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Crack initiation from a clinically relevant notch in a highly-crosslinked UHMWPE subjected to static and cyclic loading

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Abstract

Crosslinked Ultra High Molecular Weight Polyethylene (UHMWPE), which is used as a bearing material in total joint replacement components, is subjected to static and cyclic loads *in vivo*. Resistance to crack initiation from a notch as a function of static and cyclic loads is not well understood for crosslinked UHMWPE. This study estimated the resistance of crosslinked UHMWPE (crosslinked with 100 kGy gamma radiation and remelted to extinguish free radicals) to crack initiation for a clinically relevant notch under both static and cyclic loading conditions. For cyclic loading, four frequencies were applied with a sine waveform and two frequencies were applied with a square waveform to independently estimate the effect of frequency and rate of loading on crack initiation. Crack initiation time and cycles to crack initiation were determined. Crack initiation time for fatigue loading conditions was substantially lower compared to static loading conditions. Crack initiation time decreased with an increase in test frequency. A square wave resulted in shorter crack initiation time compared to a sine wave. The results suggest that crosslinked UHMWPE is more resistant to crack initiation from a notch under static loading conditions compared to fatigue loading conditions.

Keywords

fatigue crack initiation; polymer; fatigue; notch root; crosslink density; R-ratio; frequency

Introduction:

Crosslinked ultra-high molecular weight polyethylene (UHMWPE) is widely used as a bearing material in total joint replacement components [1-5]. There are a variety of formulations, however, highly crosslinked UHMWPE formulations are generally preferred for the highly conforming bearing surface geometry found in hip replacements, whereas

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conventional and moderately crosslinked formulations have generally been preferred for the less-conforming bearing surface geometries found in knee replacements [1]. UHMWPE components experience physiological loading that is comprised of both quasi-static and cyclic components [6, 7]. Many of these UHMWPE bearing components have a notch feature as part of a locking mechanism [8-10]. Notches in components can serve as stress concentrations, rendering these regions more susceptible as sites for fracture [11]. The investigation of notch effects in both conventional and crosslinked UHMWPE components is of interest because of reports of failure of UHMWPE components due to cracks associated with design-related notch features. Crack initiation and propagation from stress concentration features such as the acetabular rim in a hip component [12-15], the stabilizing post in a tibial component [16, 17] and the rim of a total disc component [18] has been reported. In crosslinked UHMWPE acetabular liners, rim fracture was reported by Halley et al. [19]. Furmanski et al. [8] examined four retrieved crosslinked UHMWPE acetabular liners that failed *in vivo* and concluded that crack initiation from the outside of the notched rim propagated to catastrophic fracture as a result of rim loading. Other studies have also reported rim fracture of acetabular liners [14, 15, 19-21].

Fracture resistance of crosslinked UHMWPE subjected to quasi-static loading conditions has been investigated using the traditional J-R fracture resistance method [22-24]. Also, fatigue crack propagation has been widely studied for crosslinked UHMWPE [1, 25-29] using the Paris relationship for stable crack propagation [30]. However, these studies employed a razor-sharp crack in the specimen to study fracture resistance and fatigue crack propagation resistance. A recent study done by Ansari et al [31] examined the fatigue crack propagation behavior in crosslinked UHMWPE from different notch radii ranging from 0.13 mm to 3 mm. However, a razor-sharp crack (0.2-0.3mm) was implemented at the root of the notch. The study noted that the crack propagation resistance was affected by the material microstructure (e.g., crosslinking density) rather than the notch radius. However, the mechanism of crack initiation from the notch was not investigated.

