International Journal of Fatigue 77 (2015) 12–27

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Fatigue behavior and modeling of short fiber reinforced polymer composites including anisotropy and temperature effects

Seyyedvahid Mortazavian, Ali Fatemi *

Mechanical, Industrial and Manufacturing Engineering Department, The University of Toledo, 2801 West Bancroft Street, Toledo, OH 43606, USA

ARTICLE INFO

Article history:
Received 27 November 2014
Received in revised form 17 February 2015
Accepted 22 February 2015
Available online 4 March 2015

Keywords:
Fatigue
Short fiber polymer composite
Anisotropy effects
Fiber orientation effect
Temperature effect

ABSTRACT

Effects of anisotropy and temperature on cyclic deformation and fatigue behavior of two short glass fiber reinforced polymer composites were investigated. Fatigue tests were conducted under fully-reversed ($R = -1$) and positive stress ratios ($R = 0.1$ and 0.3) with specimens of different thicknesses, different fiber orientations, and at temperatures of −40 °C, 23 °C, and 125 °C. In samples with 90° fiber orientation angle, considerable effect of thickness on fatigue strength was observed. Effect of mold flow direction was significant at all temperatures and stress ratios and the Tsai–Hill criterion was used to predict off-axis fatigue strengths. Temperature also greatly influenced fatigue strength and a shift factor of Arrhenius type was developed to correlate fatigue data at various temperatures, independent of the mold flow direction and stress ratio. Micromechanisms of fatigue failure at different temperatures were also investigated. Good correlations between fatigue strength and tensile strength were obtained and a method for obtaining strain–life curves from load-controlled fatigue test data is presented. A fatigue life estimation model is also presented which correlates data for different temperatures, fiber orientations, and stress ratios.

1. Introduction

The use of short fiber reinforced polymer composites (SFRPCs) is rapidly growing, particularly in the automotive industry applications. These materials commonly processed by the injection molding technique are corrosion resistant substitutions for metallic alloys, with sufficient strength and stiffness in many applications. Lower cost and higher manufacturing rate, particularly for obtaining complex geometries, are some advantages of SFRPCs over continuous fiber composites.

Fatigue behavior of SFRPCs has been studied far less than continuous fiber composites. A recent comprehensive literature review was conducted by Mortazavian and Fatemi [1] on fatigue behavior and modeling of SFRPCs. A number of factors influencing fatigue behavior of SFRPCs including microstructural aspects and effects related to loading condition and service environment were reviewed.

Continuous cyclic softening was observed in SFRPCs due to initiation and growth of damage in the matrix, at fiber ends, or at fiber–matrix interface [2,3]. The viscous characteristics were found to be dependent on both temperature and frequency. Launay et al. [3] showed that the loss tangent of a short glass fiber polyamide-6.6 increases with frequency, while it has a dissipative peak at the glass transition temperature (T_g).

Increased fatigue performance of short fiber composites compared with unreinforced polymers is a factor of fiber length. In a study by Lavengood and Gulbransen on a short boron fiber epoxy composite [4], fatigue strength was found to increase with increased fiber length and reach a plateau at a particular fiber aspect ratio. An optimum nominal fiber length depending on fiber content and molding conditions can be used to improve fatigue performance. During the injection molding process, degradation of nominal fiber length decreases the fatigue strength of short fiber composites [5]. Due to high stress inducing fiber breakage in LCF, the effect of fiber length on axial fatigue behavior is more pronounced in LCF, as compared with HCF [6].

The effect of fiber surface modification was investigated in [7,8] and a higher fatigue strength was observed for surface modified glass fiber composites compared with unmodified glass fiber composites. Fatigue damage in SFRPCs has been characterized and modeled based on their dissipative response under cyclic loading. Evolution of hysteresis loops in either their size or slope [2,5], hysteretic energy [7,8], strain energy [9,10], and nonlinear viscoelasticity [11,12] are the parameters typically used for modeling of fatigue damage and accumulation.

* Corresponding author. Tel./fax: +1 419 530 8213.
E-mail addresses: seyyedvahid.mortazavian@utoledo.edu (S. Mortazavian), afatemi@eng.utoledo.edu (A. Fatemi).

http://dx.doi.org/10.1016/j.ijfatigue.2015.02.020
0142-1123/

Nomenclature

a_{T_0}	temperature shift factor	T	temperature
A	fatigue strength intercept	T_0	reference temperature
b	fatigue strength exponent	T_g	glass transition temperature
B	S–N line slope	α, β, ζ	general fatigue model parameters
c	fatigue ductility exponent	δ	loss tangent
C, D	temperature superposition parameters	ε_0	maximum strain
E'	storage modulus, cyclic elastic modulus	ε_a	strain amplitude
E_a	activation energy	$\Delta\varepsilon_e$	elastic strain range
K'	cyclic strength coefficient	ε'_f	fatigue ductility coefficient
N_f	cycles to failure	$\Delta\varepsilon_p$	true plastic strain range
N_t	transition fatigue life	θ	fiber orientation angle
n'	strain hardening exponent	σ_0	maximum stress
N'_f	reduced cycles to failure	σ_L	longitudinal fatigue strength
R	stress ratio	σ_T	transverse fatigue strength
S_a	stress amplitude	σ_a	true stress amplitude
S_u	maximum tensile strength	σ'_f	fatigue strength coefficient
S_{max}	maximum stress	τ_{LT}	shear fatigue strength
S'_y	cyclic yield strength		

