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Viscoplastic Crack Initiation and Propagation in Crosslinked UHMWPE from Clinically Relevant Notches up to 0.5 mm Radius

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Abstract

Highly crosslinked UHMWPE is now the material of choice for hard-on-soft bearing couples in total joint replacements. However, the fracture resistance of the polymer remains a design concern for increased longevity of the components *in vivo*. Fracture research utilizing the traditional linear elastic fracture mechanics (LEFM) or elastic plastic fracture mechanics (EPFM) approach has not yielded a definite failure criterion for UHMWPE. Therefore, an advanced viscous fracture model has been applied to various notched compact tension specimen geometries to estimate the fracture resistance of the polymer. Two generic crosslinked UHMWPE formulations (remelted 65 kGy and remelted 100 kGy) were analyzed in this study using notched test specimens with three different notch radii under static loading conditions. The results suggest that the viscous fracture model can be applied to crosslinked UHMWPE and a single value of critical energy governs crack initiation and propagation in the material. To our knowledge, this is one of the first studies to implement a mechanistic approach to study crack initiation and propagation in UHMWPE for a range of clinically relevant stress-concentration geometries. It is believed that a combination of structural analysis of components and material parameter quantification is a path to effective failure prediction in UHMWPE total joint replacement components, though additional testing is needed to verify the rigor of this approach.

1.2: Introduction

Chemical inertness, high impact strength, excellent wear resistance and other properties have made ultra-high molecular weight polyethylene (UHMWPE) a suitable bearing material against a metallic or ceramic counterface for total hip and knee joint replacements for more than fifty years [1]. Highly crosslinked UHMWPE material exhibits better wear resistance compared to conventional UHMWPEs but they generally have reduced ductility, fatigue crack propagation resistance, and fracture toughness compared to the conventional formulations [2, 3, 4, 5].

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As discussed in the literature [6, 7, 8], UHMWPE hip and knee components, have stress concentration features in them as a structural requirement. The dimensions of these notch features can be very acute or blunt depending on the design. UHMWPE components having microscopic cracks in mechanically stressed locations (such as at the root of a notch) can also act as sites of crack propagation [8]. Therefore, it is important to understand crack initiation from clinically relevant notch geometries that are used in UHMWPE total joint replacement component designs to mitigate the risk of component fracture. These notch features are subjected to static and cyclic loads during gait and other activities of daily living and one of the reasons for revision surgery can be mechanical failure at the notch region leading to component fracture [6].

From a design standpoint, crack initiation from a clinically relevant notch condition is of more interest than crack initiation from a razor sharp condition which has been previously studied [9]. In a previous study by the authors [10], crack initiation from a notch with a radius of 0.25 mm was studied with consideration of the Williams' viscous fracture model [11]. Further, we have noted that a time dependent power law, the Williams model (equations 1 and 2) appears to govern crack initiation and propagation in this material [12].

$$t_i = A \left(\frac{J_0}{J_c} \right)^{-m} \quad \text{Equation (1)}$$

$$\frac{da}{dt} = Q \left(\frac{J_0}{J_c} \right)^{m+1} \quad \text{Equation (2)}$$

where, T_i : Crack initiation time; A : Time Constant; J_0 : Initial energy at notch front at time=0; J_c : Critical fracture energy at crack initiation time; da/dt : crack propagation velocity; Q : Constant; m : power law exponent for fracture energy around the notch.

The Williams' model treats the crack tip as a process zone dominated by viscoelastic-viscoplastic effects instead of a single point on the surface [11]. In addition, the Williams' model applies to sharp cracks; however, the generalizability of the Williams' model to a blunt notch is not known. In this study, the Williams' viscous fracture model (equations 1 and 2) is extended to study the crack initiation mechanism in UHMWPE from sharp to blunt notch radii.

