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Test method

Effect of fiber orientation, stress state and notch radius on the impact properties of short glass fiber reinforced polypropylene

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ABSTRACT

Short glass fiber reinforced polypropylene (sgf-PP) is increasingly used in the automotive industry with the impact properties as key parameter. Experimentally, the impact behavior strongly depends on the specimen design, test set-up as well as temperature, and thus the characterization method should always be attuned to the occurring impact conditions of the final part. However, in order to deduce some general design criteria for sgf-PP, in this study a wide range of experimental parameters were investigated, specially focusing also on the effect of the governing, local fiber orientation distribution (FOD). Therefore, the effects of stress state (tensile, puncture and bending test), amount of stress concentration (notch radius) and temperature are characterized and discussed. The results proved that, as expected, distinctly different levels of impact strength and different dependencies on notches and notch radii are obtained for the various test set-ups. However, similarities in the temperature dependence are observed for specimens with similar governing fiber orientation.

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1. Introduction

In recent decades, the low temperature impact properties of neat polypropylene (PP) and its improvement by chemical modification or blending has attracted keen interest by both industry and research [1,2]. By reinforcing a brittle PP matrix with short glass fibers (sgf-PP), the stiffness and impact resistance are simultaneously enhanced, thus enabling the application in higher-performance structural applications such as in the automotive industry. While numerous studies have been published on the stiffness of sgf-PP considering structure/property correlations and analytical and numerical predictions (e.g. [3–7]), comparatively few investigations focused on the impact properties of sgf-PP, assessing mainly the effects of fiber length, fiber volume fraction and fiber-matrix adhesion [8–10]. Even fewer data have been published on the effect of fiber orientation on impact properties. Karger-Kocsis [11] reported that the fiber orientation and its distribution do not dominate failure and fracture properties under impact conditions owing to the restricted damage zone in this loading mode. Other authors (e.g. [8,12–15]), however, postulated that the local fiber orientation in front of the crack tip has a pronounced effect on fracture behavior, also via the resulting crack propagation path.

Another interesting study by Norman and Robertson [12] investigated in detail the changes in deformation mechanisms and impact strength as a function of a uniform fiber orientation in short fiber reinforced polymer. Generally, in sgf plastics, in addition to matrix related fracture mechanisms such as matrix yielding and cracking, fiber-related fracture mechanisms such as fiber-matrix interphase debonding and pull-out induced friction, fiber

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fracture and deformation contribute to the overall energy dissipating mechanisms. In [12], the significant and highly effective contribution of energy dissipation by fiber pull-out to the overall toughening of composites with fiber lengths lower than the critical fiber length was highlighted. With decreasing fiber orientation in the loading direction, the energy dissipation by pull-out and associated inter-phase friction and, correspondingly, the fracture impact strength decreases. Interestingly, maximal fracture impact strength is found for specimens with slightly misaligned fibers, as for quasi-unidirectional 0° specimens failure may occur by fiber fracture [12]. In a series of several papers [13,16,17] Pavan et al. reported a bi-linear relationship of fracture toughness parameters (such as K_C and G_C) with the first entry of the orientation tensor A_{11}, with the two different slopes over two ranges of orientation separated by a sharp knee point. This knee point was correlated to changes in the crack growth direction, from non-planar at high degrees of orientation corresponding to a higher slope, to planar at lower degrees of orientation and a lower slope, which was assumed to be caused by a transition in fracture mechanisms.

The impact strength is commonly characterized in standard Charpy bending impact tests according to EN ISO 179-1 and −2. According to these standards, the data generated can mainly be used in comparison with similar materials and not as basis for design calculation, as results depend on several test parameters (e.g. poor definition of stress state; notch radius and specimen dimension dependence) and are not a material-inherent property [18]. A prerequisite for a more detailed, in-depth investigation of the fracture processes by means of fracture mechanics concepts according ISO 17281, is the recording of the force and/or the fracture time signal resulting in the application of so-called instrumented impact testing. However, the force signal is prone to oscillations due to contact, inertia and transient dynamic effects, and can thus only be evaluated for test speeds up to about 1 m/s [19–21]. Visser et al. [22] highlighted the advantages of the instrumented tensile impact pendulum set-up, especially the inherent damping of the stress waves by the material itself. High speed tensile testing offers several further advantages over puncture and bending impact testing, which are the possibility (1) to test thin specimens, allowing for more precise control of the fiber orientation and to characterize this fiber orientation dependence, (2) to characterize surface strain by a high-speed camera and digital image correlation (DIC), and (3) to define the stress state which is assumed to be uniaxial and constant along the cross section, at least for unnotched specimens.

In general, in engineering parts and components, the fiber orientation and its distribution at the area of impact can differ drastically. Furthermore, depending on the type of impact, the geometry and the presence of notches, a wide range of stress states may occur during impact. Moreover, the temperature of application can vary widely, for example for sgf-PP in automotive applications, from about −30 °C in winter to elevated temperatures up to about +80 °C in engine compartment operating conditions. The aim of this paper was to characterize the fiber orientation dependence of some of these possible impact conditions (i.e. stress state, notches and temperature) for sgf-PP. Thus, three main aspects were covered:

(1) Three different test methods corresponding to three different stress states (i.e. uni-axial in tensile impact, bi-axial in instrumented puncture tests, and bi and tri-axial in unnotched and notched Charpy bending impact, respectively) were conducted, FOD dependence discussed and, if reasonable, correlated.

(2) A more detailed investigation was performed for the tensile impact test set-up by variation of several test parameters and data evaluation by means of fracture mechanics.

(3) Also in tensile impact testing, the effect of the notch radius was characterized for specimens with high fiber orientation in and perpendicular to the loading direction.

2. Experimental

2.1. Materials and specimens

The material employed throughout this study was a commercial sgf-PP of the type Fibremod™ GD301FE supplied by Borealis Polyolefine GmbH (Linz, A). The polymer matrix is a PP homopolymer, the sgf content of the material was 32 w% and fiber matrix adhesion was improved by chemical coupling agents. For tensile impact testing, specimens from a novel quasi-unidirectional (UD) tool with a cross-section of 2 × 10 mm were used which provide a high and uniform (no layer structure) fiber orientation in 0° and 90° to the load direction. The 0° specimens had a free clamping length of 70 mm and the 90° specimens of 30 mm. This difference in clamping length results in different strain rates at equivalent test speeds (i.e. deformation rates). Double edge notched specimens (DENT) with symmetric notches of 1, 1.75, 2.5, 3.25 and 4 mm radius (R1-R4) were produced by milling, and razor blade notches (RN notch) were pressed into the specimen, all with a residual ligament length of 6 mm. For instrumented puncture testing, 3 mm thick plates were injection molded with dimensions 60 × 60 mm. For Charpy bending impact tests, a 4 mm thick plate (150 × 210 mm) was injection molded via a fan end-gate at the shorter plate edge, and specimens according ISO 179-1 were milled out at different positions of the plate and at different angles (0°, 45° and 90°) to the main melt flow direction (MFD) (see Fig. 1 right). In Fig. 1, the fiber orientation ellipses of the respective specimen are also shown, which will be discussed below.

The FOD in the middle of the respective specimen type was characterized by means of micro computed tomography (μ-CT) experiments. For this purpose, a Nanotom (GE Phoenix|x-ray, Wunstorf, Germany) μ-CT device was used at a resolution of 2 μm voxel edge length. Scan parameters were set such that contrast and data quality was optimized. The 3D data were analyzed by an automatic software pipeline (for further details see [23]). The FOD can mathematically be represented by the orientation tensor, and is

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