In a previous study by the authors [27], when crosslinked UHMWPE was subjected to cyclic loading, fatigue crack propagation resistance was found to depend on the maximum stress intensity factor in a loading cycle, $K_{\max}$, rather than the amplitude of stress intensity (K). Although crosslinked UHMWPE falls in the category of a ductile polymer [32], the crack propagation behavior of UHMWPE from an initiated crack under cyclic loading conditions is effectively brittle in nature, i.e., having relatively low crack propagation resistance and little dependence on cyclic crack driving forces [33]. The findings for crosslinked UHMWPE [27], as well as findings for non-crosslinked UHMWPE [33] support that static creep loading is a dominant mechanism for crack propagation in crosslinked UHMWPE. As a result of this finding, previous studies by the authors [34, 35] focused on the role of static creep loading on determining crack initiation time and crack propagation velocity from a notch in crosslinked UHMWPE. It was found that the Williams' viscous fracture model [36] was able to predict both crack initiation and propagation velocity from a notch in two crosslinked UHMWPE formulations. However, cyclic loading and the effects of frequency and rate of loading (as affected by waveform) on crack initiation time were not investigated. While some polymers are more resistant to failure (i.e., time to initiate and propagate a crack to failure) under static loading conditions, other polymers are more resistant to failure under

fatigue loading conditions [37-39]. Additionally, some polymers are more resistant to crack initiation than crack propagation and vice versa [40, 41].

The objective of this study was to investigate the time for crack initiation from a clinically relevant notch under cyclic loading conditions and to compare the results with the crack initiation time under static loading conditions for a highly-crosslinked UHMWPE.

Methods:

UHMWPE crosslinked with 100 kGy of gamma radiation and post-processed by remelting to extinguish free radicals [42] (Orthoplastics Ltd, Lancashire, England) was used as the test material for this study. This generic material served as a surrogate for highly crosslinked, remelted formulations used in total hip acetabular components [1]. Round compact tension test specimens were made according to ASTM 1820-01 [43], with: width, $w=40$ mm; thickness, $b=20$ mm; and notch depth, $a=17$ mm. The specimens also had side grooves with a depth of 2 mm on both sides. A notch radius of 0.25 mm was implemented. The test specimen geometry was the same as that used in a previous study by the authors [34]. A total of 24 round compact tension specimens were tested under various cyclic loading conditions (described, below). Four additional specimens were tested under creep (static loading) conditions.

To examine the effect of loading rate and test frequency on crack initiation, specimens ($n=4$) were tested at four test frequencies (0.1 Hz, 1 Hz, 3 Hz and 5 Hz) and with a sine waveform. The tests were conducted with maximum load, $P_{\max}=800$ N and R-ratio ($P_{\min}/P_{\max}$) of 0.1. To separate the effect of loading rate and consider only the effect of frequency on crack initiation, tests were also conducted utilizing a square wave with R-ratio = 0.1 and $P_{\max}=800$ N. For the square wave tests, two frequencies, 0.1 Hz and 5 Hz, were implemented ($n=4$ /group). For the creep tests ($n=4$), the same $P_{\max}$ load used in the cyclic tests (800 N) was applied as the static load. Overall, there were seven test groups (six fatigue and one creep loading) (Table 1). Both the cyclic and the static tests were conducted under mode-I loading conditions. The maximum load of $P_{\max}=800$ N was selected based on the results from a previous study [35] where crack initiation from notches of variable radii under static loading conditions were evaluated, utilizing loads varying from 800N to 1000N. In that study, finite element analysis was conducted to assess the initial J-Integral condition, J_0 , at the notch as well as the critical condition, J_C , for crack initiation. In that study, time to crack initiation increased with increase in notch radii and decrease in applied static load. For the Remelted 100 kGy UHMWPE material, the lower load value of 800 N combined with a notch radius of 0.25 mm resulted in a time for crack initiation of 67,272 secs ($J_0=3.82$ kJ/m² to $J_C=16.6$ kJ/m²) under static loading. In the current study, it was decided that the longer time frame for data acquisition for cycles-to-initiation afforded by a load of 800 N would be experimentally beneficial.

All tests were conducted on an Instron closed-loop servohydraulic test frame (Instron 8511, Canton, MA). For the fatigue tests, a fan was directed towards the specimen to help mitigate any potential temperature rise at the notch during load cycling. For all tests (fatigue and creep), the notch surface was observed using a video microscope as in a previous study by

the authors [35](Figure 1). The notch surface was also examined during testing to observe multilayer vs single-layer crack initiation as reported in a previous study by the authors [34]. Crack initiation was defined as the time when tearing on the notch surface occurred continuously across the thickness of the specimen and a new crack surface was formed on the notch.