Accordingly, the objective of this study was to investigate the relationship between crack initiation time and propagation velocity of two generic highly crosslinked UHMWPE formulations to the initial applied J-integral (J_0), for various applied loadings and three notch geometries with radii: approximately 0 mm ("sharp"), and 0.25mm and 0.5 mm ("blunt"). For this purpose, the applicability of the Williams' viscous fracture model [11] was examined, which should allow the prediction of time-dependent crack initiation and propagation for an arbitrary notch geometry from a single notch fracture experiment and a limited number of applied loading conditions.

1.3: Materials and Methods

Two generic highly crosslinked (remelted 65 kGy and remelted 100 kGy) UHMWPE formulations were tested in this study (Orthoplastics, Ltd). The materials were stored in the freezer prior to testing to mitigate oxidation [13]. Both materials were irradiated with gamma radiation and heated above the melt temperature to consume the free radicals. The materials were received in the form of ram extruded rods of 75 mm in diameter.

Eleven round compact tension specimens for remelted 65 kGy material and ten for remelted 100 kGy were machined per ASTM 1820-01 [14] in the transverse direction with the following geometry: notch depth, $a=17\text{mm}$; length, $w=40\text{mm}$; thickness, $b=20\text{mm}$; and side groove depth of 2 mm on each side. Three notch radii of ~ 0 mm, 0.25 mm and 0.5 mm were evaluated (Figure 1).

An Instron 8511 (Instron, Canton, MA) servo-hydraulic load frame was used to apply a constant load. An Infinity video microscope was focused on the face of the notch to visually obtain the crack initiation time (t_{iv}). Crack initiation was defined as the time when initial tearing occurred through the thickness at the surface of the notch root. Any crack tip blunting prior to crack initiation was visually noted for all three radii tested. A travelling microscope was used to record crack growth during the test. The crack propagation velocity (v) after crack initiation was assessed by fitting a linear regression line to the crack growth data, according to our previously developed method [12].

As per the previous study [12], a video microscope (Infinity, Hatfield, PA) was focused normal to the notch surface. The frame rate was initially maintained at approximately 15 frames per second to capture the rapid material deformation at the notch surface during initial loading and was then reduced to approximately 1 frame per second when deformation reached a steady state. A custom LabVIEW program (version: LabVIEW 2009, National Instruments, Austin, TX) that utilized the inbuilt vision acquisition feature was used to capture the test video. Analysis of the video was used to provide an estimate of crack initiation time (t_{iv}). Crack initiation was defined as the time when the tearing on the notch surface occurred continuously across the thickness of the specimen and a new crack surface was formed on the notch.

The applied J_0 for each applied load and the critical energy (J_c) value at initiation time (t_{iv}) were obtained from a finite element analysis (FEA) simulation of the crack initiation experiments. 2D FEA models (Figure 2) of the compact tension specimens were created. Three FEA models were created to simulate the crack initiation tests for each of the three different notch radii. The region near the notch was meshed with fine elements and the region away from the notch was assigned coarse mesh (Figure 2). Continuum plane strain elements with reduced integration were assigned to the models. The J-integral was computed in ABAQUS (Abaqus 6.9, Dassault Systemes, Providence, Rhode Island) via the standard contour integral method, taking the notch root node as the crack tip, and choosing the integration contour remotely enough to ensure path independence during monotonic loading. The load values from the experiments were applied as a distributed pressure on the surface of the pin hole, ramping to up to the target constant load over 0.1 seconds. A hyperelastic-

viscoplastic material definition (Three Network Model) [15], calibrated to uniaxial tensile data obtained in a previous study by the authors was applied to the 2D model [12]. In the previous study, for both materials, dogbone specimens with a constant gage region were tested to calibrate the TNM material model to creep and monotonic tensile strain-to-failure. For each material, two specimens each were tested in creep mode at a constant load of 20 MPa and 14 MPa up to large strains and two specimens were tested in monotonic tension to failure at a strain rate of 30 mm/min. The material model coefficients are given in Table 1.

The viscous fracture model (equations 1 and 2) were fit for crack initiation time (t_{iv}) and propagation velocity with applied J_0 obtained from the FEA of each notch geometry.

