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Peak Stress Intensity Factor Governs Crack Propagation Velocity In Crosslinked UHMWPE

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Abstract

Ultra high molecular weight polyethylene (UHMWPE) has been successfully used as a bearing material in total joint replacement components. However, these bearing materials can fail as a result of in vivo static and cyclic loads. Crack propagation behavior in this material has been considered using the Paris relationship which relates fatigue crack growth rate, da/dN (mm/cycle) versus the stress intensity factor range, K (K_{max} - K_{min} , MPa $\sqrt{m}$). However, recent work suggests that the crack propagation velocity of conventional UHMWPE is driven by the peak stress intensity (K_{max}), not K . The hypothesis of this study is that the crack propagation velocity of highly crosslinked and remelted UHMWPE is also driven by the peak stress intensity, K_{max} , during cyclic loading, rather than by K . To test this hypothesis, two highly crosslinked (65 kGy and 100 kGy) and remelted UHMWPE materials were examined. Frequency, waveform and R-ratio were varied between test conditions to determine the governing factor for fatigue crack propagation. It was found that the crack propagation velocity in crosslinked UHMWPE is also driven by K_{max} and not K , and is dependent on loading waveform and frequency in a predictable quasi-static manner. The current study supports that crack growth in crosslinked UHMWPE materials, even under cyclic loading conditions, can be described by a relationship between the velocity of crack growth, da/dt and the peak stress intensity, K_{max} . The findings suggest that stable crack propagation can occur as a result of static loading only and this should be taken into consideration in design of UHMWPE total joint replacement components.

Keywords

fatigue crack propagation; fracture; stress intensity factor; crosslinked UHMWPE; peak stress intensity

Introduction

Crosslinked Ultra high molecular weight polyethylene (UHMWPE) has proven to be a successful bearing material. UHMWPE joint replacement components are widely used as a bearing material in total hip and total knee replacements¹. These components experience physiological loading that is comprised of both cyclic and quasi-static components^{2,3}. Fracture of UHMWPE total hip and total knee replacement components can occur and is one reason for revision surgery. A recent study has investigated *in vivo* fracture of acetabular components and concluded that fracture occurred as a result of crack initiation from acute notches in a variety of component designs, in regions outside the cyclically loaded bearing region and thus likely due to non-cyclic overload events⁴.

Linear Elastic Fracture Mechanics (LEFM) has been used to study the fracture characteristics of many metals and has also been applied to study the fracture and fatigue properties of some viscoelastic polymers, including UHMWPE⁵. The stresses near the crack tip are defined through the stress intensity factor, K (MPa $\sqrt{m}$) and can be generally expressed as:

$$K = F\sigma\sqrt{\pi a} \quad (\text{equation 1})$$

where F is a factor accounting for geometry; σ is applied stress and ' a ' is the crack length.

It has been shown for many materials that the stress intensity factor, K , controls fatigue crack propagation via the cyclic stress intensity range, ΔK ($K_{\max} - K_{\min}$). Furthermore, it was demonstrated by P.C. Paris⁶ that there is a region of stable crack growth for which there is a relationship between the fatigue crack growth rate, da/dN (mm/cycle) and ΔK (Figure 1):

$$\frac{da}{dN} = C \Delta K^m \quad (\text{equation 2})$$

where C and m are a function of both intrinsic (e.g., material properties) and extrinsic (e.g., environment) factors⁵. The Paris region of stable crack propagation is preceded by the threshold region, described by K_{th} , below which fatigue crack growth is not expected to occur.

Beyond the Paris relationship⁶, a variety of fatigue crack propagation models have been proposed to describe the kinetics of fatigue crack growth under general loading conditions^{7,8}. For example, both the Walker model and Forman model⁹ explicitly include a term that accounts for the effect of mean stress on fatigue crack growth. Other models, such as the Zheng model⁷ and Lal and Weiss model account for near-threshold effects in fatigue crack growth^{7,10}. In addition, it has been shown by Ritchie et al¹¹ that, for some materials, stable crack growth even under cyclic loading conditions is governed by quasi-static forces such that the behavior is better described in terms of the peak stress intensity factor ($K_{\max}$), rather than by the Paris relationship, as follows:

$$\frac{da}{dt} = Y K_{\max}^n \quad (\text{equation 3})$$

where da/dt is the velocity of crack propagation and Y and n are constants analogous to those in the Paris relationship. It is not unexpected that polymers lacking a crazing or other cyclic damage mechanism would undergo static mode crack propagation, as the local deformation process at the crack tip is viscoplastic and therefore quasi-static in nature^{12,13}. Recent studies support that a static mode mechanism is critical to understanding fatigue crack propagation in HDPE^{14,15} and conventional (uncrosslinked) UHMWPE^{12,13}, according to equation 3.

