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Application of Viscoelastic Fracture Model and Non-uniform Crack Initiation at Clinically Relevant Notches in Crosslinked UHMWPE

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Abstract

The mechanism of crack initiation from a clinically relevant notch is not well-understood for crosslinked ultra high molecular weight polyethylene (UHMWPE) used in total joint replacement components. Static mode driving forces, rather than the cyclic mode conditions typically associated with fatigue processes, have been shown to drive crack propagation in this material. Thus, in this study, crack initiation in a notched specimen under a static load was investigated. A video microscope was used to monitor the notch surface of the specimen and crack initiation time was measured from the video by identifying the onset of crack initiation at the notch. Crack initiation was considered using a viscoelastic fracture theory. It was found that the mechanism of crack initiation involved both single layer and a distributed multi-layer phenomenon and that multi-layer crack initiation delayed the crack initiation time for all loading conditions examined. The findings of this study support that the viscoelastic fracture theory governs fracture mechanics in crosslinked UHMWPE. The findings also support that crack initiation from a notch in UHMWPE is a more complex phenomenon than treated by traditional fracture theories for polymers.

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 the last four decades [1]. In total hip replacements, the acetabular component is typically composed of a UHMWPE liner seated within a metallic shell to transmit loads across the joint, and in total knee replacements the tibial component is typically composed of a UHMWPE insert seated on a metallic tray [2]. Components made of UHMWPE are designed with stress concentration features such as notches, typically as part of a mechanism to lock the modular components in place during service [3].

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In the last two decades, highly crosslinked UHMWPE formulations have been introduced for use in total hip and knee replacements because of their improved wear resistance compared to conventional (uncrosslinked or lightly crosslinked during radiation sterilization) UHMWPE formulations [4, 5]. Though highly crosslinked UHMWPEs exhibit better wear resistance compared to conventional UHMWPEs, the highly crosslinked formulations generally have reduced ductility, fatigue crack propagation resistance, and fracture toughness compared to the conventional formulations [6].

Because the bearing components are subjected to static and cyclic loads as a result of gait and other activities of daily living, one of the reasons for revision surgery is mechanical failure leading to component fracture [7]. Furthermore, crack initiation from a stress-concentration design feature (e.g., a sharp corner of a locking mechanism on an acetabular component) has been observed to lead to catastrophic failure of UHMWPE components in vivo [3, 8, 9]. 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 [10]. 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.

UHMWPE falls in the category of a ductile polymer with elongation at failure as high as 350%–400% [11]. However, the crack growth behavior of UHMWPE from an initiated crack under cyclic loading conditions has been reported to be effectively brittle in nature, i.e., having relatively low crack propagation resistance and little dependence on cyclic crack driving forces [12]. The effect of a stress concentration (such as a notch) on crack initiation has not been well-studied for UHMWPE, though there is evidence that these features can instigate catastrophic cracks in vivo [13]. However, under monotonic loading conditions, an apparent increase in yield strength resulting in notch strengthening has been observed for this material [14]. Thus, it is of interest to investigate the effect of notch design on the initiation of fracture in UHMWPE.

Fracture behavior of UHMWPE

The fracture behavior of UHMWPE has been studied using linear elastic fracture mechanics (LEFM) and elastic-plastic fracture mechanics (EPFM) theories [15–17]. The fatigue crack propagation behavior [18] and the J-integral behavior [19] of crosslinked UHMWPE formulations have been investigated both qualitatively and quantitatively using the Paris relationship and J-R curves [19–22] but crack initiation as an independent phenomenon has not been well-studied. In general, crack initiation from a razor sharpened stress concentration has been investigated in some polymers [23, 24] but not from a blunt notch or under constant load conditions. Overall, for UHMWPE, the mechanism of crack initiation from a notch-type stress concentration has not been well-studied.

A recent study [25] has shown that the fracture behavior of UHMWPE cannot be predicted using traditional LEFM and EPFM fracture theories [12, 16]. That is, it has been shown that the time-dependent behavior of the polymer needs to be taken into account. Thus, there is a need to implement a more relevant fracture theory for UHMWPE.

