Crack Propagation Resistance Is Similar Under Static and Cyclic Loading in Crosslinked UHMWPE

A Pilot Study

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Abstract

Background Recent work suggests crack phenomena (eg, crack initiation and propagation) in UHMWPE do not depend on cyclic damage mechanisms. Materials for which crack phenomena occur in static (noncyclic) mode should exhibit similar crack propagation behavior under static and cyclic loading conditions.

Questions/purposes Do cracks in UHMWPE stably propagate from acute notches under static loading with a velocity dependent on crosslink density? Are material-ranking evaluations for crack propagation resistance similar under static and cyclic loading conditions? Does time to failure for a notched specimen under static loads yield the same material rankings as crack propagation data?

Methods Notched compact tension specimens were machined from UHMWPE gamma-irradiated with a 0-, 50-, 75-, or 100-kGy dose and subsequently remelted. Static loads were applied until failure occurred or 2 weeks had elapsed. Crack propagation rates and time to failure were recorded and compared to data from cyclic experiments.

Results Static and cyclic loading both produced stable crack propagation and similar performance rankings of material groups, except in the case of the unirradiated material, which did not fail under static loads. Normalized measures of crack propagation velocities generally showed

quantitative agreement between the two methods. Normalized time to failure under static loading also agreed well with crack propagation velocity.

Conclusions Crack propagation under static loading produced qualitatively and quantitatively similar performance results as those under cyclic loading. Time to failure under static loads corresponded closely with the crack propagation velocity and may itself be a robust metric of crack propagation resistance.

Clinical Relevance Total joint arthroplasties may experience superficial cracking in the UHMWPE bearing surface or catastrophic fracture. Quantifying resistance to crack phenomena in UHMWPE is important to design engineers and to clinicians using crosslinked UHMWPE materials under challenging mechanical conditions.

Introduction

Fracture toughness and resistance to crack propagation of UHMWPE have been important for total joint arthroplasties, stemming from oxidation issues in conventional formulations and extending to concerns about reduced material strength and toughness evident in wear-resistant crosslinked UHMWPE formulations. While reports of clinical fracture or crack-related failures remain rare for crosslinked UHMWPE implants, clinically retrieved components have been reported involving catastrophically fractured bearings [4, 15], intact components containing initiated subcritical cracks [6], and bearing surfaces exhibiting extensive apparently brittle surface cracking [5]. Crosslinked formulations of UHMWPE provide an excellent wear-resistant bearing surface in total joint arthroplasty, but the long-term resistance to crack-related damage phenomena in these materials is unclear.

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Substantial progress has been made in the past 15 years regarding an understanding of the fracture and fatigue behavior of UHMWPE [3, 7–10, 12, 13, 16]. Currently, the fatigue performance of a UHMWPE formulation is evaluated chiefly by its resistance to fatigue crack propagation under cyclic loading conditions [3, 8, 12]. The stress intensity at the inception of crack growth K_{insep} (often reported as ΔK_{insep} for cyclic loading) has been used to establish the minimum conditions for detectable and stable crack growth (typically about 10^{-6} mm/cycle) and is commonly compared between formulations to establish relative fatigue resistance [3]. A relative decrease in K_{insep} generally shifts the stable crack propagation uniformly to lower values of stress intensity [3, 8, 12], and such a shift is known to accompany crosslinking in UHMWPE [3, 8, 12]. The reduced toughness and crack propagation resistance of crosslinked formulations of UHMWPE are of interest for clinical applications, particularly in light of recently reported cases of brittle damage or catastrophic fracture of highly crosslinked THA bearings [4–6, 15].

Fatigue crack propagation data have been useful for comparing the relative fatigue performance of UHMWPE materials, but their utility as an intrinsic material property has been questioned [11]. Limitations inherent in the use of fatigue crack propagation data include the use of the linear elastic fracture mechanics stress intensity factor K to describe crack tip conditions in a highly nonlinear, viscous solid. While nonlinear fracture mechanics have been used to describe crack growth and fracture conditions in UHMWPE [9, 13, 16], these do not typically include viscous dynamics, which likely are a strong factor in the behavior of the material in the fracture process zone. Recent work suggests crack propagation in conventional UHMWPE correlates to the maximum of the cyclic waveform (as opposed to the load excursion) [7] and demonstrates frequency independence and predictable waveform effects [11]. Such behavior is characteristic of materials that do not require cyclic loading to propagate fatigue cracks but rather propagate cracks in a quasistatic manner, ie, static mode crack propagation [14]. It follows, then, cracks should propagate in UHMWPE under static loading and crack propagation in UHMWPE under either applied cyclic or static loading will result in identical information about the material resistance to crack propagation since either case depends on the same intrinsic material behavior.

We asked whether (1) cracks would initiate from acute notches and stably propagate under static loading with a velocity dependent on crosslinking radiation dose, (2) crack propagation under static loading would result in quantitatively similar material crack propagation resistance data to those obtained under cyclic loading conditions, and (3) specimen failure time under a static

load would yield a similar evaluation of material crack propagation resistance as crack velocity under a static or cyclic applied load.

Materials and Methods

Notched compact tension specimens of various crosslinked formulations of UHMWPE were subjected to cyclic or static tensile loading. The resulting crack propagation velocity for each was measured, along with the time to failure under static loading. A power law regression fit was made to the stable propagation velocity data (ie, the Paris equation [Eq. 3]), and the leading coefficient of this fit then corresponded to the velocity at a reference value ($1 \text{ MPa m}^{1/2}$) of the driving force. Trends in the normalized power law coefficients from cyclic experiments were compared to the normalized propagation velocities from the static load experiments and to the normalized failure time under static loading to quantitatively evaluate the correspondence of these three separate measures of crack propagation resistance.

