# Fatigue Crack Propagation Testing in UHMWPE

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## Objective

Fatigue crack growth resistance of UHMWPE used in articulating implants is an important characteristic, as rim cracking in acetabular liners has been observed in the past,[1] and there are concerns about crack resistance effects on the locking mechanism and post strength of tibial inserts,[2] especially in highly crosslinked UHMWPE,which has reduced resistance to fatigue crack propagation[3]

Fatigue crack propagation resistance has conventionally be tested according to ASTM E647, a standard written for metals, and which only reports the $DK_{th}$, or the threshold asymptomatic value of stress intensity factor DK where da/dN approaches 1E-10 m/cycle.[4] Researchers working with UHMWPE typically also report the Paris regime parameters (*C* and *m*), which are obtained from the fitted da/dN vs DK curve for zone II of the fatigue crack growth curve.[5] Differences in test methodology, equipment, sample geometry, and data analysis techniques can make comparisons of fatigue crack test data challenging. To this end, a new ASTM test method for fatigue crack propagation (FCP) specific to UHMWPE is being developed. As part of this method, a new automated optical system has been developed to aid in collecting crack propagation data, in an effort to improve the quality and density of the data, and to provide more uniformity in data comparison between labs. This paper discussions a comparison of the new optical system tested at two laboratories on a highly crosslinked UHMWPE.

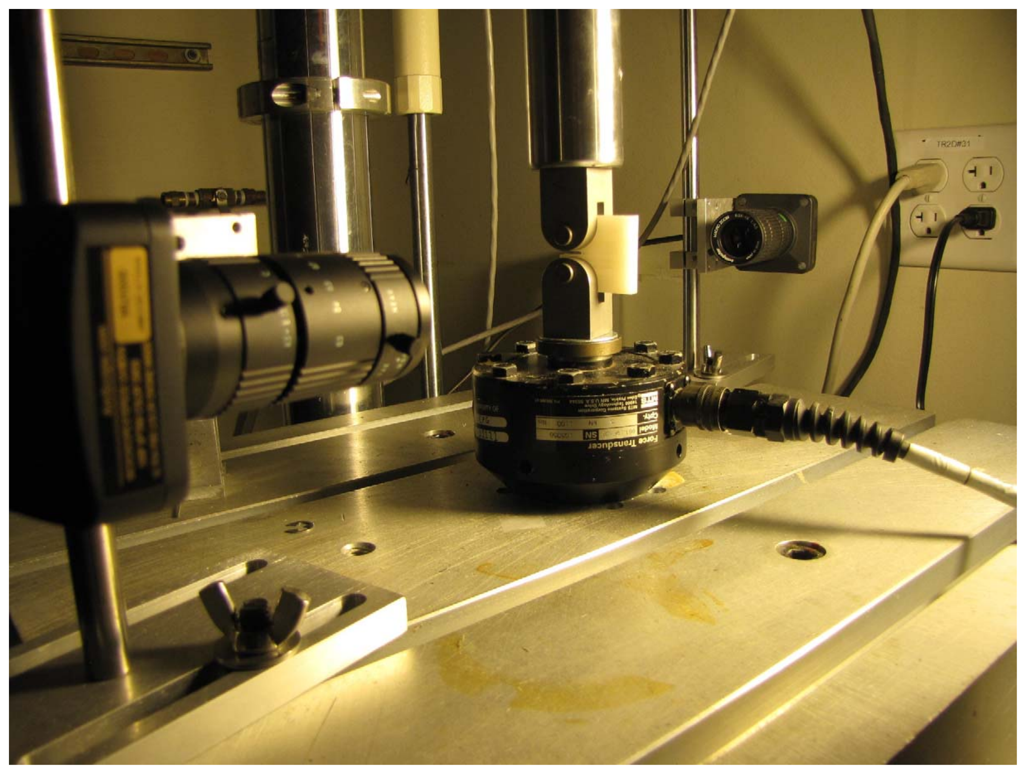

**Figure 1: Dual camera automated optical system**

## Materials and Methods

GUR 1050, gamma irradiated to 50 kGy and remelted (Marathon) was tested. A single set of test specimens were machined and razor pre-notched at one lab, using C(T) specimens (W = 40 mm, B = 10 mm). Samples were tested at a $\Delta P$ of 347 N, an R of 0.1, a frequency of 3 Hz, and a sinuisoidal wave form. Lab 1 used an electrodynamic load frame with chilled air blowing on the test specimen, and Lab 2 used a servohydraulic frame with ambient air cooling the specimen.