The hypothesis of this study is that the fatigue crack propagation average velocity (da/dt) in highly crosslinked UHMWPE is driven by the peak stress intensity, $K_{\max}$, during cyclic loading, rather than by the stress intensity factor range, ΔK . The objective of this study was to test this hypothesis by examining the fatigue crack propagation behavior of two crosslinked UHMWPE formulations using the relationships given in equations 2 and 3.

Methods

Two highly crosslinked UHMWPE formulations, crosslinked with 65 kGy and 100 kGy of gamma radiation and post-processed by remelting above the melt transition and slowly

cooled (Orthoplastics Ltd, Lancashire, UK), were investigated in this study. The materials were received in the form of ram-extruded cylindrical rod with a diameter of 75 mm. These two generic crosslinked formulations were selected for study as they represent two types of “1st generation” crosslinked UHMWPE formulations that are in clinical use in total knee and total hip replacement components¹⁶. All rods were stored in a freezer to minimize oxidation prior to specimen fabrication¹⁷. Remelted 65 kGy materials are generally used in the knee implants while UHMWPE materials crosslinked with a higher radiation dose of 100 kGy is normally used in the hip implants where high wear resistance is desired.

Round compact tension specimens were machined according to ASTM E647-11¹⁸ in the transverse direction with: notch depth, $a=18\text{mm}$; specimen length, $w=40\text{mm}$; thickness, $b=18\text{mm}$; and, side groove depth of 2 mm on each side. The crack was razor sharpened an additional 1.6 mm at a rate of 0.16 mm/min beyond the machined notch making the total crack length 19.6 mm.

Four test conditions were evaluated that utilized a mix of different waveforms, frequencies and load ratios:

1. Square wave/frequency = 1 Hz/ $R=0.1$ (where $R = P_{\min}/P_{\max}$)
2. Sine wave/frequency = 0.1 Hz/ $R=0.1$
3. Sine wave/frequency = 3 Hz/ $R=0.5$
4. Sine wave/frequency = 5 Hz/ $R=0.1$

Two specimens were tested for each condition. The test conditions were selected such that a range of behaviors for the Paris relationship would be obtained, while these conditions should show substantially less variation according to the static mode crack growth model (equation 3). For example, a square waveform and a sine waveform were used in test conditions 1 and 2 to evaluate the effect of time under maximum load on crack growth for the same load ratio ($R; \min/\max$), to which the Paris relation is insensitive. The frequency was altered between the sine waveform test conditions 2, 3 and 4 to evaluate the effect of the rate of crack growth as a function of number of cycles (da/dN) in comparison to time (da/dt). Similarly, the R-ratio was altered in these test conditions to evaluate the effect of increased mean (static) stress on crack growth.

Testing was conducted under ambient (dry, room temperature) laboratory conditions on an Instron 8511 servohydraulic load frame (Instron, Norwood, MA). The cyclic loads were initially applied such that the cyclic stress intensity would be in the threshold regime. The cyclic loads were gradually increased by 5%-10% until crack growth occurred. Thereafter, the cyclic loads were held constant and the driving force was allowed to increase via crack extension. A travelling microscope (Daedal Inc, Philadelphia, PA) with 5 micron resolution was used to measure crack growth by determining the position of the crack tip and the position of the back edge of the specimen. The load and position data from the test frame were sampled at 500 Hz throughout the test using a LabVIEW program.