Crack initiation time (t_{iv}) was measured from the video recordings and reported in seconds. Crack initiation time was defined as the time when observed void sites forming on the notch surface coalesced and formed a single crack through the thickness of the specimen. For the fatigue tests, the number of cycles to crack initiation (N_{iv}) was also recorded.

The mean and standard deviation of crack initiation time and number of cycles to crack initiation were determined for each cyclic test group. Test groups were compared using an unpaired two sample Student's t-test. A one-tailed p value was calculated based on a continuous normal distribution using MATLAB software [45]. Statistical significance was set at $p < 0.05$.

In a previous study by the authors, a power law relation was obtained between crack initiation time and applied static load for crosslinked UHMWPE [35]. A similar relationship was postulated in this study between cyclic crack initiation time (obtained through video observation of the notch surface) and test frequency (eq. 1). The crack initiation time obtained from the cyclic tests was normalized to the mean crack initiation time obtained from the creep tests:

$$\frac{t_{iv, sine [or] square}}{t_{iv, creep}} = Af^{-x} \quad \text{Equation(1)}$$

where t_{iv} is crack initiation time obtained from video observation for creep, sine wave and square wave tests, A is a constant, f is frequency of cyclic loading and x is a power law exponent. Once the crack initiation time, t_{iv} , was captured from the experiments, an average value of crack initiation time was used from each test case. A linear regression was performed on the logarithmic form of equation 1 and the exponent 'x' was obtained for both the sine wave and square wave data separately.

Results:

For the sine wave tests, crack initiation time (t_{iv}) progressively decreased with an increase in test frequency and number of cycles to crack initiation (N_{iv}) increased with test frequency (Table 2, Figure 2). A similar behavior was observed for the square wave tests (Table 2, Figure 3), although only two cyclic frequencies were applied to the square wave condition. Crack initiation time, t_{iv} , decreased by an order of magnitude between the creep and fatigue crack initiation tests at 5 Hz for both waveforms. None of the specimens tested under fatigue loading and creep loading conditions showed a multi-layer crack initiation phenomenon previously observed in some specimens tested under creep conditions [34, 35] (Figure 4). In

the previous study voids formed at multiple layers on the notch surface and coalesced into a single crack [34, 35]. This phenomenon was not observed in this study.

The fatigue test groups generally demonstrated a significant difference in t_{iv} and N_{iv} between the extremes of the test frequencies for a given waveform, i.e., between 0.1 Hz, 3 Hz and 5 Hz for the sine waveform and between 0.1 Hz and 5 Hz for the square waveform (Tables 3 and 4, respectively). Between waveforms, there was a significant difference in t_{iv} between test conditions except when comparing each waveform at the lowest test frequency of 0.1 Hz (Figure 5). For both waveforms, there was a significant difference in t_{iv} between the creep test condition and the cyclic test conditions (Table 3). The power law model (equation 1) qualitatively describes the reduction in crack initiation time (t_{iv}) with increase in applied frequency (Figure 6). Regression analysis resulted in $R^2 = 0.951$ for the sine wave data ($p = 0.024$).

Discussion:

The resistance to crack initiation from a notch as a function of static and cyclic loads is not well understood for crosslinked UHMWPE. Accordingly, the objective of this study was to evaluate the crack initiation time and number of cycles to crack initiation from a clinically relevant notch for a crosslinked UHMWPE material. We found that crosslinked UHMWPE exhibits better crack initiation resistance to a static load compared to cyclic loading scenarios having the same maximum load as the static loading condition. Contrary to the findings on crack propagation behavior of crosslinked UHMWPE [27], we found that crack initiation is not solely governed by the maximum load applied in a cycle [35] but is also affected by the cyclic loading parameters such as frequency and waveform.

