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Test method

Local microstructure and stress distributions at the crack initiation site in a short fiber reinforced polyamide under fatigue loading

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ABSTRACT

This work aims to study the influence of the fiber distribution on the damage onset in a short glass fiber reinforced polyamide under fatigue loading. A fatigue test of a notched specimen was interrupted at crack initiation, then a small sample around the notch was machined from the specimen and analyzed by means of X-Ray Computed Tomography (X-Ray CT) for the quantitative description of the fiber distribution. The real microstructure was reconstructed and then simulated in the Finite Element Method (FEM) code ABAQUS. The analysis gives an insight into the local matrix stress distributions at the notch tip.

1. Introduction

Short Fiber Reinforced Plastics (SFRPs) are extensively used in the automotive industry as load bearing materials. Major advantages are offered by the injection molding technology in terms of design of complex geometries, high production output rates, low production waste, good reproducibility. The increasing use of these materials in structural applications has driven the development of lifetime prediction models. The advantage of using predictive models is that lifetime estimation is possible in the design phase of the product development, thus reducing the number of prototypes needed before the series production.

The understanding of the damage mechanisms supports the development of reliable lifetime prediction models. A literature review by Fatemi and Mortazavian [1] has shown that many papers have been devoted in the last decades to the investigation of fatigue behavior of SFRPs laying the basis for the development of lifetime prediction models.

Nowadays, the improvement of the investigation techniques enables a deeper understanding of the damage mechanisms. In addition, with the increase in computational power, it is possible to model the observed damage mechanisms and to integrate them in a lifetime prediction model. In SFRPs fiber-matrix interactions lead to microscopic stress concentrations which represent potential sources of damage initiation. The knowledge of the fiber orientation distribution at potentially critical locations such as notches or section changes is a fundamental step for the development of a lifetime prediction model. In Refs. [2,3] the authors investigated the damage mechanisms in short glass fiber reinforced polyamide under fatigue loading using specimens with molded notch. It was found that the crack initiation position is not at the notch tip as for homogenous materials but at clusters of through-the-thickness oriented fibers located around the notch. In the present work, the real microstructure around the notch is investigated by means of X-Ray CT and simulated using a FEM software with the aim to investigate the local matrix stress distributions at crack initiation.

The microstructure of SFRPs is characterized by three variables: fiber volume fraction, fiber aspect ratio and fiber orientation. Only the global fiber volume fraction is known beforehand. Fiber aspect ratio, local fiber volume fraction, fiber orientation depend on several factors such as process parameters, mold geometry, fiber volume fraction. Typically, the influence of the fiber orientation on the mechanical behavior of SFRPs has been studied by machining specimens from an injected plate at different orientations with respect to the Mold Flow Direction (MFD) [4–14]. The elastic and

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strength properties of SFRPs are lower if the loading direction is perpendicular rather than parallel to the MFD. This result was proved for SFRPs under static loading conditions irrespective of the temperature and strain rate [10,12], under impact loading conditions [14] and under fatigue loading conditions [8,9,11,13]. However, even for dog-bone plain specimens, not all the fibers are aligned in the MFD. Fiber orientation distribution varies through the specimen thickness. Close to the surface of the specimen, fibers are well aligned to the MFD, whereas at the mid-plane region, fibers are aligned transversely to the MFD. This structure is better known by the name shell-core morphology where shell indicates the layer near the mold wall, and core indicates the layer at the middle thickness. De Monte et al. [10,11] observed that the ratio between the thickness of the core and shell layer increases with increasing the thickness of the specimen. In this scenario, the response of thicker specimens is less influenced by the global fiber orientation (i.e. more isotropic) than that of thinner specimens. Hine et al. [15] reported that the thickness of the shell and core layers is not constant in an injection molded transverse ribbed plate but varies along the MFD.