Fiber orientation is another important factor controlling fatigue performance and the degree of anisotropy of SFRPCs [13–15]. The orientation distribution of fibers is mainly controlled by a complex flow field in the injection molding process and also dependent on the geometry of fibers and the component, viscoelastic behavior of matrix, and melt and mold temperatures [16]. The effect of fiber orientation can be evaluated by obtaining specimens with different thicknesses or fiber orientation angles.

A shell–core morphology typically exists across the specimen thickness, where a higher degree of fiber alignment occurs in shell layers compared with the core layer. As the ratio of core thickness to the specimen thickness increases, less anisotropic fatigue behavior is observed [17]. A thinner core layer in specimens from edge of molded plaques results in higher fatigue performance as compared with specimens from middle of plaque [18]. Tsai–Hill criterion was suggested by Bernasconi et al. [13] to estimate off-axis fatigue strength of SFRPCs. The off-axis fatigue strength as a function of thickness and mold location has been found to be proportional to the corresponding tensile strength in several studies [13,17,19].

Fatigue strength of SFRPCs was found to decrease by increasing the temperature from below to above T_g [17,20,21]. However, fatigue strength normalized by tensile strength at the corresponding temperature was reasonably correlated in [21]. At temperatures above T_g, similar slopes were observed at different temperatures in several studies [22,23].

In SFRPCs the mechanisms of fatigue failure are related to many factors including stress amplitude level, fiber orientation distribution, fiber–matrix interface, and temperature. Fatigue failure typically occurs in four stages including deformation at fiber ends, initiation of crack, crack growth, and unstable crack growth in the last cycle [24]. Matrix rupture or fiber–matrix interfacial debonding in LCF and crack propagation in HCF resulted in a shift in S–N curve slopes between HCF and LCF regions [25]. Due to increased craze formation in short glass fiber polyamide-6.6 in HCF, the level of surface roughness was found to be higher in the HCF compared with LCF [26].

Matrix brittle failure and fiber pull-out were observed in mold flow oriented samples, while brittle fracture surface was observed in samples perpendicular to the mold flow direction of short glass fiber polyamide-6.6 in [15]. As temperature increased, crazes in fibril structure were more pronounced. In matrix-dominant areas, cracks were formed normal to the loading direction, while in fiber-dominant areas cracks were observed in matrix and along the interfacial bonding for aligned and off-axis fibers, respectively [2]. Fatigue damage mainly developed at the interfacial bonding of fiber and matrix, but matrix microcracks were dominant in the core layer [27].

This study investigated the effects of anisotropy and temperature on cyclic deformation and fatigue behaviors of two short glass fiber reinforced thermoplastics. Incremental step cyclic tests were conducted in various mold flow directions and temperatures to evaluate transient and stable cyclic deformation behaviors. Viscoelastic behavior was also studied from the results of dynamic mechanical tests. Anisotropy of fatigue behavior was investigated by performing fatigue experiments with different thicknesses, and making specimens with different fiber orientation angles, as well as microstructural examination of fracture surfaces. The effect of temperature on fatigue behavior was also studied and a model was developed to represent this effect. Correlations between fatigue strength and tensile strength are also presented and strain–life curves are developed from the load-controlled fatigue test results. A fatigue life prediction model is also applied to all fatigue data to account for the effects of temperature, fiber orientation angle, and stress ratio. Tensile behaviors of the considered materials were characterized and modeled through conducting tensile tests in a range of temperatures and strain rates on samples prepared in several mold flow directions in [28,29]. The effect of moisture on tensile and fatigue behaviors of these materials was also investigated in [30].

2. Experimental program and procedures

2.1. Materials and specimen

One of the materials investigated is short glass fiber reinforced polybutylene terephthalate, containing 30 wt% glass fibers (here designated as PBT) and another material used is short glass fiber reinforced polyamide-6, with 35 wt% glass fibers and about 10 wt% rubber impact modifier (here designated as PA6). T_g was obtained at about 60 °C for both PBT and PA6 from peak loss tangent in dynamic mechanical analysis tests (DMA). Melt point is at about 220 °C for both materials. Common applications of PBT and PA6 are in the automotive industry. Fiber length, diameter and orientation distributions after injection molding process are described in [29]. Mean fiber length and diameter were obtained as 0.25 mm and 10 microns, respectively.