A viscoelastic fracture theory, attributed to J.G. Williams [26], and applicable to polymers in general, accounts for the deformation at the crack tip and relates the energy available at the crack tip to both crack initiation time and crack propagation velocity as a power law relationship [27]:

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

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

where t_i is the crack initiation time, da/dt is the crack propagation velocity, m is the time-dependence exponent (which decreases with increasing time dependence), A and Q are coefficients dependent on material properties including elastic modulus and viscous time constant, J_0 is the energy release rate for the blunt notch at the first instant of the application of a constant load, and J_c is the critical energy release rate for incipient crack propagation (i.e., initiation) which is assumed to be a material constant. This viscoelastic fracture theory has been previously successfully used to estimate the fracture resistance for other thermoplastics from a sharp crack [28, 29] but initiation from a notch has not been explored.

If it is assumed that a critical energy release rate (J_c) governs crack initiation in this material, then the viscoelastic fracture theory should predict crack initiation. In the case of a notch, the material tearing process is expected to occur at the root of the notch once a critical material condition, which coincides with J_c , is reached at that location. A uniform and well-defined crack initiation phenomenon is assumed to occur on the surface of a notch. The viscoelastic fracture theory assumes that the crack initiation time has a fixed value for a given set of initial geometric and loading conditions. In addition, the theory does not consider a distributed, multi-layer crack initiation phenomenon occurring on the surface as a possible initiation mechanism, but rather assumes single layer initiation at the most critical location on the crack face (Fig 1). However, if the stress experienced by the notch is constant across the length of the notch and is approximately constant over some breadth of the notch root, the material tearing may start at a variety of locations near the notch root once a critical state is reached. Under that scenario, multiple initiation sites could occur at a distance from each other (Fig 1) and initially grow independently from each other and ultimately either coalesce or inhibit the growth of neighboring initiation nuclei.

There were two objectives to this study. The first objective was to examine the utility of a time-dependent fracture mechanics theory supporting crack initiation occurring at single critical fracture energy (J_c) for highly crosslinked UHMWPE. The second objective was to investigate crack initiation from a blunt notch in two generic crosslinked formulations of UHMWPE under constant load conditions as a means by which to better understand the intrinsic mechanism(s) of crack initiation in UHMWPE formulations used in orthopaedic total joint replacements. Accordingly, in this study, we tested two hypotheses: 1) the Williams viscoelastic fracture theory is applicable to crosslinked UHMWPE (eqn 1 and eqn 2); and 2) the crack initiation time in crosslinked UHMWPE is affected by and positively correlated to the distance between multiple layers of crack initiation (δ) occurring on the surface of a notch, i.e., $t_i \propto f(\delta)$.

MATERIALS AND METHODS

Two highly crosslinked UHMWPE materials were used for this study: GUR 1050, moderately crosslinked with a 65 kGy dose ("remelted 65 kGy") and highly crosslinked with a dose of 100 kGy ("remelted 100 kGy") of gamma radiation in an inert environment. Both materials were post-processed by remelting above the melt transition and then slowly cooled (Orthoplastics Ltd, Lancashire, UK). The materials were received in the form of ram-

extruded cylindrical rod with a diameter of 75 mm. All rods were stored in a freezer to minimize oxidation before and after specimen fabrication [30, 31].

Round compact tension specimens were machined according to ASTM 1820-01 in the transverse direction with the following geometry: notch depth, $a=17\text{mm}$; specimen length, $w=40\text{mm}$; and thickness, $b=20\text{mm}$, with a side groove depth of 2 mm on each side (to impose an approximately constant driving force across the crack face) (Fig 1). A notch root radius of 0.25 mm was implemented to investigate the crack initiation phenomenon from a notch having a finite radius and to mimic the geometry of notches found in the locking and antirotation features often found in orthopaedic total joint replacement components [10]. Such a notch design feature approach has been successfully used to study crack initiation and propagation in ductile metals [32].