A machine vision system using dual cameras was used at each lab (Fig. 1). Images were acquired at 21 FPS, while the samples were being flexed in the load frame and the crack length *a* was computed in real time as a function of load cycles *N*, reported as an average of the crack length from each camera. Fatigue crack growth rate da/dN was calculated using the secant method.[4] $DK_{th}$ was calculated by performing a linear regression on data obtained in growth rates between 1E-10 m/cycle and 1E-8 m/cycle and determining the required DK to produce a da/dN of 1E-10 m/cycle. Linear regression was also performed in the Paris regime (defined here as da/dN values between 1E-7 and 1E-5 m/cycle) for determination of *m* and *C* parameters.

## Results

Exemplary crack length and processed data is shown in Fig. 2 through Fig. 4. Statistical analysis of the results shows no statistically significant difference in results in *C* ($p$=0.039), but a statistically significant difference in the $DK_{th}$ and *m* ($p$=0.006, 0.001). The difference in $DK_{th}$ was 2.5%, and was 18% for *m*. The higher calculated stress intensity factors and tail off for Lab 2 data is likely caused by feedback loop problems on the servohydraulic load frame at high displacements occurring near sample failure.

| | | $DK_{th}$ | m | c |
|---|---|---|---|---|
| Lab 1 (n = 8) | Average | 1.063 | 9.039 | 7.70E-09 |
| | Std. Dev. | 0.013 | 0.130 | 8.94E-10 |
| | RSD [%] | 1.3 | 1.4 | 11.6 |
| Lab 2 (n = 2) | Average | 1.090 | 7.666 | 1.11E-08 |
| | Std Dev. | 0.013 | 0.429 | 2.57E-09 |
| | RSD [%] | 1.2 | 5.6 | 23.1 |

