducted the modified Wyoming Iosipescu (ASTM D5379) [7] and the V-Notched Rail test (ASTM D7078) [10] on different talc-filled polypropylene compounds together with digital image correlation (DIC). It was observed that the D5379 method introduced less misalignment and, therefore, produced better strain uniformity between the notches. The ASTM D7078 method allowed larger strains under shear stress, which is better suited for stiffer materials. Nunes [14] proposed a modification of the ASTM B831 [15], a standard test method for thin aluminium alloy specimens, by adding a fixture plate in order to reduce the out-of-plane distortions during shear tests. Since there are a number of sources of uncertainties in finite element simulations for obtaining high quality and reliable material testing data [16], a shear methodology that minimises the non-uniform strain distributions during the experiment needs to be identified, hopefully from the existing tests.

This study is aimed at identifying the most robust shear test methodology that can be used to determine the shear stress-strain curves

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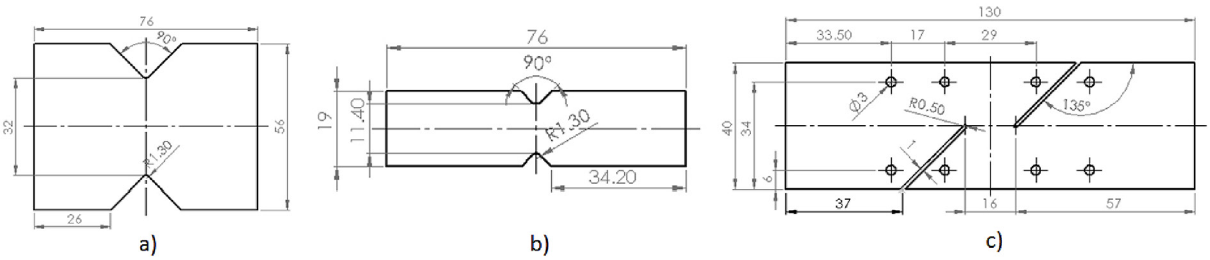

Fig. 1. Shear specimens produced: a) ASTM D7078; b) ASTM D5379; c) ASTM B831 modified by Nunes [14]. All dimensions in mm.

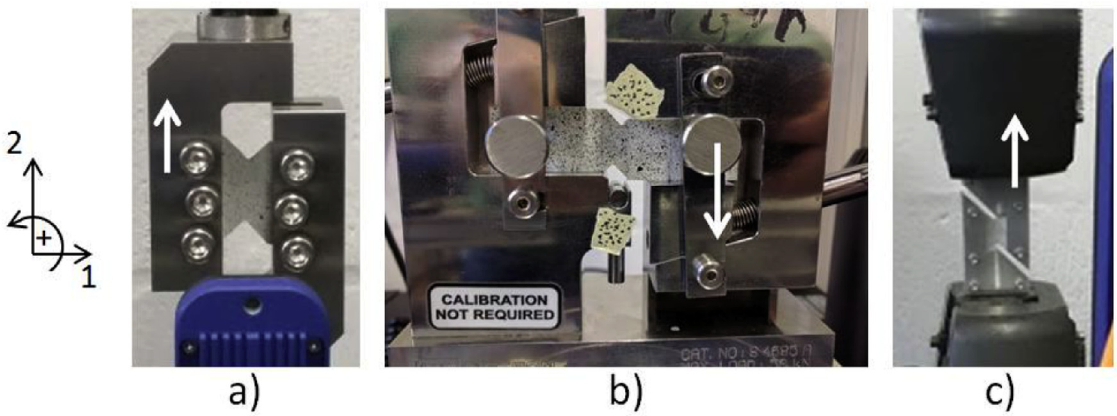

Fig. 2. Shear test fixtures used: a) ASTM D7078; b) ASTM D5379; c) ASTM B831 modified by Nunes. All were mounted on the same universal testing machine. White arrows indicate the loading directions of the fixtures.

until failure for thin injection-moulded plaques of a polymer material, in this case polypropylene. Therefore, the mechanical response of thin-walled structures can be more accurately predicted using FE codes. The V-notched rail shear test, the V-notched beam test and the slotted shear test modified by Nunes [14] were analysed by using DIC to identify the methodology that can produce a uniform stress state up to large strains.

2. Methodology

2.1. Material

The specimens used for the experimental investigation were machined from injection-moulded plaques made of mineral-filled polypropylene. A CNC milling machine was used to cut the desired geometries in order to reduce uncertainties in the material test data derived from damaged samples [17].

The shear test methods analysed in this paper were based on two standard tests for composite materials, i.e. the V-Notched Rail standard (ASTM D7078) and the V-Notched Beam standard (ASTM D5379) (known also as the modified Wyoming Iosipescu test). In addition, the slotted shear ASTM B831 test modified by Nunes [14] was also investigated because it was successfully applied to a polymer material, PTFE. In this study, the capability to measure the mechanical shear behaviour of polypropylene is assessed.

Test pieces with the nominal dimensions shown in Fig. 1 were cut from the centre of 3.15 mm thick, 150 mm wide and 250 mm long injection-moulded plates, as prescribed in ISO 294–5:2013, in order to avoid edge and injection gate effects.

A random speckle pattern was applied to the surface under investigation to allow the correct working of the DIC algorithm. In calculating corresponding points between subsequent images taken by the imaging device, and for correlation between cameras in stereoscopic systems, black and white Plastikote Super Matt paints were used. To improve the accuracy of the strain analysis, specimens with speckle size larger than 2 mm for ASTM D7078 and 1 mm for ASTM D5379 and ASTM B831 were discarded.

2.2. Apparatus

The three fixtures shown in Fig. 2 were used to test the machined specimens presented in Fig. 1. The D7078 method uses a fixture with two separate halves, one connected to each side of the test piece. The sample is fastened between the two blocks in each half of the fixture using three bolts, and one side is pulled upward during the test. In the D5379 test, the force is transmitted to the specimen by edge loading, again using a fixture with two separate halves, one connected to each side of the test piece. In Fig. 2b, the left half fixed the sample while the right half of the fixture is forced down, sliding on a bearing post. For the modified B831 test, the commonly used uniaxial tensile test grips were used with a fixture with two separate halves, comprising four 1.5 mm thick aluminium holders (designed by Nunes [14]) tightened to the specimen. The top half was pulled at a constant crosshead speed and shear strain was introduced in the centre of the test piece.

The experimental fixtures were mounted in the same electro-mechanical testing machine (fitted with a 10 kN load cell), which was operated in a temperature (23 ± 2 °C) and humidity (50 ± 10%RH) controlled laboratory. A constant crosshead speed of 2 mm/min was used to meet quasi-static test requirement in every test. The force was logged in synchronisation with the image acquisition of the DIC system. The speckle pattern on the specimens provided a way of calculating corresponding points between subsequent images taken by the imaging device. 3D DIC data were post processed using DaVis software from LaVision to measure the 3D deformation field of the speckled surface. A subset size of 13 × 13 pixel^2 was selected to accurately calculate the local shear strain distribution in the material between the two notches.

2.3. Stress-strain calculation

When material models are calibrated, true stress-strain curves are required and they are usually derived from the total (elastic and plastic) engineering quantities in the area of interest. In this paper, the nominal stress and strain were extracted at the centre of the specimen (i.e. the