Summary

The mechanical behavior of a material can differ substantially between static or steady applications of load or deformation versus dynamic or variable applications of load. A material that shows a high mechanical strength, such as polystyrene, may look very weak in fatigue. As a result, devices that are to be subjected to cyclically varying loads or deformations should be analyzed in fatigue mode, particularly if the device is expected to see hundreds of thousands to millions of cycles in its anticipated lifetime of use.

This application note describes fatigue crack propagation analysis, specifically on ultra high molecular weight polyethylene.

Background

When testing the fatigue behavior of materials, one can test the samples in either an unnotched format (i.e. smooth) while measuring resultant load vs. cycles, or one can deliberately introduce a notch or defect and monitor the crack propagation as a function of number of cycles and load. The latter tends to be a more rigorous assessment of the material's tolerance to defects, which can either be introduced during manufacturing or during use.

ASTM E647 "Standard Test Method for Measurement of Fatigue Crack Growth Rates" describes a general protocol for measuring the fatigue crack propagation testing of materials. Originally specified for metals, this standard has been applied to polymer for several years.

In this test, a plot of change in crack length (da) for each tensile fatigue cycle (dN) is plotted as a function of a stress intensity factor (ΔK), which is a function of the crack length, the applied load, and the geometry of the test specimen. A typical plot for a fatigue crack propagation (FCP) test is shown in Figure 1. In Regime I, little significant crack propagation occurs. For many materials, once da/dN reaches approximately 10^{-6} mm/cycle, the crack propagation tends to grow linearly on a log-log plot. This region is Regime II, also known as the Paris Regime. Some materials enter a third regime (Regime III), where unstable crack growth begins.

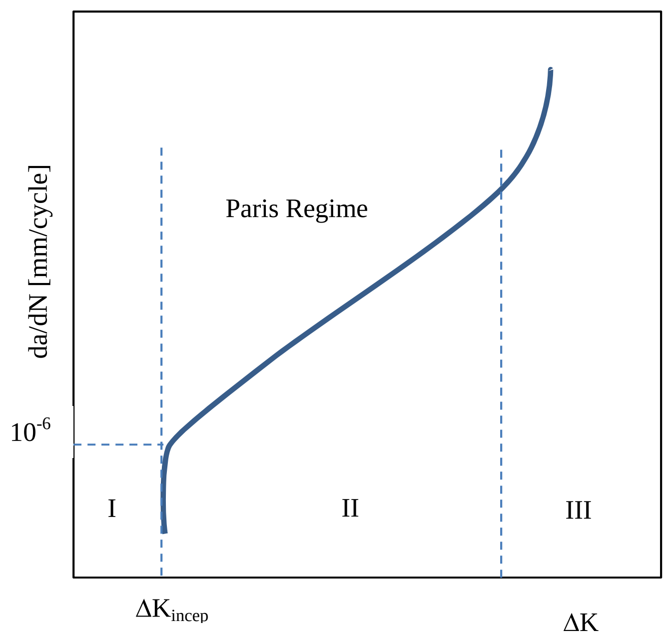

Figure 1: Typical plot for a fatigue crack propagation test, showing the three zones and calculated terms. This is normally a log-log plot.

Procedure

The standard test specimen configuration is a compact tension specimen, shown in Figure 2. A larger notch is machined using a regular notch cutter. A pre-crack is usually then generated by pushing a razor blade into the notch.

The control mode is a constant force (P = load) and $\Delta P = P_{max} - P_{min}$ is normally held constant for each specimen. Specimens are tested with an R-ratio of 0.1 (P_{min}/P_{max}), a sinusoidal waveform, and a frequency of 3 Hz. The length of the growing crack is monitored automatically with two digital cameras on either side of the test specimen, which capture and record images of the crack through the test cycle as a function of number of cycles, *N*. The number of cycles (*N*) for each growth period was recorded. Specimens were cycled until failure occurred. The secant or point-to-point technique for computing the crack growth rate is used for calculating da/dN. The method involves calculating the slope of the straight line connecting two adjacent data points according to the following equation:

$$\frac{da}{dN} = \frac{(a_{i+1} - a_i)}{(N_{i+1} - N_i)}$$

where *a* is the length of the crack [m] and *N* is the number of cycles.

