Fatigue Crack Initiation and Propagation Behavior of Neat PEEK under Notched Conditions

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Statement of Purpose: 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 and to determine the relative time spent in crack initiation vs. crack growth.

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. To compare the fatigue behavior of the geometries, the sets of fatigue data were fitted with:

$$\sigma_a = AN^d \qquad (1)$$

where σ_a is the axial engineering stress amplitude, N is the lifetime, and d and A are constants. Robust ANCOVAs using S-Plus [2] were conducted to test for significant differences in the values of d and A between the three geometries ($\alpha = 0.05$). Representative fracture surfaces from each geometry were examined in a Hitachi S-4500 SEM. Using the fractographs of multiple specimens and the equation [3]:

$$N_{growth} = \frac{1}{C(\Delta\sigma\sqrt{\pi})^{m'}} \int_{a_i}^{a_f} \frac{da}{(F\sqrt{a})^{m'}} \qquad (2)$$

The lifetime, N_{growth}, for a crack to grow from a crack length of a_i to a length prior to fracture of a_f, was estimated. F is the stress intensity factor for a notched bar with a crack found by Yates [4], and C and m' are the Paris constants estimated using data from Tseng [5] (values of C and m' and were taken as 6×10^{-10} and 4.5)

Results: In all cases, the cyclic stress vs. displacement curves showed little hysteresis. The stiffness decreased significantly during the last 200-300 cycles prior to failure for the moderate and deep geometries. The fracture surfaces of the specimens all appeared to have a similar micromechanism of fracture. There is first a region/front of initiation emanating from the notch (Figure 1). Next, there is a region of stable fatigue crack growth containing sporadic void coalescence ahead of the crack front. There were fatigue striations evident on the surface in this region. Finally, there was a zone of concentrated void coalescence ahead of the crack tip, followed by fast fracture. The ANCOVA of the regression of equation 1(Table 1), found that the moderate and deep notch did not have statistically significantly different d, but did have different A's. Both the moderate and deep had significantly different d when compared to the razor geometry.

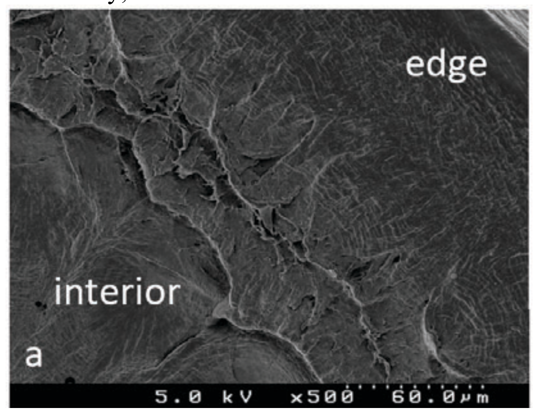

Figure 1. Region/front of crack initiation

	Moderate	***Deep***	***Razor***
A (MPa)	152	120	131
d	-0.043	-0.042	-0.063
R^2	0.95	0.90	0.92

Table 1. Results of the regression analysis

Using equation 2 on selected moderate and deep specimens it was found that the average cycles spent in crack propagation ranged from 300-800, while total lifetime ranged from 1,000 to 180,000.

Conclusions: This work found that crack propagation lifetime was a minor part of the total lifetime for the moderate and deep notch geometry conditions. This is supported by two other findings, the aforementioned steeper behavior of the razor notched specimens, and the observation that the stiffness and cyclic displacement only showed a change in behavior during the last 200-300 cycles in the moderate and deep geometries.

The significantly higher loads sustained by PEEK (300-400%) at a given lifetime when compared to similar studies using UHMWPE [6] suggests that PEEK has excellent notched total-life fatigue resistance, and is a promising material for use in orthopaedic implants.

References: 1) Kurtz, S, Biomat, 2007; 2) Neter, Appl. Linear Stat. Models, 1996; 3) Dowling, Mech Behavior of Mat, 1999; 4) Yates, J Strain Anal, 1991; 5) Tseng, Dissertation, U Texas Arlington, 1996. 6) Sobieraj, Dissertation, Case Western Reserve U, 2008.