1.4: Results

Qualitatively, it was observed for the ~0 mm notch radius condition that crack blunting prior to crack initiation was negligible. In the two other notch conditions, crack initiation began at the outside edges of the specimen and gradually spread to the center of the notch, after which time stable crack growth ensued. As-such, crack initiation (notch root tearing) appeared nearly instantaneous for the case of the ~0 mm notch radius for all applied J_0 conditions, whereas it was delayed for the two finite notch radii. FEA predicted a substantial reduction in J_0 with increasing notch root radius (Table 2). The initiation times and propagation velocities varied across different notch radii for any given load, indicating a relationship between crack initiation phenomena and notch geometry conditions. However, the initiation time (t_{iv}) and propagation velocity (v) followed the viscous fracture model (equations 1 and 2) for any applied crack driving force (J_0) (Figure 3).

For the remelted 100 kGy material, crack initiation time and propagation velocity data showed good agreement with a magnitude of exponent 'm' of 5.12 (as-fitted from equation 1) and 4.66 (as-fitted from equation 2), respectively (Figure 3), except for anomalously rapid surface tearing in the sharp notch case. For the remelted 65 kGy material, the magnitude of exponents obtained was 6.87 and 4.07 for equation 1 and equation 2, respectively, which were again in reasonable agreement with each other. Crack initiation time for the sharp notch was estimated from the crack growth vs. time data obtained from the traveling microscope ligament reduction data, where the initiation time is identified as the onset of stable crack propagation. In other words, the formation of a new surface on the notch was observed instantaneously upon loading for the case of ~0 notch radius.

The viscous fracture model relationships rank the fracture resistance of the materials in similar manner to that of the Paris relationship for cyclic crack propagation (e.g., $da/dn = C K^m$, where da/dn is crack growth per cycle, and K is the range of the stress intensity factor at the crack tip) [16, 17]. That is, the remelted 100 kGy material is shown to be less resistant to fracture from a notch than the remelted 65 kGy material. The critical J-integral, J_c , estimated from the FEA simulations of the crack initiation experiments (Table 2), qualitatively were in good agreement between the two blunt notch conditions for both crosslinked UHMWPE materials. In addition, J_c (estimated from the FEA simulations) for the remelted 65 kGy material was 18% higher than for remelted 100 kGy material (Table 2) suggesting that increasing crosslinking reduces the fracture resistance of the polymer. Note

that J_c could not be obtained from the FEA model for the test condition of a zero-notch radius. The model could not simulate the static loading conditions with a sharp notch condition as it was unstable in the initial stages of the creep loading regime.

1.5: Discussion

The objective of this study was successfully achieved and it was found that the Williams' viscous fracture model (equations 1 and 2) could adequately describe crack initiation time and propagation velocity for remelted 65 kGy and remelted 100 kGy UHMWPE for various loadings and notch acuities up to a notch radius of 0.5mm. Thus, this work supports that the results from one crack initiation and propagation experiment for a few constant loading conditions can predict results for other extrapolated loads and alternative notch root geometries. This could of use in the development and analysis of new UHMWPE materials and joint replacement component design combinations.

To our knowledge, we are the first to report a mechanistic approach to crack initiation and propagation in UHMWPE for a range of clinically relevant stress- concentrating geometries. The effect of notch root radius (or, equivalently, applied J- integral, J_0 on crack initiation time and propagation velocity was effectively described with the use of the Williams' viscous fracture model [11] for a crosslinked UHMWPE. Therefore, the present study elucidates a means to estimate crack initiation time and propagation velocities from clinically relevant notches under quasi-static loading conditions. It should be noted that the onset of tearing in the sharp notch did not correspond to the onset of stable crack growth, as observed via the travelling microscope. Ligament reduction-based initiation time data [12], while typically less precise than those obtained from notch root observation, agreed reasonably well with the model fit to the data from the other notches, excluding the sub-threshold test conditions, supporting the applicability of the model even for sharp notches. The discrepancy between initial tearing and growth inception at sharp notches in ductile solids has been observed in other materials; referred to as the problem of "non-propagating fatigue cracks." [18].

