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Notched fatigue behavior of PEEK

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ABSTRACT

Poly(ether-ether-ketone) (PEEK) has been used as a load bearing orthopaedic implant material with clinical success. All of the orthopaedic applications contain stress concentrations (notches) in their design; however, little work has been done to examine the fatigue behavior of PEEK in the presence of a notch. This work examines both stress-life (S–N) fatigue behavior and the fracture behavior of unfilled PEEK under tension–tension loading in circumferentially grooved round bar specimens with different elastic stress concentration factors. It was found that the majority of the loading was elastic in nature, and that there was only a small portion on the lifetime where there was a detectable change in structural behavior prior to gross fracture. Fractographic analysis via SEM further elucidated the potential fracture micromechanisms. Additional analysis was conducted to estimate the percent of the lifetime spent in crack initiation vs. propagation, and it was found that the specimens spent the majority of the time in the crack initiation phase.

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1. Introduction

Poly(ether-ether-ketone) (PEEK), is a semi crystalline polymer that has an approximate crystallinity of 30–35% and a Tg of 143 °C [1]. In addition to high strength, unfilled PEEK has several attractive properties: transparency to X-rays, no artifacts created in CT images, and excellent biocompatibility [1,2]. Another reason that PEEK is of interest is that both carbon fiber reinforced (CFR) and hydroxyapatite (HA) filled and/or HA coated PEEK have been developed. This has the benefit that the mechanical properties of the material can be tailored by altering the composite formulation [1].

Since the 1990s unfilled PEEK has been used in both cervical and lumbar spinal cages in vertebral fusion surgeries with considerable clinical success [1]. Medtronic Sofamor Danek has launched the CD Horizon Legacy PEEK pedicle-based, posterior rod for use as a dynamic stabilization system for the spine [3]. An artificial disc fabricated entirely from unfilled PEEK (NUBAC intradiscal arthroplasty device for the lumbar spine by Pioneer Surgical Technology, Marquette, MI) is currently in an international multi-center prospective clinical trial with 225 of these devices implanted since December 2004 [4].

All of these unfilled PEEK devices have design stress concentrations and/or undergo multiaxial loading conditions. We have previously reported on the monotonic behavior of unfilled PEEK in the presence of stress concentrations (generically referred to as notches) [5]. However, since devices used in clinical situations will experience cyclic loading the fatigue behavior of PEEK in the presence of stress concentrations is of clinical interest. There have been some reports in the literature on the fatigue crack propagation behavior of PEEK [6–8], and also on the stress-life (S–N) behavior [9]. However, there has been little work on the S–N fatigue behavior of PEEK in the presence of a stress concentration [10]. In addition, no work to the author's knowledge has attempted to estimate the contribution of crack initiation versus propagation to the cyclic lifetime, and none of the works were conducted in a physiologically relevant environment. The goal of this study was to determine the S–N behavior of PEEK in the presence of a stress concentration and to estimate the duration of initiation versus propagation in a physiologically relevant environment.

2. Materials and methods

The PEEK material used in this study was OPTIMA LT1™ (Invibio, Inc., West Conshohocken, PA), which is an unfilled PEEK formulation. Three tensile specimen geometries were machined and tested. Two circumferentially U-shaped grooved specimen geometries, "Moderate" (OD = 8 mm, ID = 6 mm, notch radius = 0.9 mm, $k_t = 2.1$) and "Deep" (OD = 8 mm, ID = 6 mm, notch radius = 0.45 mm, $k_t = 2.7$) were tested to examine the effect of different elastic stress concentration factors (k_t) on the tension–tension fatigue behavior of PEEK. A circumferentially razor grooved dog-bone ("Razor", OD = 8 mm, ID = 6 mm, $k_t > 10$) was also tested, to examine the effect of