For the remelted 65 kGy material, fourteen compact tension specimens were tested, with two to four specimens each under mode I loading conditions at one of four constant tensile loads, corresponding to finite element analysis (FEA) estimated crack tip driving forces, J_0 (described below): 6.3 kJ/m^2 (1000 N, $n=4$); 4.62 kJ/m^2 (850 N, $n=4$); 4.1 kJ/m^2 (800N, $n=4$); and, 5.19 kJ/m^2 (900 N, $n=2$). For the remelted 100 kGy material, a smaller data set of seven compact tension specimens were tested at five different FEA estimated crack tip driving forces, as follows: 5.35 kJ/m^2 (950 N, $n=3$); 5.92 kJ/m^2 (1000 N, $n=1$); 4.82 kJ/m^2 (900 N, $n=1$); 4.25 kJ/m^2 (850 N, $n=1$); and, 3.82 kJ/m^2 (800 N, $n=1$).

An Instron 8511 (Instron, Canton, MA) servo-hydraulic load frame was used to apply the specified constant load to a specimen. Applied load and displacement at the loading pins was recorded throughout each test.

For each loading condition, the value of J_0 was determined using 2D finite element simulations of the compact tension specimen in ABAQUS 6.10 (Dassault Systemes, Providence, RI). Plane strain quadratic elements were used in the 2D model. An advanced hyperelastic-viscoplastic constitutive material model known as the Three Network Model (TNM) was implemented to capture the time-dependent response of the material [33].

For both materials, dogbone specimens with a constant gage region (diameter, 7.5–8.0mm, gage length, 14 mm, Fig 2) 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 a 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 creep tests were conducted on an Instron 8511 (Instron, Canton, MA) servohydraulic load frame using threaded grips. The load was applied at a rapid rate and held for 10 days or until failure, whichever occurred first. All tests were conducted under ambient laboratory conditions. A non-contact video extensometer was used to capture strain during the creep test. The video extensometer was calibrated using a calibration bar of 200 mm length. LabVIEW (National Instruments, Austin, TX) programs were used to record strain vs. time from the video extensometer and also load and displacement from the testing frame. Load and displacement were collected at a frequency of 25 Hz for the first 2 hrs after which the frequency was decreased to 0.1 Hz for the remainder of the test.

The monotonic tension strain-to-failure tests were conducted on a screw driven Instron testing frame (Model number: 4411, Instron, Canton, MA). The same specimen geometry that was used for the creep tests was used for the monotonic tension tests. A strain rate of 30 mm/min was applied under ambient laboratory conditions. A calibrated non-contact video extensometer was used to capture strain. Load, displacement and strain from the video

extensometer were recorded using LabVIEW programs. The data acquisition frequency was maintained at 25 Hz throughout the test.

True stress and strain were calculated by assuming constant volume during deformation. True stress vs. true strain behavior from the creep and monotonic tension tests was used to calibrate the TNM, with particular emphasis on the nine time-dependent parameters of the TNM, using a custom written Matlab code (Veryst Engineering, Boston, MA). The calibrated model was then used to predict J_0 values for all the experimental load conditions.

For the purposes of evaluating crack initiation time and the mechanism of crack initiation, a video microscope (Infinity, Hatfield, PA) was focused normal to the notch surface (“eye” in Fig 1a). The videos obtained had a resolution of 1634×1238 pixels. 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 the deformation reached a steady state. A custom LabVIEW program 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. It was also noted whether initiation occurred at the “root” of the notch or peripherally “away” from the notch (initiation position). For the case where crack initiation occurred simultaneously on multiple parallel layers, the vertical distance between the crack initiation layers (δ) was also measured based on the calibrated videos. When multiple layer initiation was observed, at least five measurements of δ were taken across the thickness of the specimen and averaged. A $\delta = 0.05$ mm was considered a single layer initiation condition, due to the resolution of the measurement method.

