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Damage initiation and evolution in short fiber reinforced polyamide under fatigue loading: Influence of fiber volume fraction

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ABSTRACT

This paper investigates the influence of fiber volume fraction on damage mechanisms in a short glass fiber reinforced polyamide (PA66) under fatigue loading. Uniaxial fatigue tests were carried out on notched specimens with different fiber contents (0%, 15%, 25%, 35%, 50% in weight). Some fatigue tests were interrupted before failure with the aim to analyze the crack path. Some other fatigue tests were carried out until specimen failure in order to analyze the fracture surface. Specific fractographic features were investigated: ductile/brittle appearance of the fracture surface, pulled-out/broken fibers, degree of fiber-matrix interfacial adhesion. The damage investigation was performed by using Field Emission Scanning Electron Microscopy (FESEM).

1. Introduction

Due to the increasing use of Short Fiber Reinforced Plastics (SFRPs) in structural applications, lifetime prediction models play an important role in the durability estimation of injection molded parts. Several studies have been conducted on the fatigue behavior of SFRPs. A comprehensive literature review recently published by Mortazavian and Fatemi [1] summarized the results published in the last forty years. The effect of loading conditions, microstructure and environmental factors on the lifetime of SFRPs have been investigated considering a wide range of polymers. In spite of that, lifetime prediction models found in the literature are mostly extensions of phenomenological models originally developed for isotropic materials [2,3]. This strategy implies that the attainment of a critical damage state is independent of the nature of the material. Often new parameters have to be included in the model for taking into account material peculiarities (i.e. anisotropy, viscoelasticity, etc.) increasing the effort for material characterization. In the last years, the improvements of the damage investigation methods showed that final failure in SFRPs is the result of the progression of damage mechanisms occurring at different scales. It was shown that the understanding of material behavior arises through the study of the interaction between the material constituents (fiber, matrix, fiber-matrix interface). In order to reproduce the fatigue behavior of SFRPs, lifetime prediction models should include the relevant damage mechanisms. Mechanisms-based models aim to obtain an accurate estimation of the lifetime to failure reducing empirical parameters and assumptions. The development of a mechanisms-based lifetime prediction model is based on the following steps: i) identification of damage initiation; ii) understanding of damage evolution until final failure; iii) quantification of damage; iv) analysis of the effect of damage on the material response (i.e. decrease of stiffness); v) definition of a criterion that identifies the attainment of the critical damage state with regard to the design function; vi) incorporation of the model into the structural analysis. The first two points were addressed in a recent paper of the authors [4]. In that paper, the damage mechanisms in plain and notched PA66-GF35 specimens under fatigue loading were studied. Basing on experimental observations, the authors proposed a damage scenario including the relevant

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mechanisms. In the present paper, the damage investigation is extended to consider the effect of fiber volume fraction using notched specimens under fatigue loading. With this work, the authors aim to extend the knowledge of the damage mechanisms in polyamide-based materials for the development of a lifetime prediction model.

In literature, the effect of fiber fraction on the mechanical behavior of SFRPs was studied with regard to the static response of plain specimens [5,6], the fatigue crack propagation [7–11] and the fracture toughness [12] of Compact Tension (CT) specimens. The study of the influence of fiber fraction on damage initiation and evolution in the presence of stress gradients generated by small radius slits has been first investigated in this work. In literature, more emphasis has been given to the influence of fiber orientation on the lifetime of SFRPs. In fact, a change in fiber content results in a variation of the other microstructural variables. The higher the fiber volume fraction the shorter the average fiber length will be due to fiber-fiber and fiber-machine interaction during injection molding [5,6,12–15]. The fiber volume fraction also influences the fiber orientation. Bernasconi [6] and Thomason [16] observed that the higher the fiber volume fraction the more the fibers are aligned in the Mold Flow Direction (MFD). Instead, the analysis of the influence of the fiber orientation on fatigue behavior of SFRPs can be conducted by machining specimens from injection molded plates at different orientations with respect to the MFD [17–22]. Such approach keeps the other microstructural variables unchanged. However, the fiber orientation distribution is not constant in the material but varies along the thickness forming the typical shell-core morphology. At the mold walls, fibers are oriented in the MFD (shell layers). At the mid-thickness, fibers are oriented transversely to the MFD (core layer). The core layer is larger with increasing the specimen thickness affecting the mechanical behavior of SFRPs. In Refs. [17,18], De Monte and coworkers reported that 1 mm thick specimens machined from a plate at different orientations with respect to the MFD exhibit a marked anisotropic material response both under static and fatigue loading. Instead, 3 mm thick specimens showed a more isotropic mechanical response.