The William's relationship for crack propagation is similar to the Paris relationship for crack propagation (and agrees reasonably well with fatigue crack propagation data for this formulation [19]). It is also notable that the exponent from fits to equations 1 and 2 are similar to that predicted from a FEA study using a hyperelastic- viscoplastic constitutive law for similar notch geometry [20], pointing to viscoplasticity as the mechanistic driving force for the time and geometry dependence of crack phenomena in UHMWPE.

It is suggested that a combination of structural analysis of components and material parameter quantification is a path to effective failure prediction in UHMWPE total joint replacement bearings, regardless of formulation, though further testing is needed to verify the rigor of this approach. However, with further validation, such an experimental-numerical program would allow for prediction of fatigue lifetime (crack initiation time) for a given combination of notch geometry and material, permitting flexibility and better assurance of fracture resistance in the design of new components.

There remain some potential obstacles to the application of the approach, such as difficulty in obtaining unique values of the material parameters in the constitutive model. In addition, the findings in a previous study by the authors [12] of distributed multi-layer crack initiation over the notch root surface [10, 12] presents a situation that potentially violates the assumption of J-integral as the only driving force of crack phenomena in UHMWPE.

Another limitation to the work concerns the application of the J-integral to a relaxation process, where during the constant load segment the stress-strain field violates proportional loading and therefore strictly speaking invalidates the J-integral as the crack driving force [21, 22]. The Williams model uses a simple assumption of power-law relaxation of the material, which in this case apparently corresponds to the power-law viscoplasticity active locally at the crack tip and not in the rest of the body per se. The initial value of the J-integral, J_0 , however, is the result of a load ramp and is a strictly valid parameter to compute. The experimental results show that J_0 is an effective correlating parameter via the Williams power-law model for a range of mechanical conditions and materials, establishing its utility even if only as a heuristic. The success of this model as a correlation motivates both its application for engineering design and further study of the time-dependent J-integral as a valid fracture mechanical parameter. This simple power-law relaxation process underlying the Williams model is expected to be equally applicable to other UHMWPE formulations, including variations in molecular weight and crosslink density, as these are only expected to quantitatively affect the values of the parameters in the model but not to qualitatively change the physics of the process. Other complications of material behavior, such as anisotropy from pre-orientation of the polymer during component processing or crazing effects (not typically seen in UHMWPE) may require a more sophisticated treatment. Applicability of the Williams model to address such issues would depend on the extent to which they are negligible in the description of the material in the crack-affected region as a power-law relaxing, initially homogeneous and isotropic continuum.

In summary, this study found good agreement with a mechanistic theory of crack initiation and propagation for two generic highly crosslinked UHMWPE formulations for a range of clinically relevant notch geometries. The power law coefficients obtained for two crosslinked UHMWPE materials are in good agreement with the flow stress exponents of the material model. The findings support that the Williams' fracture model can be a useful tool with which to predict crack initiation from notches subjected to constant loads in UHMWPE.

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References

1. Kurtz, Steven M. UHMWPE Biomaterials Handbook. Third.
2. Atwood SA, Van Citters DW, Patten EW, Furmanski J, Ries MD, Pruitt LA. Tradeoffs amongst fatigue, wear, and oxidation resistance of cross-linked ultra-high molecular weight polyethylene. *J Mech Behav Biomed*. 2011; 4:1033–45.
3. Sobieraj MC, Rimnac CM. Ultra High Molecular Weight Polyethylene: Mechanics, Morphology, and Clinical Behavior. *J. Mech. Behav. Biomed. Mater.* 2009; 2:433–43. [PubMed: 19627849]