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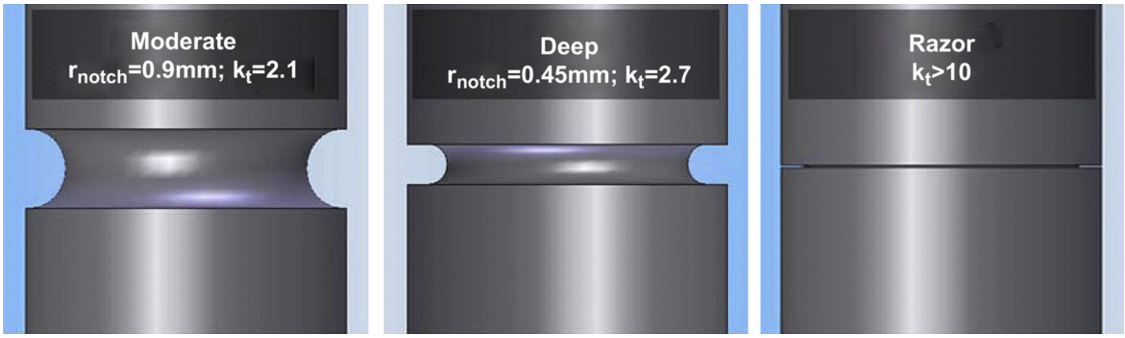

Fig. 1. The specimen geometries used in the testing.

an extreme stress concentration on the tension–tension fatigue behavior (Fig. 1). Prior to mechanical testing, specimens were pre-conditioned in a 37 °C phosphate-buffered saline (PBS) bath for 8 weeks to simulate physiological conditions.

All tests were conducted under tension–tension loading with a minimum tensile load of 30 N at 2 Hz on an Instron 8411 servohydraulic frame (Instron Inc, Norwood, MA). The R-ratio (ratio of minimum load to maximum load) was ≤ 0.02. The tests were conducted in a 37 °C PBS bath. Stress ranges were selected with the intention to capture lifetimes in the low-to-intermediate (1000–100,000) cycle range.

Load and crosshead displacement were periodically recorded up to failure using LabView in addition to the cycles to failure. Also, to estimate the size of the plastic zone during cyclic loading, the Von Mises stress distributions based on the Neuber equations [11] were calculated.

Using the load and crosshead displacement data, a secant stiffness, k (GPa/m), was determined for each cycle:

$$k = \frac{\Delta\sigma}{\Delta x_{\text{cyclic}}} \tag{1}$$

where $\Delta\sigma$ is the cyclic engineering stress amplitude (based on the ID = 6 mm) and Δx_{cyclic} is the corresponding cyclic displacement (Fig. 2). The evolution of creep displacement Δx_{creep} and cyclic displacement were evaluated by used of creep displacement and cyclic displacement versus lifetime curves. The total displacements at failure, $\Delta x_{tot,f}$, and the creep displacement at failure, $\Delta x_{creep,f}$, were also found (Fig. 2). To check if the dependence on these two values on the stress amplitude the following ANOVA was conducted:

$$\Delta x_{\text{f}} = \mu + \gamma[\Delta\sigma] \tag{2}$$

where Δx_{f} is either $\Delta x_{creep,f}$ or $\Delta x_{tot,f}$.

For the moderate geometry, 28 specimens were tested at seven stress levels; for the deep geometry, 27 specimens at six stress levels were tested; and, for the razor geometry, 25 specimens at five stress levels of the razor geometry were tested ($n = 1$–6 specimens per stress level). To compare the fatigue behavior of the geometries, the sets of fatigue data were fitted with the S–N Basquin relationship [12]:

$$\Delta\sigma = AN^d \tag{3}$$

where $\Delta\sigma$ is the axial engineering stress amplitude, N is the lifetime, and d and A are constants. The fitting was conducted using non-linear regression in MATLAB. Robust ANOVAs using S-Plus were conducted to test for significant differences in the values of d and A between the three geometries ($\alpha = 0.05$) [13].