From the crack advance data, crack growth rates (da/dt , da/dN) were calculated based on successively obtained measures of the crack length. The applied stress intensity factor range (K), and the peak stress intensity ($K_{\max}$) were calculated based on ASTM E-647-11¹⁸. The experimental data was plotted with the Paris relationship (equation 2) and the peak stress relationship (equation 3). The Paris relationship (equation 2) and peak stress relationship (equation 3) were fitted to the experimental data between the crack growth rates of 10^{-4} mm/cycle and 10^{-2} mm/cycle to obtain C and m and 10^{-4} mm/sec and 10^{-2} mm/sec to obtain Y and n for all testing conditions.

To evaluate whether waveform effects were predictable from purely static mode growth (equation 3) a velocity normalizing factor Q was employed, which describes the theoretical ratio of average crack velocity under non-sinusoidal load waveforms to that driven by a sine wave with the same peak stress. Q was determined by integrating equation 3 using the instantaneous stress intensity K versus time measured during the test, while the exponents n employed were taken from the respective power-law fits (Table 1). By taking the ratio of a_{square} to a_{sine} the computed velocity ratio of an experimental square wave to an ideal comparison sine wave is:

$$Q = \frac{\Delta a_{\text{square}}}{\Delta a_{\text{sine}}} = \frac{\int_0^{\lambda} (K_{(t)\text{square}})^n dt}{\int_0^{\lambda} (K_{(t)\text{sine}})^n dt} \quad (\text{equation 4})$$

Note that this equation also explicitly accounts for load ratio effects as well, and also for the non-ideal shape of the experimental waveforms.

Results

The fatigue crack growth behavior in the Paris regime was successfully obtained under all four test conditions for both the Remelted 65 kGy and Remelted 100 kGy materials (Figures 2 and 3, Table 1). Both crosslinked materials tested showed K_{max} dominated crack growth (Figures 4 and 5, Table 1), in that the data much more effectively collapse to a single curve for the peak stress relationship than for the Paris relation. For each material, the crack propagation behavior was distinctly different for each of the four testing conditions when plotted using the Paris relationship (da/dN versus K). However, the data collapsed to a single stable crack propagation power-law relationship when the average velocity was correlated to K_{max} (da/dt versus K_{max} , Figures 4 and 5, Table 1). As expected, for each material, the rate of crack propagation for the square waveform was higher than for the sine waveform, and the difference agreed well with the velocity normalizing factor Q . The values obtained for Q , using equation 4 were 2.8 and 2.1 for remelted 65 kGy and remelted 100 kGy materials, respectively. Based on the coefficient Y of the peak stress relationship (Table 1), the Remelted 100 kGy material is less resistant to fatigue crack growth than the Remelted 65 kGy material. The coefficient, C , for the Paris relationship also ranks the materials similarly¹².

Discussion

The hypothesis of the study was supported by the experimental results, suggesting that for these two formulations of highly crosslinked UHMWPE, stable crack growth under cyclic loading is quasi-static, depending on K_{max} and not K . The testing conditions were designed in such a way that the peak stress intensity dependence of crack growth could be assessed for the crosslinked UHMWPE materials. The FCP data for a given material for the range of loading waveforms collapsed, according equation 3, but remained distinct according to the Paris relationship (equation 2), particularly when considering the relative insensitivity of crack growth to load ratio and the predictability of waveform effects. These findings support that K_{max} governs fatigue crack propagation in a static mode manner.

This work is consistent with earlier work reported for conventional (non-crosslinked) UHMWPE material where it was found that crack growth was dependent on K_{max} and is governed by quasi-static driving forces¹³. Static mode fracture holds that even a static load will drive crack propagation in UHMWPE without the application of any cyclic loading¹⁹. It is worth noting that the prior work in conventional UHMWPE also employed a load ratio

varying, constant $K_{\max}$ test condition, which resulted in a stark contrast in its non-correlation to equation 2 and its collapse to equation 3. Such a test condition was omitted from this study due to the longer duration of tests in this testing method, which at high load ratios can result in extensive crack blunting and loss of self-similarity of the driving force.

When evaluating the constants in the Paris relationship, a value of $m < 4$ is considered to be ductile and a value of $m > 8$ is characteristic of brittle behavior in fracture mechanics²⁰. The power-law exponents obtained for both crosslinked UHMWPE materials in this study are intermediate in value relative to the criteria above. However, the dependence on $K_{\max}$ to propagate the crack suggests that fatigue crack propagation happens in a more brittle manner¹², despite the fact that the failure strain under uniaxial tensile loading conditions typically exceeds 200% for crosslinked UHMWPE formulations²¹. Thus, the findings of this study support that the fracture mechanism driving crack propagation in conventional and crosslinked orthopaedic UHMWPE from a notch or crack needs to be investigated considering it as a brittle material, employing static mode fracture mechanics approaches, and thus avoiding interpretation of the crack propagation process as essentially cyclic.

