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Fatigue of short fiber thermoplastic composites: A review of recent experimental results and analysis

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ABSTRACT

Cyclic deformation and fatigue behavior of two short fiber thermoplastic composites (SFTCs) under a number of loading and environmental conditions are investigated. The considered environmental effects include those of low and elevated temperatures as well as moisture (or water absorption). Fatigue behavior is also explored under the action of non-zero mean stress (or R ratio) in addition to fully-reversed ($R = -1$), as well as various cyclic loading frequencies. Material anisotropy and geometrical discontinuity effects (i.e. stress concentration) are other aspects considered in this study. Mechanisms of fatigue failure are also assessed under environmental effects. Based on experimental observations and analysis, a number of analytical and empirical models are developed for estimating fatigue behavior under different conditions. Empirical equations are presented to characterize self-heating under cyclic loading. Tsai-Hill criterion is applied to account for the effect of fiber orientation on fatigue life. Mean stress effect is corrected with several mean stress parameters and a shift factor of Arrhenius type is defined to characterize the effect of temperature on fatigue life. Two methodologies are presented to estimate fatigue properties based on tensile properties, in addition to approximation of strain-life curves based on load-controlled fatigue data. Estimation of notched fatigue behavior based on smooth (un-notched) fatigue behavior is also presented.

1. Introduction

Application of short fiber thermoplastic composites (SFTCs) is increasingly growing due to their remarkable properties. Light weight, low manufacturing cost with a high volume production rate, and the capability to be molded in complex geometries are the main characteristics of SFTCs. A wide range of effects related to microstructure, environment and load conditions are involved in fatigue design of SFTCs. However, a relatively small number of studies have been conducted on fatigue behavior characterization of SFTCs, although components made of these materials are typically subjected to cyclic loads. Due to the complexity as well as a large number of parameters influencing mechanical behavior of SFTCs, fatigue behavior has been mainly investigated through experimental techniques, while less attention has been given to fatigue behavior modeling [1].

Under cyclic loading, a continuous softening is generally observed in SFTCs, which is typically due to initiation and growth of damage in the matrix as well as at fiber ends and fiber-matrix interface [2,3]. Thermoplastic materials exhibit time dependent properties and relatively low melting temperatures. As a result, significant effect of load frequency is observed on fatigue behavior of SFTCs [4].

Increased fatigue performance of SFTCs is a function of fiber reinforcement, its orientation and distribution which in turn is associated with the geometry of fibers and the component, viscoelastic behavior of the matrix, and flow field during the injection molding process [5]. A shell-core morphology across the thickness of a molded part has frequently been reported for SFTCs, where higher fiber alignment exists in two shell layers compared with the core layer [6]. Recently, micro-tomography studies have been performed on SFTCs for their fatigue damage investigation [7]. However, the effect of fiber orientation effect has often been evaluated through conducting fatigue tests on samples with different thicknesses and with fibers in different orientation with respect to the loading [6].

Environmental effects including temperature and moisture on fatigue behavior of SFTCs have been explored in several studies. A significant degradation of fatigue strength has been observed from temperatures below to above the glass transition temperature (T_g) [6]. A recent extensive survey has been performed on high temperature fatigue behavior of SFTCs in [8]. The effect of water

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absorption is a function of the polymer type and fiber-matrix coupling agents [9].