The cyclic stress intensity (ΔK) and the average crack growth rate (da/dN) for each specimen are then plotted. The cyclic stress intensity (ΔK) is calculated according to the following equation:

$$\Delta K = \left(\frac{\Delta P}{B\sqrt{W}}\right) f\left(\frac{a}{W}\right)$$

$$f\left(\frac{a}{W}\right) = \frac{(2 + a/W)}{(1 - a/W)^{3/2}}\left[0.886 + 4.64\frac{a}{W} - 13.32\left(\frac{a}{W}\right)^2 + 14.72\left(\frac{a}{W}\right)^3 - 5.6\left(\frac{a}{W}\right)^4\right]$$

where: ΔP = load range [N], B = thickness [m], W = width [m], $f(a/W)$ = geometric correction factor for compact tension specimen. Linear regression analysis is performed on each resulting curve. The slope and intercept obtained from the linear regression analysis were used to determine the exponent, *m* and the coefficient, *C*, from the Paris equation $da/dN = C\Delta K^m$. The Paris regime is usually defined as the data in the crack growth range of $1\text{x}10^{-4}$ mm/cycle to $1\text{x}10^{-2}$ mm/cycle for UHMWPE.

The cyclic stress intensity at inception (ΔK_i) is also calculated. Linear regression is performed on each curve at low ΔK and the x-intercept at $1\text{x}10^{-7}$ mm/cycle was reported as ΔK_i. It is important to realize that ΔK_i is load dependent and therefore will vary between tests unless the load is fixed, as it is here.

