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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. 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 (Kurtz, 2009). 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 (Atwood et al., 2011; Sobieraj and Rimnac, 2009; Urriés et al., 2004; Medel et al., 2007).

As discussed in the literature (Furmanski et al., 2009, 2011; Rimnac and Wright, 1990), 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 (Furmanski et al., 2011). 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 (Furmanski et al., 2009).

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 (Varadarajan and Rimnac, 2008). In a previous study by the authors (Sirimamilla et al., 2011a), crack initiation from a notch with a radius of 0.25 mm was studied with consideration of the Williams' viscous fracture model (Williams, 1984). Further, we have noted that a time dependent power law, the Williams model (Eqs. (1) and (2)) appears to govern crack initiation and propagation in this material (Sirimamilla et al., 2010).

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

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

where, Ti: Crack initiation time; A: Time Constant; J0: Initial energy at notch front at time = 0; Jc: 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 (Williams, 1984). 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 (Eqs. (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 0.25 mm and 0.5 mm ("blunt"). For this purpose, the applicability of the Williams' viscous fracture model (Williams, 1984) 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.

2. 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 (Kurtz et al., 2003). 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 (ASTM E-01, 1820) in the transverse direction with the following geometry: notch depth, a = 17 mm; length, w = 40 mm; thickness, b = 20 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 (Fig. 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 (Sirimamilla et al., 2010).

As per the previous study (Sirimamilla et al., 2010), 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.

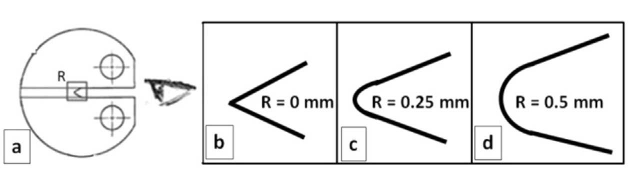

Fig. 1. (a): Round compact tension specimens were used in the study. (b): Notch radius = 0 mm. (c): Notch radius = 0.25 mm. (d): Notch radius = 0.5 mm (Sirimamilla et al., 2010).

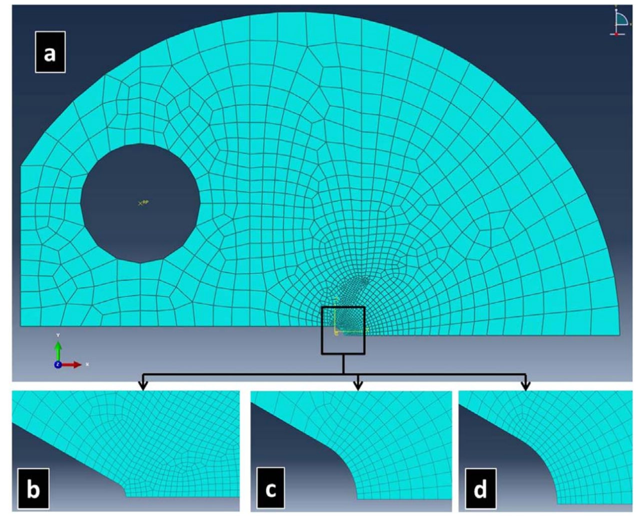

Fig. 2. (a): Half crack model of the 2D FEA model to simulate the crack initiation experiments for three different notch radius condition. (b): Notch Radius = ~0 mm (0.05 mm). (c): Notch radius = 0.25 mm. (d): Notch radius = 0.5 mm.

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 (Fig. 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 (Fig. 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 s. A hyperelastic-viscoplastic material definition (Three Network Model) (Bergstrom and Hilbert, 2005), calibrated to uniaxial tensile data obtained in a previous study by the authors was applied to the 2D model (Sirimamilla et al., 2010). 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 (Eqs. (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.

3. Results

Qualitatively, it was observed for the ~0 mm notch radius condition that crack blunting prior to crack initiation was negligible. In the two