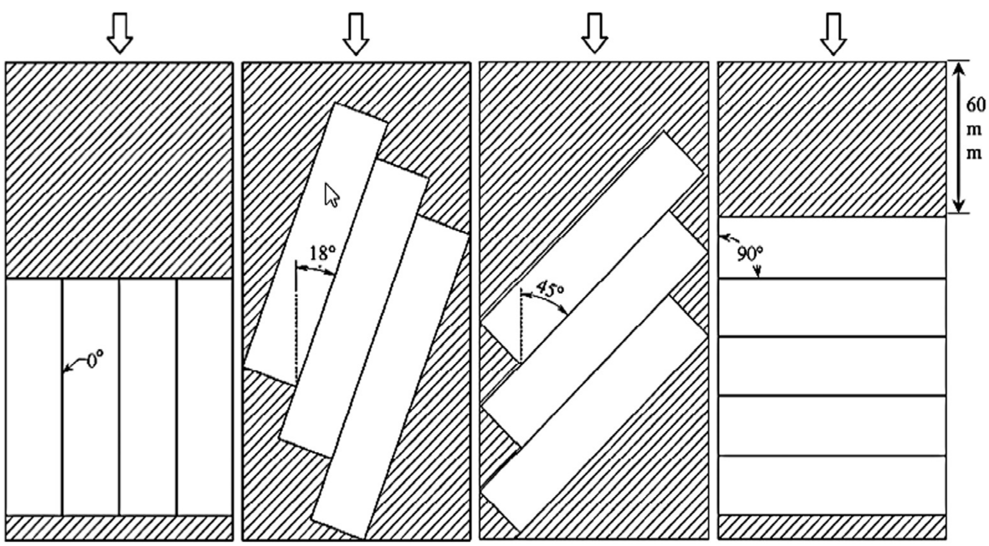
A small number of studies have been devoted to effects of mean stress or R ratio and stress concentration on fatigue behavior of SFTCs. A significant effect of mean stress, which may be accompanied by cyclic creep or ratcheting is observed on fatigue behavior of SFTCs [10]. The reduction of fatigue strength due to mean stress has been observed to be less for notched specimens as compared with smooth specimens, due to the presence of stress gradient near the notch root. Modified Goodman and Gerber mean stress equations have been used with the use of creep rupture strength to correct for the mean stress effect [11,12].

In this study, a number of aspects related to fatigue behaviors of two short fiber thermoplastic composites (SFTCs) were experimentally investigated and fatigue life estimation methodologies are presented to account for these aspects. The materials and specimen geometries used, as well as the experimental procedure are described first. Then, experimental results for the different effects considered are presented and discussed, followed by the fatigue analysis model used to represent or estimate each effect. The considered effects include cyclic deformation, load frequency and self-heating, anisotropy or fiber orientation effect, moisture, temperature, mean stress, and stress concentration.

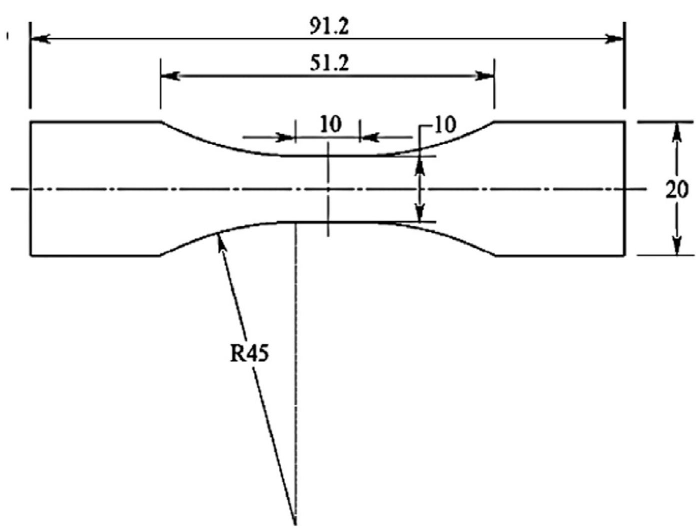
2. Material, specimen geometry, and experimental method

The two composite materials considered were a polybutylene terephthalate with 30 wt% short glass fiber (here referred to as PBT) and a polyamide-6 with about 10 wt% rubber and 35 wt% short glass fiber (here referred to as PA6). The glass transition temperature (T_g) of both materials was about 60 °C, as obtained from dynamics mechanical analysis. The average fiber aspect ratio was estimated at 26 [13,14].

Materials were injection molded in rectangular plaques with dimensions of 100 mm × 200 mm in 3 and 3.8 mm thicknesses. To study the effect of fiber orientation, rectangular strips were machined from molded plaques at 0°, 18°, 45° and 90° angles with respect to the injection mold flow direction, as shown in Fig. 1(a). A



(a)



(b)

Fig. 1. (a) Specimen cutting directions with respect to mold flow and, (b) specimen geometry designed for fatigue tests. For notched specimens a 2 mm diameter central hole was drilled in the middle of the gage section (K_t = 2.5) (all dimensions are in mm).