A travelling microscope with 5 X magnification was used to measure ligament reduction (the length of uncracked material beyond the notch) during the test (Fig 3). The distance between the root of the notch and the back surface of the specimen was recorded at regular intervals during the test to measure the ligament reduction. A back light was used to identify the root of the notch or crack tip. Due to the side grooves, the crack propagation rate at the specimen mid-plane slightly lagged that at the surface, ensuring that the measured backlit ligament length corresponded to that at the interior and not on the specimen surface. Backlighting also enabled differentiation of the true crack tip from membrane-like features that form on the tearing surface and often intersect to obscure the crack front. From the ligament reduction, true crack advance was obtained by subtracting the apparent ligament reduction due to material deformation (associated with loading of the specimen) from the total ligament reduction [25]. The material deformation was accounted for with a logarithmic fit to the initial non-linear region of the ligament reduction and subtracting it from the total ligament reduction to obtain the true crack advance or growth. A second estimate of the crack initiation time from the travelling microscope (t_{im}) and the rate of crack advance (crack propagation velocity, v) were obtained by performing a linear regression fit to the stable crack advance behavior, as has been previously reported [13]. Thus, two independent crack initiation times were recorded, one inferred from the inception of crack growth from microscopic ligament measurements and one from crack surface observation (t_{im} and t_{iv} , respectively). The two independent crack initiation times were compared for different loading conditions for both materials. Elapsed time at catastrophic fracture was also recorded (t_f). The nature of the relationship between the parameter δ and the initiation time obtained from video (t_{im}) was explored for each of the loading conditions. For all notched specimens under all load conditions, the obtained crack initiation (t_{iv}) and crack propagation velocity (v) results were used to determine the time-dependent exponent, m , in the viscoelastic fracture theory (eqn 1 and eqn 2) [27].

RESULTS

Creep and monotonic tensile tests and model calibration

For the remelted 65 kGy material, one creep specimen tested at 20 MPa failed after 10,000 sec (approximately 2 hrs 46 mins) at a true strain of 1.1. The second specimen did not fail within the specified time frame (maximum 10 days); the true strain was also 1.1 when that test was suspended. At 14 MPa, a creep time of 10 days was not sufficient to attain failure for either specimen. The true strain was 0.9 for these two tests when the tests were suspended. None of the four remelted 100 kGy specimens failed after 10 days of loading (either at 14 MPa or 20 MPa). From the monotonic strain-to-failure tests, a true failure strain of 1.43 and 1.35 was determined for the two remelted 65 kGy test specimens and a failure strain of 1.24 and 1.27 was determined for the two remelted 100 kGy test specimens.

The nine parameters that were optimized in the TNM [33] varied between the two materials. The model was calibrated with a R^2 value > 0.90 for all three (two creep and monotonic tension to failure) conditions for both materials (Fig 4, Table 1). The J_0 values predicted by the models were lower for the remelted 100 kGy material than for the remelted 65 kGy material (Tables 2 and 3).

Crack initiation tests

Crack initiation and propagation to failure occurred in all specimens. For both the materials tested, the mechanism of crack initiation occurred on a single layer in some specimens and on multiple layers (with a maximum distance δ encompassing the crack initiation layers) on other specimens tested with the same crack tip energy (Figs 5, 6). For the remelted 65 kGy material, the largest δ was approximately 0.95 mm when a J_0 of 5.19 kJ/m² was applied. The largest δ for the remelted 100 kGy material was approximately 0.72 mm at a J_0 of 5.3 kJ/m², though this data set included less repeated tests than for the 65 kGy material. The crack initiation time was strongly affected by the type of crack initiation (single layer vs. multi-layer), and a positive relationship was observed between crack initiation time (t_{iv}) and δ for both materials (Fig 7).

Cracks were also observed to originate both from the line of symmetry (central root) of the notch and at a distance away from the root (e.g., Fig 5b, 5c). Crack initiation on the notch surface always occurred initially on the outside of the specimen (intersection with the side grooves) and subsequently spread to the interior of the specimen (Fig 8). In all cases, cracks that initiated away from the symmetry plane of the notch had longer initiation times compared to cracks that initiated at the central root of the notch (Table 2). For the remelted 65 kGy material, the failure time increased by 25% to 300% as a result of multi-layer crack initiation (Table 2). For the remelted 100 kGy material, for the one test condition for which there was more than one test (load condition of 950 N; $J_0 = 5.35$ kJ/mm²), the failure time increased by 30% as a result of multi-layer crack initiation (Table 3).

For the remelted 65 kGy material, the ratio of crack initiation time to failure time for single layer initiation was 51% and 53% for 1000N. For 850 N conditions, it was higher at 71% (Fig 7). For the remelted 100 kGy material, the ratio of crack initiation to failure time for single layer initiation (800 N) was higher compared to the remelted 65 kGy material and was 78%. The ratio of crack initiation time to failure time was always higher for the multilayer initiation case than for the single layer initiation case for all the loading conditions (Fig 7) and for both materials tested. For each material individually, a clear trend could not be observed for the ratio of crack initiation time to failure time across the loads tested.