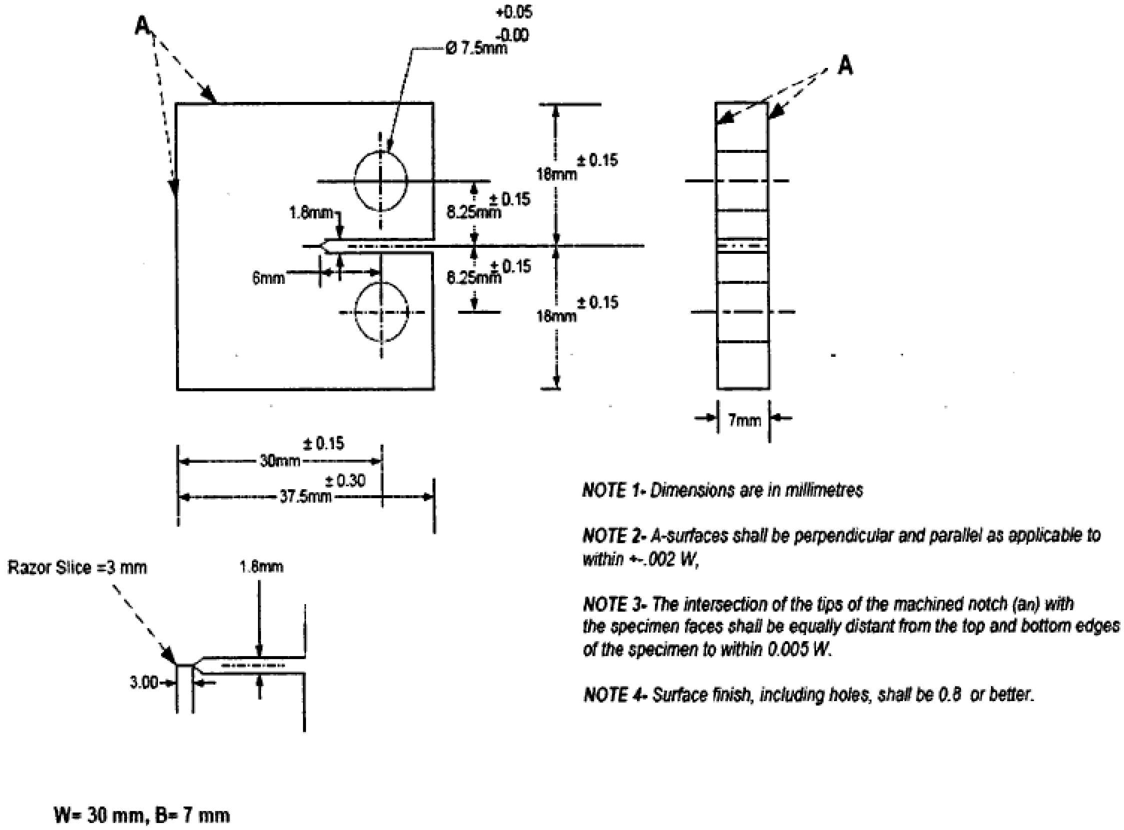

Figure 2: Fatigue crack growth specimen per ASTM E647.

Typical Results

Results from a crosslinked UHMWPE are shown in Figure 3. Regimes I and II are clearly visible. UHMWPE typically does not enter Regime III, where unstable crack propagation occurs. From this data set, the stress intensity factor at the crack inception was calculated as ΔK_{incep} = 1.35 MPa/m$^{1/2}$, and the Paris regime parameters were calculated from the Regime II slope and intercept (m = 9.0, C = 1.9E-6). As the material becomes more brittle, the ΔK_{incep} tends to decrease, although caution should be used in this interpretation, as this parameter also depends on the loads used in the test. Faster crack growth will decrease the slope *m* can also decrease the slope. *C* indicates the overall rate of crack growth.

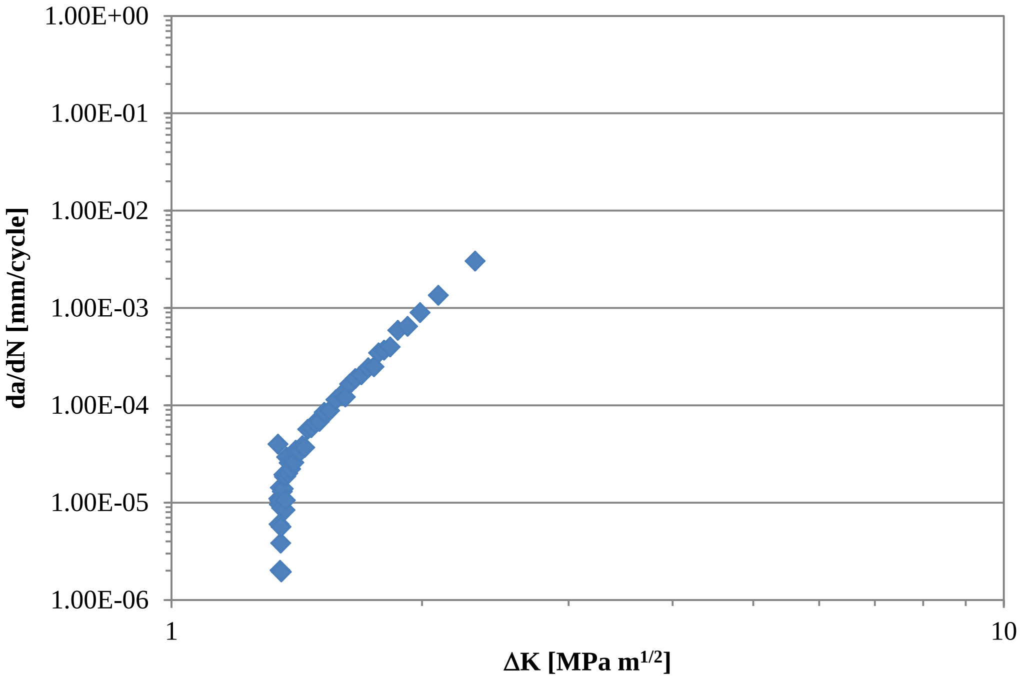

Figure 3: Typical FCP results for a crosslinked UHMWPE.