

Notched Tensile Fatigue Behavior of PEEK Under Physiologic Environmental Conditions

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Introduction:

Poly(aryl-ether-ether-ketone) (PEEK) is a semicrystalline polymer that is used in several orthopaedic applications, including hip stems, bone anchors, and spinal implants [1]. Since these components contain stress-risers, it is of interest to determine the notch behavior of PEEK in fatigue. The objective of this study was to investigate the tensile fatigue behavior of PEEK with stress concentrations of varying severity.

Materials and Methods:

PEEK OPTIMA LT1™ material was used (Invibio, Inc., West Conshohocken, PA). Three geometries of circumferentially grooved (OD = 8mm, ID = 6mm) dogbone specimens were machined and tested: Moderate (notch radius = 0.9mm, kt = 2.1); Deep (notch radius = 0.45mm, kt = 2.7); and Razor (1mm deep cut made with a razor blade). Prior to testing, specimens were pre-conditioned in a 37°C PBS bath for 8 weeks. Fatigue testing to failure (fracture) was performed in a PBS bath at 37°C on an Instron 8511 load frame. Tests were conducted using a sinusoidal waveform at 2Hz under tension-tension loading ($R \leq 0.02$). The intention was to capture lifetimes in the low-to-intermediate (1,000-100,000) cycle range. Load and displacement were periodically recorded up to failure using LabView. For the moderate geometry, 28 specimens at 7 stress levels were tested; 27 specimens at 6 stress levels of the deep geometry were tested; and, 25 specimens at 5 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: $\sigma_a = CN^d$, where σ_a is the axial engineering stress amplitude, N is the lifetime, and d and C are constants. ANCOVAs using S-Plus [2] were conducted to test for significant differences in the values of d and C between the three geometries ($\alpha = 0.05$). The fracture surfaces were inspected using stereomicroscopy and a representative fracture surface, from each geometry, was examined in a Hitachi S-4500 SEM.

Results:

In all cases, the cyclic stress vs displacement curves showed little hysteresis (Fig. 1), and appeared quite linear. All of the geometries showed slight creep ratcheting. There was no evidence of consistent or notable softening or hardening upon cycling. The exponent (d) of the cyclic stress-life (S-N) relationship was the same for the moderate and deep geometries, but different for the razor geometry. The coefficient (C) for all three geometries was found to be different (Fig. 2).

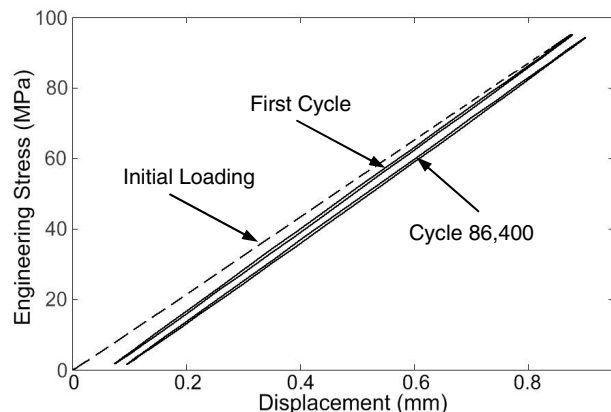


Figure 1. Stress vs displacement for a moderate notched specimen. Shown is the initial loading (dashed line), the first cycle, and one of the cycles near failure ($N = 86,400$; $N_f = 86,408$ cycles)

The fracture surfaces of the specimens all appeared to have a similar micromechanism of fracture (Fig. 3). There is first a region/front of void coalescence emanating from the notch. Next, there is a region of stable fatigue crack growth containing sporadic void coalescence ahead of the crack front (Fig. 3, right). Finally, there is a zone of concentrated

void coalescence ahead of the crack tip, followed by fast fracture.

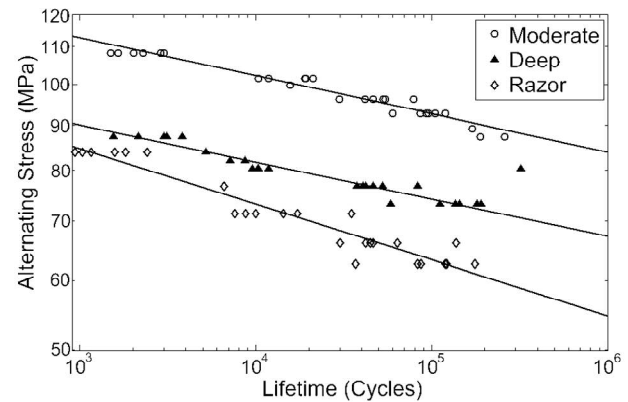


Figure 2. Experimental data and regression curves for the moderate ($\sigma_a = 152N^{-0.043}$, $R^2 = 0.95$); deep ($\sigma_a = 120N^{-0.042}$, $R^2 = 0.82$); and razor notched ($\sigma_a = 131N^{-0.063}$, $R^2 = 0.92$) specimens.

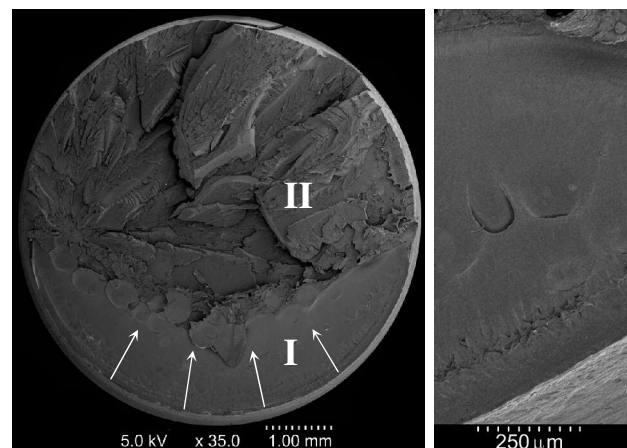


Figure 3. Left; fatigue fracture surface: I) stable fatigue crack growth and II) fast fracture. Right; higher magnification view of I.

Discussion:

This is the first report of the notched tensile fatigue behavior of PEEK in a physiologically relevant environment. The decrease in the S-N curve with increase in notch severity is consistent with an expected higher local cyclic stress at the notch root. The steeper slope of the razor sharpened notch geometry (Fig. 2) compared to the other geometries implies that fatigue initiation is an important component of the total cyclic life. Thus, sharp scratches should be avoided in the handling of PEEK components. Although there was some stable fatigue crack growth, the majority of the specimen failed in fast fracture [3]. The micromechanism of fracture in the transition from stable to unstable crack growth (i.e., void coalescence) is consistent with that reported in compact tension fracture toughness tests of PEEK [5]. Brittle type fracture behavior was expected since 37°C is well below the T_g (143°C) of PEEK. Future work will use this data to evaluate the applicability of a constitutive material model developed for another semicrystalline polymer (UHMWPE) to PEEK [4]. Additional studies will consider the notched static and cyclic behavior of carbon fiber reinforced PEEK.

References: 1) Kurtz, S, *Biomat*, 2007; 2) Neter, *Appl. Linear Stat. Models*, 1996; 3) Sobieraj, M, Paper 1121.00, WBC 2008 Amsterdam; 4) Bergstrom, J, *Biomat*, 2003; 5) Rae, P, *Polymer*, 2007

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