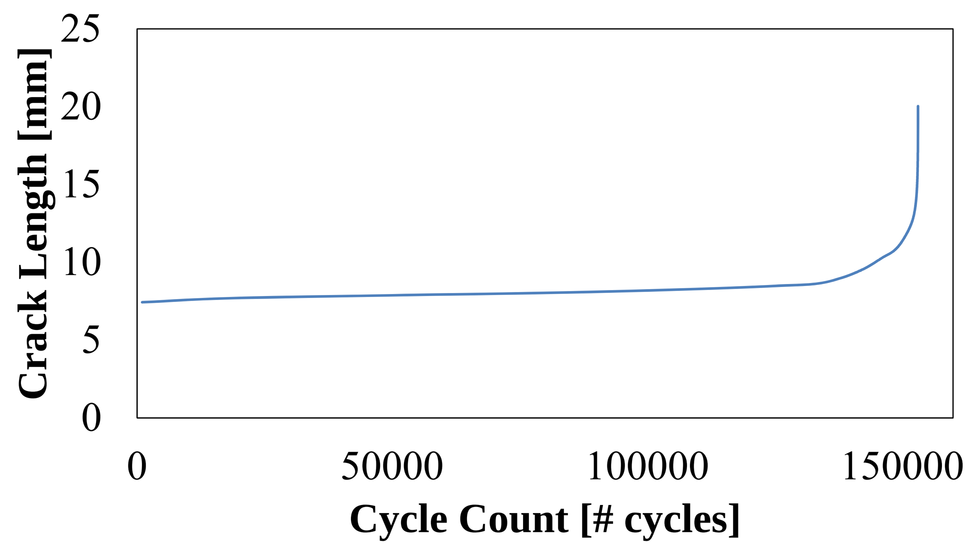


**Figure 2: Exemplary crack length data**

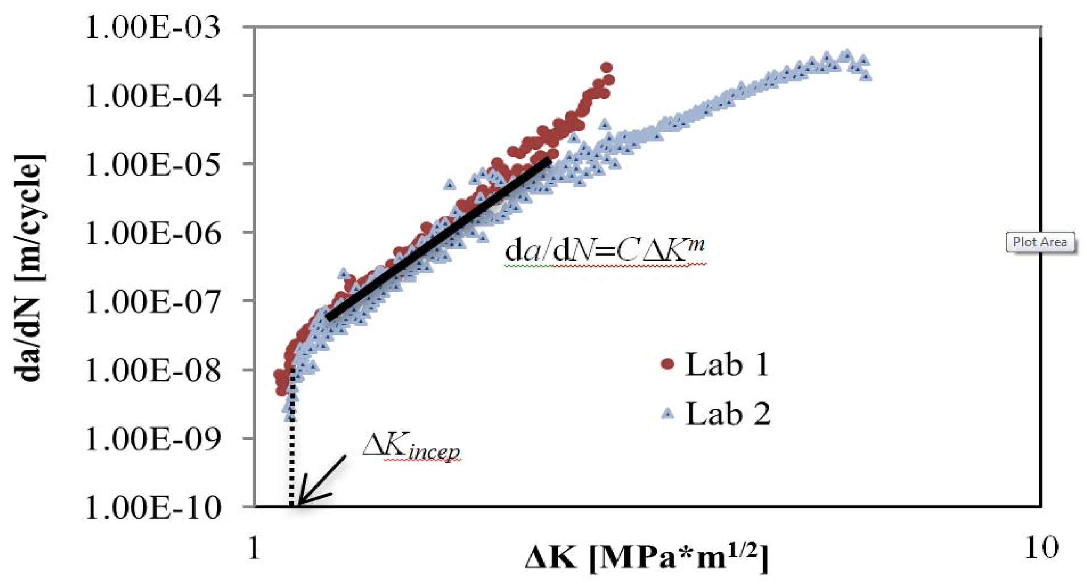


**Figure 3: Exemplary da/dN vs DK data**

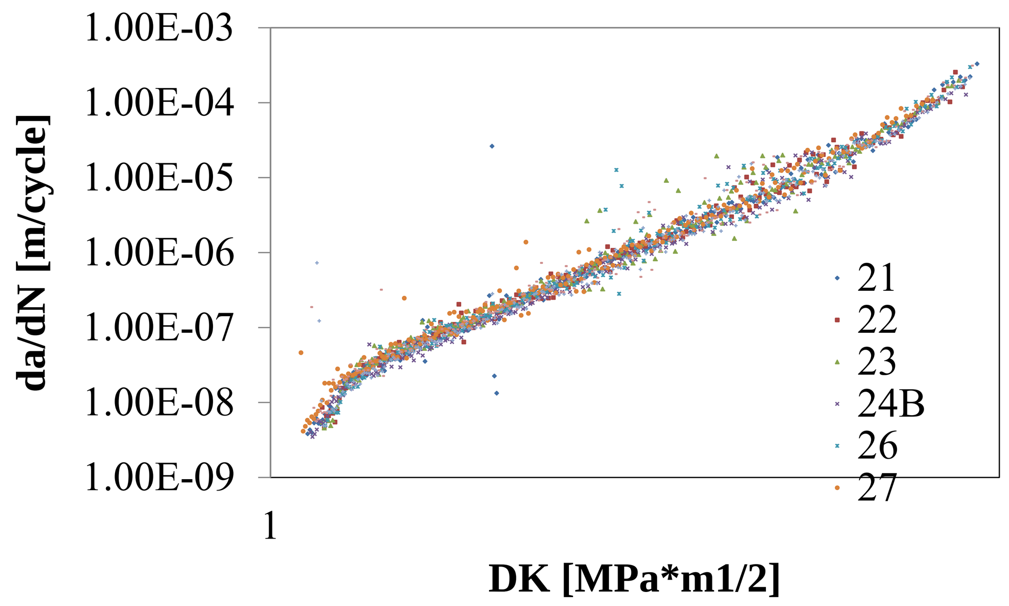


**Figure 4: da/dN vs DK data for 8 replicate Specimens at Lab 1, showing system repeatability**

## Discussion

Given the commonality of the test specimen and crack analysis system, the only potential differences were due to the sample temperature and load frame characteristics. Rimnac and co-workers observed temperature dependency on the Paris regime parameters, with higher temperature (37ºC) showing a decreased *C*, along with a reduced $DK_{th}$ compared to samples tested at room temperature.[5] The parameter *m* was not statistically significantly different in the highly crosslinked samples in the Rimnac study, however. The 37ºC data was collected in PBS, which introduced a second variable. The challenge in interpreting $DK_{th}$ is that this parameter is dependent on the initial crack length, the load regime used, the temperature, and the material.

Since all the parameters except for temperature were held constant between the two labs, it is speculated that Lab 1's used of chilled air, versus room temperature air, may have resulted in a reduction in $DK_{th}$. The servohydraulic load frame used by Lab 2 is also expected to generate additional heat during operation as compared to the electrodynamic load frame used by Lab 1. In addition, feedback loop problems on the servohydraulic load frame at high crack growth rates likely contribute to the difference in Paris regime parameters—inability of the load frame to maintain adequate force control during large sample deformations results in an undershoot of the nominal force value, which would manifest as a downward bowing of the da/dN vs DK curve.

The results indicate the utility of the automated optical system for measuring crack growth resistance in fatigue in UHMWPE. Samples did not have to be removed from the load frame for crack length analysis, avoid potential distortions of the samples, and tests could be run continuously until sample failure. The results also point out the need for more attention to temperature control and the feedback loops employed by the test load frame. Automated optical systems are being installed in two additional labs, which will permit a more extensive round robin study in anticipation of the ASTM standard for FCP in UHMWPE. Temperature effects and load frame feedback loop parameters will be considered in this study, with the possibility of active temperature control during the test.

## References

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4. ASTM E647: Standard test method for measurement of fatigue crack growth rates.
5. Varadarajan, R., Rimanc, C.M., 9th International Fatigue Congress (2006).