With regard to the clinical relevance of this study, in vivo fractures of highly crosslinked UHMWPE acetabular components have been reported⁴. In particular, Furmanski et al⁴ conducted a finite element analysis of four highly crosslinked UHMWPE retrieved acetabular cups that had fractured in vivo. Depending on the component, they reported a maximum principal stress of 17-43 MPa for the condition of femoral neck impingement at the sites of crack initiation. Taking the maximum predicted maximum principal stress of 43 MPa as the clinical value of stress, a crack size, a , of 2 mm, and setting $K_{\max} = Y_{\max} (\sigma \sqrt{a})$ (with $Y=1$) results in a $K_{\max}$ of 3.40 MPa $\sqrt{m}$. This is a high stress intensity, in the context of equation 3, in that this stress intensity would be predicted to result in catastrophic failure, at least for the test conditions examined in this study (Figures 4 and 5). Taking the minimum predicted maximum principal stress of 17 MPa and using the same geometry and crack length assumption as above results in a $K_{\max}$ of 1.34 MPa $\sqrt{m}$. This stress intensity, for the test conditions examined in this study, is sufficient to produce stable crack propagation. Thus, the findings of this study may be useful in predicting crack growth and fracture in joint replacement under clinically relevant loading conditions.

There are limitations to this study. Although $K_{\max}$ dependent crack growth was demonstrated in this study, only two waveforms, four test frequencies, and two tensile load ratios were examined. Future studies should be conducted to implement more load ratios (or load shedding R varying schemes) or waveforms to demonstrate the general applicability of fatigue crack propagation on $K_{\max}$ for UHMWPE.

This study was conducted under ambient (dry, room temperature) laboratory conditions. Fatigue crack propagation tests have been conducted at body temperature (37 C) and in physiologically relevant fluid environments^{22,23}. In particular, Baker et al.²³ examined the influence of temperature and fluid environment as separate variables on the fatigue crack propagation behavior of GUR4150HP and Hylamer-M UHMWPE. In that study, they found that fluid immersion alone had little effect on fatigue crack propagation resistance of the polyethylene formulations, whereas an increase in temperature from room temperature to 37 C of the water resulted in a substantial decrease in fatigue crack propagation resistance. This was manifested in an increase in the coefficient, C , in the Paris relationship (and thus, a reduction in the stress intensity factor for crack inception); however, the power-law exponent, m , was essentially unchanged. In the context of the current study, we might expect tests conducted at 37 C to result in a change in the coefficients of equations 2 and 3, leaving the behavior similar but shifted to lower values of the driving force. However, we would not expect that it would change the $K_{\max}$ dependence on crack growth behavior,

which derives from nature of the phenomena driving local deformation near the crack tip. The mechanisms of deformation near the crack tip are accelerated under elevated temperatures but are not likely to qualitatively change their nature over a reasonable range of temperatures or deformation rates.

An increase in FCP rates has been observed as a result of higher load amplitudes and higher frequencies for other polymers, such as PMMA²⁴. For both materials examined in this study, the elevated da/dt observed at the highest cyclic frequency of 5 Hz (loading condition 4) could be a result of heating of the process zone during testing. During testing, there was no effort to cool the specimen or crack tip. Further testing utilizing mechanisms to control and monitor crack tip heating may be warranted.

Previous studies^{23,25,26} on crosslinked UHMWPE materials have helped to qualitatively understand fatigue crack propagation in these materials using the Paris relationship. The current study supports that crack growth in crosslinked UHMWPE materials, even under cyclic loading conditions, is better described by a relationship between the velocity of crack growth, da/dt and the peak stress intensity, K_{max} . The findings of this study may be useful in the design of UHMWPE joint replacements by considering K_{max} as the driving force for fatigue crack propagation.