In injection molded parts, geometric discontinuities within the mold make the fiber orientation distribution even more complex. They represent in fact, from a fluid-dynamic point of view, locations where the melt flow direction changes and from a structural point of view, typical areas for crack initiation [16,17]. Hence, the study of the fiber orientation distribution at potentially critical locations such as geometric discontinuities is considered to be highly relevant for the lifetime prediction of injection molded parts. In Ref. [18], De Monte and coworkers compared the torsional fatigue strength of hollow plain tubular specimens, hollow tubular specimens with molded V-shaped notch ($R_{notch} = 0.2$ mm) in the central section, and hollow tubular specimens with drilled hole ($R = 1$ mm) at the same position of the V-shaped notch. They found that in the first two cases the torsional fatigue strength is similar. Instead, specimens with drilled hole exhibited lower torsional fatigue strength even though the stress concentration in this case is lower than that of V-shaped notch. This result can be explained as a reinforcement effect of the microstructure at the crack initiation site for the molded V-shaped notch. Bernasconi and coworkers [19] investigated the fatigue behavior of rectangular PA6-GF30 specimens characterized by lateral molded notches ($R = 7.5$ mm) varying the position of the injection gate. Specimens were injected either longitudinally or laterally. The fatigue strength of laterally injected specimens was found to be lower than that of longitudinally injected specimens. The authors analyzed the fiber orientation distribution around the notch tips using X-Ray CT. In spite of the different behavior of the two sets of specimens, they reported similar fiber orientation distributions near the notch in the two cases. As a continuation of this work, Bernasconi and coworkers [20] investigated the fiber orientation at the notch tip of longitudinally injected specimens for three different notch geometries ($R = 0.5$, 1.0 and 2.0 mm) reporting a significant decrease of the fiber alignment in the longitudinal direction only for the sharpest notch ($R = 0.5$ mm). Over the last decade, new methods were developed to analyze the fiber orientation distribution. An established technique is based on the analysis by means of optical or electron microscopy of the footprints left by the fibers on a polished section [21,22]. Nowadays, this method is largely applied due to the easy set-up but allows the analysis of the fiber orientation distribution on a single section. Inaccuracies in measurement may arise when the fibers cross the plane almost perpendicularly. In this case, small ellipticity changes of the footprints result in a strong variation of the measured angles [23].

The use of the X-Ray CT has been on the rise in recent years. This technique, although it requires an expensive facility, enables a three dimensional description of the microstructure without the need of polishing the sample [24–26]. Unlike the optical method, X-Ray CT does not need the destruction of the sample which can be thus analyzed a second time. However, in order to reach high resolution, either very small specimens are needed or a small sample has to be machined from a specimen/part [27]. X-Ray CT can be thus considered a semi-destructive method. The continuous improvement of this investigation technique in terms of resolution and image contrast provides support for the investigation of the damage mechanisms [27–33].

This paper is organized as follows: In Section 3.1, the quantitative description of the microstructure around a molded notch is presented. For this purpose, a sample surrounding the notch tip and containing a crack propagated due to fatigue loading was analyzed by means of X-Ray CT. In Section 3.2 a procedure for the reconstruction of the volume analyzed by means of X-Ray CT is described and the local stress distributions around the notch are studied with the FEM software ABAQUS (Version 6.11/Standard) [34].

The present analysis aims to study the microscopic matrix stress distribution for a configuration that is representative of geometric discontinuities in injection molded parts and therefore represents a first step for the development of a multi-scale lifetime prediction model for SFRPs.

2. Experimental

2.1. Material system

The material studied in the present investigation is a short glass fiber reinforced polyamide containing 35 wt% glass fibers (designation PA66-GF35). The specimen has a molded-in central slit. The notch tip radius is ($R_{notch} = 0.2$ mm). The dimensions of the specimen are shown in Fig. 1. This specimen geometry was proposed by Sonsino and Moosbrugger in Ref. [17] with the aim to reproduce high stress concentrations such as those observed in real parts. The notch was molded-in reflecting most of the structural discontinuities in injection molded parts that are designed in the mold and not obtained by machining operations afterwards.

The specimen was injected along the horizontal direction in Fig. 1. Some of the fatigue tests on notched specimens performed in Ref. [35] were interrupted to study the fatigue damage mechanisms along the crack path. One of the specimens used for these tests was investigated by means of X-Ray CT with the aim to quantitatively analyze the fiber orientation distribution around the notch, at crack initiation. The fatigue test was carried out on a 10 kN servo-hydraulic testing machine. The loading direction corresponds to the horizontal direction in Fig. 1. The test was load controlled. The load ratio R ($= \sigma_{min}/\sigma_{max}$) was set to 0. The applied stress (calculated on the net section of the specimen) is $\sigma_a = 18$ MPa. The specimen was stored in a drum containing a drying agent (silica gel pearls) right after injection molding. Hence, we assumed that the specimen was tested in dry-as-molded (DAM) conditions. The fatigue test was carried out at room temperature and humidity. High frequency was set ($f = 20$ Hz) in order to accelerate the fatigue test. Infrared thermal analyses during fatigue tests on the same notched specimens in the same testing conditions revealed that the temperature increase before the crack initiation is less than 3 °C [2]. In analogous fatigue tests on dog-bone plain specimens, the testing frequency should be in the range 1–8 Hz depending on the load level in order to avoid material self-heating. Instead fatigue tests of notched specimens can be carried out at higher frequency mainly due to two reasons: i) lower load levels are required for specimen failure; ii) the stressed material is the volume around the notch tip and not the entire specimen section as in the case with plain specimens. Hence, the heat is released to the surrounding material.