The ligament reduction obtained from the travelling microscope had an initial non-linear region, followed by a stable crack growth region leading to non-linear catastrophic fracture

(Fig 9). The crack initiation time obtained from the travelling microscope (t_{im}) differed across specimens with single layer initiation to multi-layer initiation (Table 2 and 3) for the same loading conditions. The crack propagation velocity (v) increased with increase in J_0 , as expected from the Williams model. Generally, the propagation velocity was lower when there was multi-layer initiation (e.g., Table 2); this was the case for both materials.

For the remelted 65 kGy material, for nearly every test condition, t_{iv} was greater than t_{im} by a factor of one to three (Table 2). This was also the case for the remelted 100 kGy material (Table 3).

For both materials, a power law relationship predicted by the viscoelastic fracture theory was applied to all the initiation times obtained for all the loads tested (Fig 10). The exponent, m , obtained for the remelted 65 kGy material via eqn 1 and eqn 2 was 9.56 and 6.42, respectively. The exponent, m , obtained for the remelted 100 kGy material via eqn 1 and eqn 2 was 5.58 and 5.8, respectively. Thus, the exponents obtained from eqn 1 and eqn 2 were in agreement for remelted 100 kGy (with < 4% difference) but varied by 32% for remelted 65 kGy material.

DISCUSSION

The first hypothesis that the viscoelastic theory can be applied to crosslinked UHMWPE was addressed by fitting equations 1 and 2 to the crack initiation and propagation behavior. The viscoelastic fracture theory was found to fit both single and multi-layer behavior, for both materials (Fig 10, eqn 1 and eqn 2). In the case of the 100 kGy irradiated formulation, the agreement between the initiation and propagation exponents was found to be good, indicating applicability of the Williams fracture model, while the initiation exponent (eqn 1) for the 65 kGy formulation was found to be substantially higher than that from the propagation exponent (eqn 2). In comparing the propagation data for the two materials, the exponents are similar with a substantial shift in the intercept, which is consistent with observations from fatigue crack propagation studies on similar materials [18, 22, 34]. Thus, the greater initiation exponent obtained for the remelted 65 kGy material relative to its propagation exponent, is inferred to be due to an effect not considered in the simple viscous fracture model employed here, such as an increased sensitivity to multi-layer crack initiation.

The second hypothesis of the study, that a distributed, multi-layer crack initiation phenomenon can affect the fracture properties of crosslinked UHMWPE material, was also supported in that the crack initiation time obtained from multi-layer crack initiation tests were higher by 25%–300% for the remelted 65 kGy material and by 30% for the remelted 100 kGy material than the values obtained from crack initiation tests that displayed single layer crack initiation behavior. The crack initiation time (t_{iv}) was found to be dependent on the distance between multiple crack initiation layers (δ) occurring on the notch surface. It was also found that crack initiation in some cases did not occur ideally in the center of the notch root, and in these cases the initiation time (t_{iv}) was substantially greater than when initiation occurred at the root (“Root” vs. “Away”, Table 2).

The phenomenon of multi-layer crack initiation could be a result of consumed energy during deformation near the crack tip being distributed across multiple crack initiation layers on the notch surface, or neighboring nuclei shielding one another and relaxing the local stress severity. Also, finite element analyses [35] predict the local deformation state at the root of the notch to be similar over a relatively broad area of the root surface under a specified load. Given that UHMWPE does not undergo material instabilities (e.g, necking or crazing) [11], this nearly-constant region of deformation may permit multi-layer crack initiation due to the

lack of a preferential location for initial failure. Another possible reason for multi-layer crack initiation may be machining defects or residual stresses on the surface of the notch. Such machining defects could act as potential sites for crack initiation.

With respect to creep and monotonic tensile behavior, the two materials were found to be qualitatively similar. However, as expected, there were quantitative differences, with the remelted 100 kGy material behaving in a less ductile manner (Fig 4, [11]). The quantitative differences were captured with higher stress exponentials (m_A and m_B), lower shear moduli (μ_A , μ_{Bi} and μ_{Bf}) in the time dependent networks and a lower locking stretch (λ_L) in the TNM constitutive material model for the remelted 100 kGy versus the remelted 65 kGy material (Table 1).