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References

1. Li S, Burstein AH. Ultra-High-Molecular-Weight Polyethylene - the Material and Its Use in Total Joint Implants. *J Bone Joint Surg Am*. Jul; 1994 76A(7):1080–1090. [PubMed: 8027119]
2. Bartel DL, Bicknell VL, Wright TM. The Effect of Conformity, Thickness, and Material on Stresses in Ultrahigh Molecular-Weight Components for Total Joint Replacement. *J Bone Joint Surg Am*. Sep; 1986 68A(7):1041–1051. [PubMed: 3745241]
3. Pedersen DR, Brand RA, Davy DT. Pelvic muscle and acetabular contact forces during gait. *J Biomech*. Sep; 1997 30(9):959–965. [PubMed: 9302620]
4. Furmanski J, Anderson M, Bal S, et al. Clinical fracture of cross-linked UHMWPE acetabular liners. *Biomaterials*. Oct; 2009 30(29):5572–5582. [PubMed: 19643471]
5. Anderson, T. Fracture Mechanics.
6. Paris PC, Gomez MP, Anderson WE. A rational analytical theory of fatigue. *The Trend in Engineering*. 1961; 13:9–14.
7. Beden SM, Abdullah S, Ariffin AK. Review of Fatigue Crack Propagation Models for Metallic Components. *European Journal of Scientific Research*. 2009; 28(3):364–397.
8. Hertzberg, R. Deformation and Fracture Mechanics of Engineering Materials. 1995.
9. Forman RG. Study of fatigue crack initiation from flaws using fracture mechanics theory. *Engineering Fracture Mechanics*. 1972; 4(2):333–345.
10. Xiulin Z, Hirt MA. Fatigue crack propagation in steels. *Engineering Fracture Mechanics*. 1983; 18(5):965–973.
11. Ritchie RO, Gilbert CJ, McNaney JM. Mechanics and mechanisms of fatigue damage and crack growth in advanced materials. *Int J Solids Struct*. Jan; 2000 37(1-2):311–329.
12. Furmanski J, Rinnac CM. Crack Propagation Resistance Is Similar Under Static and Cyclic Loading in Crosslinked UHMWPE: A Pilot Study. *Clin Orthop Relat R*. Aug; 2011 469(8):2302–2307.
13. Furmanski J, Pruitt LA. Peak stress intensity dictates fatigue crack propagation in UHMWPE. *Polymer*. Jun 4; 2007 48(12):3512–3519.

14. Bucknall CB, Dumbleton P. Effects of Loading History on Fatigue Crack-Growth in High-Density Polyethylene and Toughened Poly(Methyl Methacrylate). *Polym Eng Sci.* Jan; 1987 27(2):110–115.
15. Dumbleton P, Bucknall CB. Comparison of Static and Dynamic Fatigue Crack-Growth Rates in High-Density Polyethylene. *Int J Fatigue.* Jul; 1987 9(3):151–155.
16. Kurtz SM, Muratoglu OK, Evans M, Edidin AA. Advances in the processing, sterilization, and crosslinking of ultra-high molecular weight polyethylene for total joint arthroplasty. *Biomaterials.* Sep; 1999 20(18):1659–1688. [PubMed: 10503968]
17. Kurtz SM, Hozack W, Marcolongo M, Turner J, Rimnac C, Edidin A. Degradation of mechanical properties of UHMWPE acetabular liners following long-term implantation. *J Arthroplasty.* Oct; 2003 18(7):68–78. [PubMed: 14560414]
18. 647-11 A. Standard Test Method for Measurement of Fatigue Crack Growth Rates.
19. Sirimamilla P, Furmanski J, Rimnac C. Non uniform de-cohesion affects crack initiation in crosslinked UHMWPE. *Transactions 57th ORS.* 2010 Poste 0333.
20. Dowling, N. *Mechanical Behavior of Materials.*
21. Kurtz SM, Villarraga ML, Herr MP, Bergstrom JS, Rimnac CM, Edidin AA. Thermomechanical behavior of virgin and highly crosslinked ultra-high molecular weight polyethylene used in total joint replacements. *Biomaterials.* Sep; 2002 23(17):3681–3697. [PubMed: 12109694]
22. Varadarajan R, Rimnac C. Fatigue Crack Inception and Propagation Resistance of Highly Crosslinked and Post Processed UHMWPE In a Physiologically Relevant Environment. *ORS.* Vol 522009:0661.
23. Baker DA, Hastings RS, Pruitt L. Compression and tension fatigue resistance of medical grade ultra high molecular weight polyethylene: the effect of morphology, sterilization, aging and temperature. *Polymer.* Jan; 2000 41(2):795–808.
24. Bucknall CB, Dumbleton P. Acceleration of Fcp in Toughened Pmma Following a Step Increase in Load Amplitude. *Int J Fatigue.* Apr; 1987 9(2):103–108.
25. Rimnac C, Wright T. The Fracture Behavior of UHMW-PE. *Ultra High Molecular Weight PolyEthylene as Biomaterial in Orthopedic Surgery.* 1990:28–31.
26. Baker DA, Hastings RS, Pruitt L. Study of fatigue resistance of chemical and radiation crosslinked medical grade ultrahigh molecular weight polyethylene. *J Biomed Mater Res.* Sep 15; 1999 46(4): 573–581. [PubMed: 10398019]