There are several possible reasons why cyclic loading reduces the crack initiation time relative to quasi-static loading. The negative effect of an increase in test frequency on crack initiation time may be due to process zone viscoplasticity [31, 35]. During cycling, the sequence of loading, unloading and reloading may concentrate damage at a single layer (i.e., as opposed to multi-layer initiation, [34]) at the root of the notch, resulting in more rapid crack initiation. In fact, we only observed single layer crack initiation in the fatigue tests. In addition, we observed more overall material deformation under the static creep loading condition, both in this study and in a previous study [34]. Under cyclic loading, the phenomenon of gross material deformation does not appear to occur to the same extent as under static loading; this may also contribute to more rapid crack initiation.

Crosslinked UHMWPE is a rate dependent material [46]. Thus, rate of loading, as affected by the use of a sine wave versus a square wave, could have affected damage accumulation in the process zone. For the same frequency of 5 Hz, the square wave resulted in a shorter crack initiation time (Table 3) compared to the sine wave. As a square wave imparts a higher rate of loading compared to a sine wave, we can conclude that an increase in cyclic loading rate reduces crack initiation time in crosslinked UHMWPE.

In a previous study by the authors, crack initiation from clinically relevant notches up to 0.5 mm was investigated and it was found that the crack initiation time was a function of the

initial applied energy at the notch, according to a power law relationship [35]. The initial applied energy at the notch, J_0 , was estimated using finite element analysis [35]. Based on the results of the current study, it is postulated that the crack initiation time is also a function of frequency and loading rate, in addition to the initial applied energy at the notch.

The current study has some limitations. This study only focused on one crosslinked formulation of UHMWPE. However, the techniques developed in this study can be used to study other formulations of UHMWPE and we would expect the general trends in response to loading mode, test frequency and loading rate to be similar. Although the current study provides new insight into fatigue crack initiation from a notch in crosslinked UHMWPE, to better understand the damage mechanics in the process zone, numerical modeling of the process zone, including temporal evolution to achieve a critical stress-strain state, should also be investigated, but was beyond the scope of this study. Finally, material properties (e.g. crystallinity, crosslink density, presence of additives) also influence the stress-strain state of the process zone, as shown by Ansari et al. [31]. These variables are relevant, and would be of interest in future work, given the numerous formulations of crosslinked formulations of UHMWPE currently clinical use [1].

The evaluation of fracture surfaces through scanning electron microscopy may also be useful in describing the nature of the process zone damage during initiation from a notch in static and cyclic testing conditions. Temperature variations at the crack tip as a function of cyclic frequency has been reported previously for other polymers [47, 48]. Although a cooling fan was used in the study, a rise in temperature at the notch tip cannot be completely neglected and was not accounted for in this study. However, the work of Connelly et al [49] for conventional UHMWPE suggests that temperature increase at the crack tip of UHMWPE should be essentially negligible at test frequencies of 5Hz and lower.

In summary, the current study is an initial step towards developing a better understanding of the potential *in vivo* failure mechanisms of crosslinked UHMWPE joint replacement components that undergo fracture. *In vivo* loading includes cyclic as well as static loads at stress concentration features in joint replacement components. This study supports that crack initiation estimates based on traditional J-R resistance curve approaches may underestimate the time for initiation of a crack from a component stress concentration *in vivo*. A better understanding of the relationship between crack initiation time and fatigue loading parameters may provide useful guidance in UHMWPE component design. The methods developed in the current study can be applied to other crosslinked UHMWPE formulations, such as second generation hindered phenol antioxidant UHMWPE [50], to evaluate fatigue crack initiation resistance and may be useful as a comparative measure between UHMWPE formulations.

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Figure 1:

(a): Direction of view for the observation of the notch surface on a compact tension specimen. The eye represents the video microscope used in the study, (b): Notch surface showing crack initiation from a single layer on application of load in the mode I direction. (c): Notch surface showing crack initiation from multiple layers on application of load in the mode I direction [34].

Figure 2:

Variation of crack initiation time (t_{iv}) with applied frequency for sine wave testing. (b): Variation of number of cycles to crack initiation (N_{iv}) with frequency applied for sine wave testing. Data shown are mean and standard deviation.