The results of this study support that crack initiation from design-related notches in UHMWPE total joint replacement components may involve multi-layer or single layer crack initiation phenomena which could either delay or accelerate fracture, respectively. Typically, for both polymers and metals, crack initiation is modeled as a single layer phenomenon [36]. However, multi-layer behavior has been observed; for example, creep crack initiation from a notch was studied in metallic Cr-Mo-V alloy systems [37, 38] and the formation of several microcracks prior to the formation of a dominant crack was reported (similar to what was observed in this study). Overall, the findings of the current study support that multi-layer crack initiation needs to be taken into account when modeling crack initiation in crosslinked UHMWPE. Traditional approaches [16] that assume single layer initiation that occurs at the center of the notch root may be conservative for UHMWPE materials.

For the test conditions of this study, the ratio of crack initiation time to failure time was higher, in general, for the remelted 100 kGy material versus the remelted 65 kGy (Tables 2 and 3, Figure 7b). Crack initiation dominating the fracture process is a hallmark of brittle fracture behavior. This result is also consistent with other reports for remelted 100 kGy and remelted 65 kGy formulations that demonstrate that increasing crosslinking of the material makes it more brittle and less defect tolerant [6, 17, 34, 39].

Multi-layer crack initiation also reduced the propagation velocity, v ; thus, multi-layer crack initiation affected both initiation time and propagation velocity (Table 2 and 3). As seen in Figure 8, multi-layer initiation leads to a tortuous crack front, with the jumps between initiation nuclei generating a local mode III tearing. This tearing likely increase the specific energy consumed in crack propagation, thus reducing the crack propagation velocity. It is worth noting that these local mode III tears result in the “diamond pattern” fracture surface features that have been widely reported for UHMWPE [6, 34].

In earlier studies, the crack propagation characteristics in both uncrosslinked and highly crosslinked UHMWPE were shown to be mechanistically brittle where, during cyclic loading, the cyclic component is dominated by the static component of the maximum applied stress intensity to propagate a crack [12]. The present study supports that a constant load can induce progressive damage in the material and initiate and propagate a crack from a notch in crosslinked UHMWPE. For crosslinked UHMWPE, the propagation velocities in this study cannot, in general, be directly compared to propagation velocities obtained in previous fatigue crack propagation studies [18, 34] as the geometry and loading conditions differ between studies. However, the propagation velocities obtained are similar to those in another study by the authors [25, 40] which also implemented static loading conditions on notched compact tension specimens made of crosslinked UHMWPE.

UHMWPE (uncrosslinked or crosslinked) has relatively low fracture toughness [34] compared to metal alloys. In addition, the fracture toughness is reduced by crosslinking [34]. The low fracture toughness makes this family of materials potentially susceptible to cracks

and stress concentrations, that is, less defect tolerant. The utility of assessing crack initiation performance separately from crack propagation resistance is therefore evident for UHMWPE, particularly when crosslinked.

The observed initial non-linear region in ligament reduction prior to crack initiation is believed to be dominated by gross specimen deformation. FEA predictions support that the initial non-linear region is likely primarily from gross specimen deformation [41]. In contrast to the measurement of crack initiation time from the video microscope (t_{iv}), the crack initiation time from the travelling microscope (t_{im}) does not capture material tearing on the notch surface. Therefore, it is important to note that the standard approach of using crack advance measurements taken with a travelling microscope to determine crack initiation time could lead to an erroneous value when initiation occurs via a multi-layer initiation mechanism (Table 2 and 3). Rather, estimation of crack initiation time should involve physical observation of crack tip tearing phenomena, such as was obtained in this study (e.g., t_{iv}).

This study investigated the resistance of two formulations of crosslinked UHMWPE to crack initiation from a notch; however, only one notch radius was employed. Future studies should include the effect of different notch root radii on crack initiation resistance in this family of materials. In this respect, it is possible that the phenomenon of multi-layer initiation might be exacerbated (that is longer initiation time) by larger radii. It is also expected that the multiple layer separation distance, δ , is bounded by the acuity of the notch, but this has not been systematically investigated. Finally, although the study supports a strong relationship between δ and initiation time (t_{iv}), a direct relationship between crack initiation (single layer versus multi-layer) and component failure is still to be established.