4. Urriés I, Medel FJ, Ríos R, Gómez-Barrena E, Puértolas JA. Comparative cyclic stress-strain and fatigue resistance behavior of electron-beam- and gamma-irradiated ultrahigh molecular weight polyethylene. *J Biomed Mater Res B Appl Biomater*. 2004 Jul 15; 70(1):152–60. [PubMed: 15199596]
5. Medel FJ, Peña P, Cegoñino J, Gómez-Barrena E, Puértolas JA. Comparative fatigue behavior and toughness of remelted and annealed highly crosslinked polyethylenes. *J Biomed Mater Res B Appl Biomater*. 2007 Nov; 83(2):380–90. [PubMed: 17680670]
6. Furmanski J, Anderson M, Bal S, Greenwald AS, Halley D, Penenberg B, et al. Clinical fracture of cross-linked UHMWPE acetabular liners. *Biomaterials*. 2009; 30:5572–82. [PubMed: 19643471]
7. Rimnac C, Wright T. The Fracture Behavior of UHMW-PE. *Ultra High Molecular Weight PolyEthylene as Biomaterial in Orthopedic Surgery*. 1990:28–31.
8. Furmanski J, Kraay MJ, Rimnac CM. Crack Initiation in Retrieved Cross-Linked Highly Cross-Linked Ultrahigh-Molecular-Weight Polyethylene Acetabular Liners An Investigation of 9 Cases. *J Arthroplasty*. 2011; 26:796–801. [PubMed: 20851567]
9. Varadarajan R, Rimnac CM. Evaluation of J-initiation fracture toughness of ultra-high-molecular-weight polyethylene used in total joint replacements. *Polym Test*. 2008; 27:616–20. [PubMed: 20671815]
10. Sirimamilla, P., Furmanski, J., Rimnac, C. Non-uniform Crack Initiation from Clinically relevant Notches in Crosslinked UHMWPE Subjected to Quasi Static Loading; 56th Transactions of the ORS; 2011.
11. Williams, JG. *Fracture Mechanics of Polymers*. Ellis Horwood Ltd; 1984.
12. Sirimamilla, P., Furmanski, J., Rimnac, C. Non uniform de-cohesion affects crack initiation in crosslinked UHMWPE; Transactions 57th ORS; 2010. Poster 0333
13. 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*. 2003; 18:68–78.
14. ASTM E1820-01. Standard Test Method for Measurement of Fracture Toughness.
15. Bergstrom JS, Hilbert LB. A constitutive model for predicting the large deformation thermomechanical behavior of fluoropolymers. *Mech Mater*. 2005; 37:899–913.
16. Medel FJ, Pena P, Cegoñino J, Gomez-Barrena E, Puertolas JA. Comparative fatigue behavior and toughness of remelted and annealed highly crosslinked polyethylenes. *J Biomed Mater Res B*. 2007; 83B:380–90.
17. Sirimamilla A, Furmanski J, Rimnac C. Peak stress intensity factor governs crack propagation velocity in crosslinked ultrahigh-molecular-weight polyethylene. *Journal of Biomedical Materials Research. Part B, Applied Biomaterials*. 101:430–5. DOI: 10.1002/jbm.b.32850
18. Suresh, S. *Fatigue of Materials*. 1998.
19. Sirimamilla, P., Furmanski, J., Rimnac, C. Peak Stress Intensity Governs Crack Propagation in Crosslinked UHMWPE; 5th UHMWPE Conference; 2011.
20. Furmanski J, Sirimamilla P Abhiram, Rimnac Clare. Crack initiation and viscoplasticity in polyethylene joint replacement components. *Mechanics of Time-Dependent Materials and Processes in Conventional and Multifunctional Materials*. 3:295–301.
21. Rice JR. A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks. *Journal of Applied Mechanics*. 1968; 35:379–386.
22. Anderson, Ted L. *Fracture Mechanics: Fundamentals and Applications*. Fourth.

Figure 1.

(a): Round compact tension specimens were used in the study. (b): Notch radius = 0 mm.

(c): Notch radius = 0.25 mm. (d): Notch radius = 0.5 mm [7].