To estimate the time spent in propagation vs initiation, a linear elastic fracture mechanics (LEFM) approach was taken. According to Yates [14], the stress intensity, K, for a circumferentially grooved round bar is given by:

$$K = F\sigma\sqrt{\pi a} = F\sigma\sqrt{\pi\left(l + \frac{D-d}{2}\right)} \tag{4}$$

where a is the effective crack length, D is the outer diameter of the specimen, d is the inner diameter, l is the distance of the crack from the notch, and F is the stress intensity factor (Fig. 3). The stress intensity factor, F, is given by multiplying the solution of Tada et al. [15] for the stress intensity factor of a crack in a round bar, F_{Tada}, by a correction factor, F_{Yates} that accounts for the notch, and the length of the crack relative to it:

$$F = F_{\text{tot}} = F_{\text{Tada}} \times F_{\text{Yates}}$$

$$F_{\text{Tada}} = \frac{1.122 - 1.302\left(\frac{2l+D-d}{D}\right) + 0.988\left(\frac{2l+D-d}{D}\right)^2 - 0.308\left(\frac{2l+D-d}{D}\right)^3}{\left(\frac{d-2l}{D}\right)^{\frac{3}{2}}} \tag{5}$$

$$F_{\text{Yates}} = 4.012\left(l\sqrt{\frac{2}{\rho(D-d)}}\right)^{\frac{1}{2}} - 5.244\left(l\sqrt{\frac{2}{\rho(D-d)}}\right) + 2.245\left(l\sqrt{\frac{2}{\rho(D-d)}}\right)^{\frac{3}{2}}$$

$$\text{if} \quad 0 \leq l \leq 0.4\sqrt{\frac{\rho(D-d)}{2}}$$

$$F_{\text{Yates}} = 1$$

$$\textit{if} \quad l > 0.4\sqrt{\frac{\rho(D-d)}{2}}$$

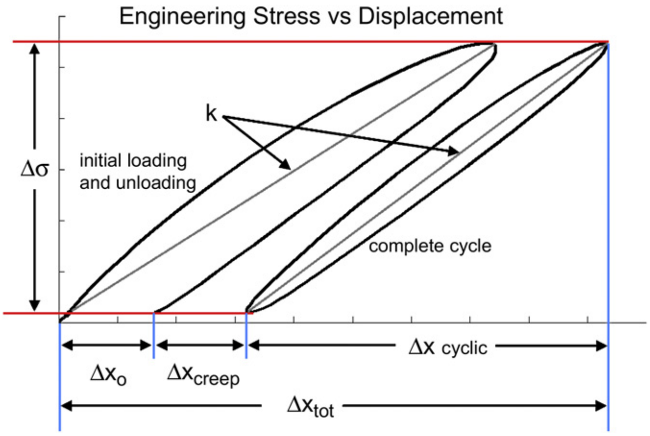

Fig. 2. Diagram illustrating definitions for the cyclic stress amplitude ($\Delta\sigma$), displacements (Δx_{o}, Δx_{creep}, Δx_{cyclic}, Δx_{tot}), and secant stiffness (k).

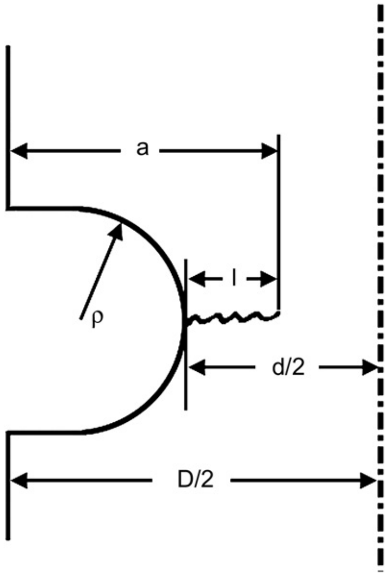

Fig. 3. Diagram illustrating the definitions (a, l,D, d, ρ) for the linear elastic notch fracture mechanics approach.

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