In Refs. [4,23], the authors used rectangular specimens with a central molded-in notch in order to reproduce the fiber orientation at structural discontinuities in injection molded parts. The MFD was parallel to the long dimension of the specimen. It was observed that around the notch, fibers are mostly oriented through-the-thickness. This is because the insert used for creating the notch is an obstacle for the melt flow that affects the local fiber orientation distribution. For this specimen geometry, the variation of fiber volume fraction affects the fiber orientation globally but also around the notch where damage is expected to initiate. The present damage investigation enables the study of different fiber distributions at crack initiation without milling operations and thereby considering the effect of local structural discontinuities.

In the present work, the damage investigation is divided in two parts. Section 4.1 is dedicated to the analysis of the crack path. Fatigue tests were interrupted before specimen separation. The side surface of the specimens was polished for microscopic investigations. Section 4.2 is dedicated to the analysis of the fracture surface. For this purpose, fatigue tests were carried out until specimen separation into two parts. The damage analysis was carried out at multiple scales. The influence of fiber volume fraction on the specimen failure mode (stable/unstable Fatigue Crack Propagation (FCP)) was primarily investigated observing the fracture surface of failed specimens with unaided eye. Meso- and micro-scale investigations were carried out by means of Field Emission Scanning Electron Microscopy (FESEM). At meso-scale, the effect of fiber volume fraction on the crack path was investigated. At micro-scale, damage mechanisms were studied by analyzing the following fractographic features: ductile/brittle matrix fracture behavior, fiber failure/pull-out and degree of fiber-matrix interfacial adhesion.

From the analysis of the damage mechanisms, a damage scenario from the first noticeable event of damage to the specimen failure is proposed. This damage scenario is the basis for the development of a multi-scale model for the lifetime prediction of SFRPs.

2. Materials, geometry and test equipment

The material investigated in the present paper is a short glass fiber reinforced polyamide (PA66). Five material systems were tested varying the fiber content (V_f = 0%, 15%, 25%, 35%, 50% by weight).

Uniaxial fatigue tests were carried out on a 10 kN servo-hydraulic testing machine. The fatigue tests were performed under load control, applying a sinusoidal load with constant amplitude. The load ratio R (= $\sigma_{min}/\sigma_{max}$) was set to 0 for all the performed fatigue tests. Test frequency was evaluated according to the following criteria: i) avoid the hysteretic heating of the material, i.e. a temperature increase above 5 °C compared to the test temperature; ii) for each load level, test at the highest possible frequency in order to reduce the testing time. The resulting test frequency was in the range of 4–20 Hz depending on load level and fiber fraction. It was increased with reducing the load level. As shown later on in this paper, the fatigue strength of short glass fiber reinforced polyamide specimens increases with increasing fiber volume fraction. For this reason, with the same load level, higher test frequency was set for higher fiber contents. The temperature increase on the specimen surface was monitored using an infrared camera (FLIR ThermCAM SC500).

Specimen geometry and dimensions are reported in Fig. 1. Specimens were injected along the longitudinal direction (horizontal direction in Fig. 1) which is also the loading direction. The notch is a central slit of 10 mm with notch radius of 0.2 mm. The stress concentration factor (referring to the net section) calculated using isotropic material model is Kt_{net} = 9.81. The notch geometry is the result of a study aimed to reproduce high stress gradients in injection molding parts [2]. The notch was created through an insert within the mold reproducing geometric discontinuities in injection molded parts.

The fatigue tests were carried out at room temperature. Relative humidity in the room was not controlled during the fatigue tests. The specimens were tested in dry-as-molded condition (about 0.1% moisture content). For this aim, they were stored in a drum containing a drying agent (silica gel pearls) right after injection molding. Short fiber reinforced polyamide is used in under-the-hood applications at high temperature (T > 100 °C). In general this material absorbs moisture from the environment. However for

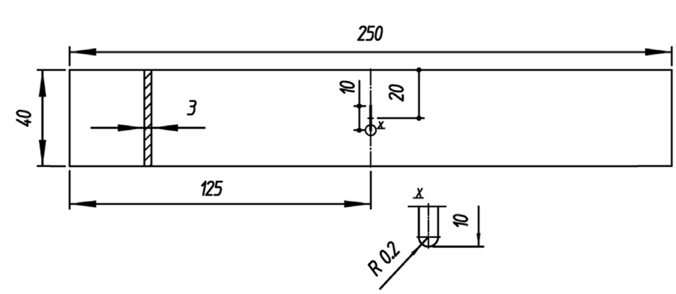

Fig. 1. Specimen geometry and dimensions (in mm).