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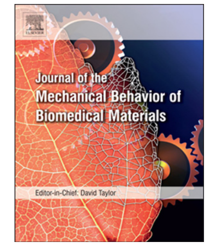

Research Paper

Effects of microstructural inclusions on fatigue life of polyether ether ketone (PEEK)

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ABSTRACT

In this study, the effects of microstructural inclusions on fatigue life of polyether ether ketone (PEEK) was investigated. Due to the versatility of its material properties, the semi-crystalline PEEK polymer has been increasingly adopted in a wide range of applications particularly as a biomaterial for orthopedic, trauma, and spinal implants. To obtain the cyclic behavior of PEEK, uniaxial fully-reversed strain-controlled fatigue tests were conducted at ambient temperature and at 0.02 mm/mm to 0.04 mm/mm strain amplitudes. The microstructure of PEEK was obtained using the optical and the scanning electron microscope (SEM) to determine the microstructural inclusion properties in PEEK specimen such as inclusion size, type, and nearest neighbor distance. SEM analysis was also conducted on the fracture surface of fatigue specimens to observe microstructural inclusions that served as the crack incubation sites. Based on the experimental strain-life results and the observed microstructure of fatigue specimens, a microstructure-sensitive fatigue model was used to predict the fatigue life of PEEK that includes both crack incubation and small crack growth regimes. Results show that the employed model is applicable to capture microstructural effects on fatigue behavior of PEEK.

1. Introduction

Polymeric materials have evolved from being inexpensive substitutes for metals to becoming materials of choice for engineering applications due to their many advantageous properties such as high strength to weight ratio and low density relative to metals. The use of polymer-based structures has grown over the last several decades in part due to improved versatility in synthesizing tailored polymers for desired engineering applications. Additionally, there is a growing interest among industries and government agencies in utilizing polymers in structural applications to address energy consumption and greenhouse emission concerns, since these materials are lightweight and in most cases recyclable.

Polymers are generally classified into two groups, thermoplastics and thermosets, based on the molecular bonding and

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Nomenclature

a_i	initial crack length
C_I	material dependent constant for the low cycle fatigue regime
C_{II}	material dependent constant for the high cycle fatigue regime
C_{Inc}	coefficient in the modified Coffin–Mansion equation
C_M	micro notch strain coefficient in low cycle fatigue
C_N	micro notch strain coefficient in high cycle fatigue
D	inclusion particle diameter
da/dN	crack growth rate
GO	grain orientation
GS	grain size
K'	cyclic strength coefficient
l	length of local plastic deformation region near the inclusion particle
N_f	number of cycles to failure
N_{Inc}	number of cycles to incubate a crack
N_{LC}	number of cycles required for long crack propagation
N_{MSC}	number of cycles required for propagation of a microstructurally small crack
N_{PSC}	number of cycles required for propagation of a physically small crack
N_{Total}	total number of cycles
n'	cyclic strain hardening exponent
q	exponent in the nonlocal damage parameter equation
R	load ratio
r	exponent to determine l/D ratio
S_{ut}	ultimate stress
U	load ratio parameter
y_1	material constant in the nonlocal damage parameter equation
y_2	material constant to include the mean stress/strain effect in the nonlocal damage parameter equation
z	geometric factor to obtain C_{Inc}
α	exponent in the modified Coffin–Mansion equation
β	nonlocal damage parameter
ΔCTD	range of crack tip displacement
ΔCTD_{th}	threshold of crack tip displacement
ε_a	strain amplitude
ε_{per}	cyclic strain perculation limit
ε_{th}	strain threshold limit for micro-plasticity at inclusion
ζ	material dependent parameter in the nonlocal damage parameter equation
χ	crack tip opening displacement and crack growth rate constant
η_{lim}	percolation limit
$\Delta\gamma^P_{max}/2$	maximum plastic shear strain amplitude
$\Delta\sigma/2$	stress amplitude
$\Delta\hat{\sigma}$	multiaxial fatigue term in the crack tip displacement equation

their response to an increase in temperature (Trantina and Nimmer, 1994). The bonds between the polymer chains in thermoset polymer are cross-linked and cannot be softened upon reheating. Hence, thermosets are typically rigid and cannot be recycled. On the other hand, thermoplastics contain molecular chains with relatively weak forces that enable the material to be repeatedly softened when heated and solidified upon cooling, without affecting the mechanical properties (Crawford, 1998). Thermoplastic polymers can be further divided into either amorphous or semi-crystalline. Amorphous thermoplastics contain randomly oriented long polymer chains and exhibit high melt viscosities but poor chemical and fatigue resistance. Conversely, semi-crystalline thermoplastics composed of both regions of amorphous (randomly ordered) and ordered molecular structures. They are generally more resistant to chemical as well as wear and fatigue when compared to amorphous thermoplastics (Crawford, 1998). Due to these unique properties, a semi-crystalline thermoplastic was chosen in this study.

The polymeric material selected in this research is PEEK, which is a high performance, engineering grade, semi-crystalline thermoplastic. PEEK exhibits good mechanical and electrical properties under a wide range of temperatures from cryogenic conditions to elevated temperatures. This material has a low susceptible to creep and produces low smoke and toxic gas emission. PEEK is also commonly used as a matrix material in composites in various applications such as automotive, aerospace, and biomedical. Due to the versatility of its material properties, PEEK is also found to be resistant to vivo degradation and radiation sterilization (Kurtz and Devine, 2007), transparent to x-rays, and biocompatible (Halabi et al., 2011). A number of investigations have been conducted to obtain the clinical performance of PEEK as a biomaterial for orthopedic, trauma, and spinal implants (Kelsey et al., 1997; Liao, 1994; Corvelli et al., 1997). An extensive review of PEEK as biomaterials for medical devices has been provided by Kurtz and Devine (2007). Polymeric-based components used in many of these medical applications, such as bone anchors, spinal cages, and total hip replacement, require a thorough characterization of their physical and mechanical properties, and in-service performance specifically their response to progressive and localized degradative fatigue damage caused by repeated exposure to cyclic stress and strain.

Despite the importance of understanding the fatigue failure mechanisms in polymers, only a small number of research has been performed on polymeric materials over the past decades when compared to those on metals. Due to the differences in microstructures between polymeric and metallic materials, their mechanisms underlying fatigue failure are also expected to be different. However, their overall fatigue process is similar, with crack initiating from the regions with higher stress concentration resulted from the foreign inclusions, defects, or impurities within the materials (Crawford, 1998; Lugo et al., 2014).