Figure 2.

(a): Half crack model of the 2D FEA model to simulate the crack initiation experiments for three different notch radius condition. (b): Notch Radius = ~ 0 mm (0.05 mm). (c): Notch radius = 0.25 mm. (d): Notch radius = 0.5 mm

Figure 3.

Remelted 65 kGy material: (a) Crack initiation time plotted against applied J_0 , the exponent obtained for equation 1 was -6.87 . (b): Crack propagation velocity plotted against applied J_0 , the exponent obtained for equation 2 was 4.07 : Remelted 100 kGy material: (c) Crack initiation time plotted against applied J_0 , the exponent obtained for equation 1 was -5.12 (d): Crack propagation velocity plotted against applied J_0 , the exponent obtained for equation 2 was 4.66 .

Table 1

Calibration coefficients obtained for the Three Network Model

Symbol	Unit	Description	Value (Remelted 65 kGy)	Value (Remelted 100 kGy)
μ_A	MPa	Shear modulus of network A	200.28	194.33
$\hat{\theta}$	T ($^{\circ}$ K)	Temperature factor	999	999
λ_L	-	Locking stretch	2.702	2.43
k	MPa	Bulk Modulus	2000	2000
$\hat{\tau}_A$	MPa	Flow resistance of Network A	20.62	19.47
a	-	Pressure dependence of flow	0.000122	0.000122
m_A	-	Stress exponential of network A	7.11	7.71
n	-	Temperature exponential	0	0
μ_{Bi}	MPa	Initial shear modulus of network B	38.96	33.13
μ_{Bf}	MPa	Final shear modulus of network B	14.83	9.13
β	-	Evolution rate of μ_B	9.2	9.2
$\hat{\tau}_B$	MPa	Flow resistance of Network B	18.48	17.05
m_B	-	Stress exponential of network B	9.42	10.23
μ_c	MPa	Shear modulus of network C	3.42	3.65
q	-	Relative contribution of I_2 of network C	0	0
α	T $^{-1}$	Thermal expansion coefficient	0	0
Θ_0	T	Thermal expansion reference temperature	293	293

Table 2

J_0 , J_c , Crack initiation time (t_{iv}) and propagation velocity (v) values obtained from the FEA simulation of crack initiation tests and experimental measurements for the two materials tested in the study.

Material		Remelted 65 kGy					Remelted 100 kGy					
Load (N)		1000	900	850	800		1100	1000	950	900	850	800
J ₀ (kJ/m ²)	~0 mm	9.5	7.5	6.45	5.7		N/A	N/A	N/A	8.0	N/A	6.0
	~0.25 mm	6	4.9	4.39	3.91		N/A	5.92	5.35	4.8	4.25	3.82
	~0.5 mm	4.5	3.65	3.27	N/A		7.0	5.6	4.7	N/A	N/A	N/A
	FEA predicted J _c (kJ/m ²)	-	-	-	-		N/A	N/A	N/A	-	N/A	-
Crack initiation time (t _{iv} , sec)	~0.25 mm	23	17.1	23	19.3		N/A	23.3	22	20.8	19.2	16.6
	~0.5 mm	22.3	18.2	18	N/A		21.5	18.2	14.8	N/A	N/A	N/A
	~0	3,400	8,500	11,750	22,800		N/A	N/A	N/A	2700	N/A	1400
	0.25	9,090	10,744	154,140	200,111		N/A	7,114	12,180	26,355	45,033	67,272
Crack propagation velocity (v, 10 ⁻⁶ mm/sec)	0.5	34,562	99,824	684,026	N/A		4,327	10,620	2,5020	N/A	N/A	N/A
	~0	330.3	140.5	76.4	39		N/A	N/A	N/A	302.00	N/A	98.00
	0.25	32	11.9	8.18	2.6		N/A	112.00	119.65	18.16	11.26	8.08
	0.5	9.2	5.5	0.82	N/A		273.00	85.2	16.3	N/A	N/A	N/A