In a previous study by the authors [42, 43], intrinsic polymer chain stretch at the initiation location was shown to correlate with the critical fracture energy (J_c) according to the Williams viscous fracture model. This linked the failure of material at the onset of crack initiation to a local continuum failure criterion that has been successful in describing failure in UHMWPE under multi-axial tensile deformations [44]. A better understanding of the intrinsic mechanisms governing single versus multi-layer crack initiation would facilitate guidance in the design of UHMWPE joint replacement components. In this regard, it will be important to establish a relationship between the intrinsic behavior (viscoplastic exponents and critical average molecular chain stretch of the polymer) and the extrinsic traditional fracture resistance parameters (initiation time, critical fracture energy). Such design criteria for fracture have been lacking for UHMWPE and could be valuable in the design of UHMWPE joint replacement components. This approach can also be applied to other time-dependent polymeric materials to characterize their fracture resistance.

In summary, the key objectives of this study were:

- To examine the utility of a time-dependent fracture mechanics theory supporting crack initiation occurring at a single critical fracture energy (J_c) for highly crosslinked UHMWPE
- To investigate crack initiation from a notch in crosslinked UHMWPE under constant load conditions to better understand the intrinsic mechanism(s) of crack initiation

There were two key hypotheses:

- The Williams viscoelastic fracture theory is applicable to crosslinked UHMWPE

- The crack initiation time in crosslinked UHMWPE is affected by the distance between multiple layers of crack initiation (δ) occurring on the surface of a notch

The key results and discussion points are:

- The viscous time-dependent fracture model predicts crack initiation and propagation in crosslinked UHMWPE, and there was agreement with finite element analysis predictions
- Crack initiation from a notch can occur via two different mechanisms in crosslinked UHMWPE: focused single-layer crack initiation and diffuse multi-layer initiation
- The multi-layer crack initiation phenomenon delays crack initiation from a notch, approximately in proportion to the extent of the distance between initiation layers

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Highlight

- The viscous fracture model predicts crack initiation and propagation in crosslinked UHMWPE
- An advanced numerical model was employed to evaluate the crack tip properties
- Crack initiation from a notch can occur via two different mechanisms in crosslinked UHMWPE

The multi-layer crack initiation phenomenon delays crack initiation from a notch

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Figure 1.

The theoretical assumption of crack initiation in viscoelastic polymers predicting crack initiation occurring on a single layer when subjected to loading. (a): Direction of view for the observation of the notch surface on a compact tension specimen. (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.

Figure 2.
Dogbone specimen dimension used for creep and strain-to-failure tests.

Figure 3.

Two independent methods were employed to measure the crack initiation time. A video microscope was used to observe the notch surface directly to obtain t_{iv} , while a travelling microscope was used to measure the ligament reduction versus time throughout the test to obtain t_{im} . 'A' and 'B' were external light sources used with the travelling microscope and video microscope, respectively.

Figure 4.

Calibration of the Three Network Model for the remelted 65 and the remelted 100 kGy materials: (a) and (b): Creep and strain-to-failure calibration of the remelted 65 kGy material, respectively. (c) and (d): Creep and strain-to-failure calibration of the remelted 100 kGy material, respectively.

Figure 5.

Two specimens tested at 6.3 kJ/m^2 (1000 N, Remelted 65 kGy) showed different crack initiation behavior. CF-Crack Front. Dotted line indicates the root of the notch and δ is the vertical distance between crack initiation sites. Arrows indicate the initial crack initiation sites. (a) Direction of view for (b) and (c); (b) Crack initiation occurring on a single layer at the root of the notch of a specimen; (c) Initial crack initiation sites occurring on multiple layers and at the edge of the notch of another specimen.

Figure 6.

Two specimens tested at 4.1 kJ/m^2 (800 N, Remelted 65 kGy) showed different crack initiation behavior. CF-Crack Front. Dotted line indicates the root of the notch and δ is the vertical distance between crack initiation sites. Arrows indicate the initial crack initiation sites. (a) Direction of view for (b) and (c); (b) Crack initiation occurring on a single layer at the root of the notch of a specimen; (c) Initial crack initiation sites occurring on multiple layers and at the edge of the notch of another specimen.