Figure 3:

(a): Variation of crack initiation time (t_{iv}) with frequency applied for square wave testing.

(b): Variation of number of cycles to crack initiation (N_{iv}) with frequency applied for square wave testing. Data shown are mean and standard deviation.

Figure 4:
Single layer crack initiation observed in all the specimens in the study.

Figure 5:

(a) Comparison of crack initiation time (t_{iv}) for square and sine wave tests. (b): Comparison of number of cycles to crack initiation (N_{iv}) between square and sine wave tests. Data shown are mean and standard deviation.

Figure 6: Normalized crack initiation time vs. applied frequency for sine and square wave testing. Normalized crack initiation time qualitatively decreased in a power law manner against applied frequency.

Table 1:

Test Matrix (n = 4/group).

Test Group	1	2	3	4	5	6	7
Loading condition	Static creep, 800 N	Cyclic *	Cyclic	Cyclic	Cyclic	Cyclic,	Cyclic
Waveform	N/A	Sine	Sine	Sine	Sine	Square	Square
Frequency (Hz)	N/A	0.1	1	3	5	0.1	5
R-Ratio	N/A	0.1	0.1	0.1	0.1	0.1	0.1

* $P_{\max}$ = 800 N for all cyclic tests.

Table 2:

Mean and standard deviation for crack initiation time (t_{iv}) and cycles to crack initiation (N_{iv}) for each test condition (n=4).

Test Condition	Mean t_{iv} , (seconds)	Standard Deviation, (seconds)	Mean N_{iv}	Standard Deviation (N_{iv})
Creep	54,789	16,626	N/A	N/A
Cyclic, Sine; f=0.1 Hz	23,317	8,038	2332	804
Cyclic, Sine; f=1 Hz	14,494	8,089	14494	8089
Cyclic, Sine; f=3 Hz	8,968	3,744	26904	11234
Cyclic, Sine; f=5 Hz	6,724	2,062	33622	10314
Cyclic, Square; f= 0.1 Hz	27,970	4,317	2797	432
Cyclic, Square; f= 5 Hz	2,172	1,125	10859	5628

Table 3:

P-values calculated for crack initiation times (t_{iv}) between different test conditions. The boxes shaded in gray indicate significance between groups ($p < 0.05$).

Testing condition	Creep	Sine Wave; f=0.1 Hz	Sine Wave; f=1 Hz	Sine Wave; f=3 Hz	Sine Wave; f=5 Hz	Square Wave; f= 0.1 Hz	Square Wave; f= 5 Hz
Creep	N/A	0.011	0.005	0.0048	0.005	0.021	0.004
Sine Wave; f=0.1 Hz	N/A	N/A	0.086	0.015	0.011	0.180	0.006
Sine Wave; f=1 Hz	N/A	N/A	N/A	0.140	0.075	0.018	0.027
Sine Wave; f=3 Hz	N/A	N/A	N/A	N/A	0.169	< 0.001	0.016
Sine Wave; f=5 Hz	N/A	N/A	N/A	N/A	N/A	< 0.001	0.005
Square Wave; f= 0.1 Hz	N/A	N/A	N/A	N/A	N/A	N/A	< 0.001

Table 4:

P-values calculated for number of cycles to crack initiation (N_{iv}) between different test conditions. The boxes shaded in grey indicate significance between groups.

Testing condition	Sine Wave; f=0.1 Hz	Sine Wave; f=1 Hz	Sine Wave; f=3 Hz	Sine Wave; f=5 Hz	Square Wave; f= 0.1 Hz	Square Wave; f= 5 Hz
Sine Wave; f=0.1 Hz	N/A	0.028	0.011	0.003	0.179	0.017
Sine Wave; f=1 Hz	N/A	N/A	0.065	0.011	0.031	0.236
Sine Wave; f=3 Hz	N/A	N/A	N/A	0.198	0.011	0.029
Sine Wave; f=5 Hz	N/A	N/A	N/A	N/A	0.003	0.005
Square Wave; f= 0.1 Hz	N/A	N/A	N/A	N/A	N/A	0.020