Figure 1.

Typical fatigue crack propagation behavior of a material. The region of Stable Propagation is defined by the Paris relationship, $da/dN = C \cdot K^m$. K_{th} is the threshold.

Figure 2.

Fatigue crack propagation behavior for Remelted 65 kGy UHMWPE plotted according to the Paris relationship: (a) Square wave, $R = 0.1$, and frequency=1Hz; (b) Sine wave, $R = 0.1$, and frequency=0.1Hz; (c) Sine wave, $R = 0.5$, and frequency=3Hz; (d) Sine wave, $R = 0.1$, and frequency=5Hz.

Figure 3.

Fatigue crack propagation behavior for Remelted 100 kGy UHMWPE plotted according to the Paris relationship: (a) Square wave, $R = 0.1$, and frequency=1Hz; (b) Sine wave, $R = 0.1$, and frequency=0.1Hz; (c) Sine wave, $R = 0.5$, and frequency=3Hz; (d) Sine wave, $R = 0.1$, and frequency=5Hz.

Figure 4.

FCP behavior for Remelted 65 kGy UHMWPE for all four test conditions showing the peak stress dependence of crack propagation rate: (a) FCP behavior appears distinct when plotted as da/dN versus ΔK (Paris relationship); (b) FCP behavior collapses to a single relationship when plotted as da/dt versus K_{max} . The factor to normalize da/dt for the square wave data in (b) was $Q=2.8$.

Figure 5.

FCP behavior for Remelted 100 kGy UHMWPE for all four test conditions showing the peak stress dependence of crack propagation rate: (a) FCP behavior appears distinct when plotted as da/dN versus ΔK (Paris relationship); (b) FCP behavior collapses to a single relationship when plotted as da/dt versus K_{max} . The factor to normalize da/dt for the square wave data in (b) was $Q=2.1$.

Table 1

Constants for the Paris (equation 2) and for the Peak stress dependence (equation 3) relationships.

Test Conditions	Remelted 65 kGy				Remelted 100 kGy			
	Paris (eqn 2)		Peak stress (eqn 3)		Paris (eqn 2)		Peak stress (eqn 3)	
	m	C (mm/cycle)/ (MPa m)	n	Y (mm/sec)/ (MPa m)	m	C (mm/cycle)/ (MPa m)	n	Y (mm/sec)/ (MPa m)
Square wave, f = 1Hz, R =0.1	7.64	7.04×10^{-5}	7.64	3.1×10^{-5}	7.26	2.09×10^{-4}	6.81	5.7×10^{-5}
Sine wave, f = 0.1Hz, R=0.1	6.00	2.81×10^{-4}	5.95	1.6×10^{-5}	5.22	6.38×10^{-4}	5.44	3.8×10^{-5}
Sine wave, f = 3Hz, R=0.5	5.81	3.6×10^{-4}	5.70	1.9×10^{-5}	6.10	1.5×10^{-3}	6.80	4.2×10^{-5}
Sine wave, f=5 Hz, R=0.1	6.67	1.94×10^{-5}	6.32	5.34×10^{-5}	5.07	6.42×10^{-5}	5.56	1.46×10^{-4}