Figure 7.

Effect of the maximum separation of the multi-layer initiation sites, delta (δ), on the (a) crack initiation time and (b) the ratio of initiation time (t_{iv}) to failure time (t_f). RM65: Remelted 65 kGy material; RM100: Remelted 100 kGy material.

Figure 8.

Initial crack initiation sites were discontinuous and distributed, and crack initiation occurred after local sites linked with each other to form one tearing front. The circles indicate the initial crack initiation sites. (a) Crack front prior to complete linking of initial sites (t_{iv}); (b) Crack front when the sites have linked; (c) Tearing front following linking of the sites.

Figure 9.

Deduction of a crack initiation time obtained from the travelling microscope data. (a) Ligament reduction data obtained from the travelling microscope. (b) True crack growth obtained after accounting for the ligament reduction data. The arrows indicate the crack initiation time. Black solid lines indicate the rate of crack growth rate after initiation.

Figure 10.

Application of the Williams viscoelastic fracture theory. (a): The data is fit using Equation 1. The exponents obtained are -5.56 and -9.56 for remelted 100 kGy (RM 100) and remelted 65 kGy (RM65), respectively. (b): The data is fit using equation 2. The exponents obtained are 5.8 and 6.42 for remelted 100 kGy (RM100) and remelted 65 kGy (RM65), respectively.

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
θ	T (°K)	Temperature factor	999	999
λ_L	-	Locking stretch	2.702	2.43
k	MPa	Bulk Modulus	2000	2000
τ_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
τ_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

Measures of crack initiation time, crack initiation site separation distance, propagation velocity, failure time, crack initiation position, and ratio of initiation time to failure time for the remelted 65 kGy material.

Applied J_0 (kJ/m ²)	Specimen	δ (avg),mm	t_{i1} , sec	t_{im} , sec	t_f , sec	v (mm/sec)	Initiation position	$\frac{t_{i1}}{t_f}$
6.3 (1000 N)	1	0.21	9459	4700	17220	35.56	Root	0.55
	2	0.05*	9090	7225	17760	64.75	Away	0.51
	3	0.51	15060	4300	21900	32	Away	0.69
	4	0.05*	9114	9250	17280	32	Root	0.53
5.19 (900 N)	1	0.06	10700	12500	33600	11.9	Root	0.32
	2	0.95	47300	30500	114000	9.5	Away	0.41
	1	0.21	168167	-	196800	-	Away	0.85
	2	0.68	232910	178000	267600	7.03	Root	0.87
4.1 (800 N)	3	0.18	163500	78000	201480	4.9	Root	0.81
	4	0.05*	154140	137000	215880	8.18	Root	0.71
	1	0.075	200111	160000	432000	2.6	Root	0.46
	2	0.77	1225060	735000	1728000	0.37	Away	0.71
	3	0.08	549977	241000	652080	0.847	Away	0.84
	4	0.123	864000	825000	950400	3.8	Away	0.91

* δ 0.05mm considered single layer

Table 3

Measures of crack initiation time, crack initiation site separation distance, propagation velocity, failure time, crack initiation position, and ratio of crack initiation time to failure time for the remelted 100 kGy material.

Applied J_0 (kJ/m ²)	Specimen	δ (avg), mm	t_{iv}	t_{im}	t_f	v(mm/sec)	Initiation position	$\frac{t_{iv}}{t_f}$
5.92 (1000 N)	1	0.21	7114	2640	9013	112	Away	0.77
5.35 (950 N)	1	0.75	16136	8570	18634	44.12	Away	0.86
	2	0.3	13443	7190	15737	53.3	Away	0.85
	3	0.1	12180	8000	14915	186	Away	0.81
4.82 (900 N)	1	0.18	26355	9400	27820	18.16	Root	0.94
4.25 (850 N)	1	0.55	45033	15100	48578	11.56	Root	0.92
3.82 (800 N)	1	0.05*	88245	43000	112954	8.08	Away	0.78

* δ 0.05mm considered single layer