GUR1020 compression-molded and GUR1050 ram-extruded UHMWPE resin were gamma-irradiated as follows: GUR1020, 0 kGy (Material A); GUR1020, 50 kGy (Material B); GUR1020, 75 kGy (Material C); GUR1020, 100 kGy (Material D); and GUR1050, 100 kGy (Material E) (Table 1). Irradiated materials were subsequently remelted at 147°C to eliminate residual free radicals. Two specimens were tested for Materials A, C, D, and E, and three were tested for Material B. Compact tension specimens were machined from the bulk material (Fig. 1), with crack length from the load line $a = 8.89$ mm, ligament length $b = 16.5$ mm, thickness $B = 10.8$ mm, and initial notch root radius $r = 0.13$ mm. The crack propagation direction was oriented along the ram extrusion axis for the GUR1050 specimens. Specimens were also side-grooved with the same cutter used for the notch, with a depth of 1 mm, and included an angle of 60° to inhibit crack tunneling effects by counteracting the drop in stress intensity factor that occurs near the free surface of the specimen [2, 16]. The specimen notch was left with the machined radius (ie, not razor sharpened before testing).

Static loading notch fatigue experiments were performed on an Instron 8871 servohydraulic load frame (Instron, Norwood, MA). A constant load of 500 N was applied to the specimen, corresponding to an approximate linear elastic stress intensity factor K of approximately $2.1 \text{ MPa m}^{1/2}$ as determined from the standard relation for the square compact tension specimen with the geometric coefficient $F(a/W)$ [2], applied load P , and specimen thickness B , where W is the specimen length from the load line ($W = a + b$) (Eqs. 1–2).

Table 1. Crack propagation data for fatigue and deadload loading of UHMWPE

Material	Formulation	Fatigue		Deadload		Normalized propagation		
		C (mm/s)	n	a' (mm/s)	t _f (s)	C/C _D	a'/a' _D	t _{f-D} /t _f
A	GUR1020, 0 kGy	1.23E − 6	5.12	NA	NA	0.0382	NA	NA
B	GUR1020, 50 kGy	1.19E − 5	5.77	7.16E − 5	19000	0.37	0.331	0.311
C	GUR1020, 75 kGy	1.18E − 5	8.21	1.19E − 4	10400	0.366	0.55	0.572
D	GUR1020, 100 kGy	3.22E − 5	7.8	2.16E − 4	5920	1	1	1
E	GUR1050, 100 kGy	8.13E − 5	8.25	4.99E − 4	2160	2.5	2.31	2.74

C = cyclic power law fit coefficient; a' = static load crack propagation velocity; t_f = failure time; C/C_D = normalized cyclic power law coefficient; a'/a'_D = normalized static load crack propagation velocity; t_{f-D}/t_f = normalized failure time; NA = not applicable

Fig. 1 A diagram illustrates compact tension specimen geometry, with crack length from the load line (a), ligament length (b), and initial notch root radius (r).

$$K = F(a/W) \frac{P}{B\sqrt{W}} \quad (1)$$

The value of the applied load was chosen as a moderate condition likely to result in stable crack propagation, according to cyclic loading experimental data. The load was maintained until failure, or the specimen was removed after at least a week of loading. The time to failure t_f was also recorded as a potential metric of crack propagation resistance. This test procedure was inspired by the methods in ASTM F1473 [1], which reports crack propagation resistance according to the time to failure for notched polyethylene specimens under a constant applied load.

Crack growth was monitored with a travelling microscope on a micrometer stage with a resolution of 0.01 mm fixed to the load frame, and effective crack growth (Δa_{eff}) was taken as the loss of ligament length (remaining material ahead of the crack tip in the crack plane) in the specimen (Δb), ie,

$$\Delta a_{\text{eff}} = -\Delta b \quad (2)$$

Ligament reduction was used instead of a direct crack growth metric due to gross specimen distortion that can occur during long-duration creep deformation experiments and the ambiguous behavior of the crack tip in the early stages of growth [16].

Cyclic loading fatigue crack propagation data were adapted from a pilot set of experiments conducted on identical specimens and materials as in this study but with a sinusoidal waveform at 5 Hz and a tensile load ratio $R = 0.1$ ($P_{\text{min}}/P_{\text{max}} = 0.1$). Crack propagation data from these experiments were regression fit to a power law relation with the maximum of the elastic stress intensity factor, analogous to the Paris equation (Eq. 3). This is the conventional approach for evaluating crack propagation resistance in UHMWPE, although only recently have the average velocity and peak stress intensity been recommended as the correlated parameters [7, 11]. The regression fit yields a leading coefficient and an exponent; the coefficient was used as an indicator of the expected propagation velocity at a reference value of the stress intensity ($1 \text{ MPa m}^{1/2}$) to be compared with the static loading crack propagation velocities.

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

The results of the static loading experiments were compared to those from the cyclic experiments by evaluating their relative material performance rankings. The static load crack velocity observed for each material formulation was normalized to that of the GUR 1020, 100-kGy group (Material D), giving the relative crack velocities for each group (Table 1). Similarly, the coefficient C of the power law fit (Eq. 3) for the cyclic data for each material was normalized to that of Material D, and the resulting ratios are directly analogous to the velocity ratios for the static load tests. The failure time t_f for each group was also normalized to that of Material D. The computed normalized velocities for the static load tests were compared to the normalized velocity coefficients of the cyclic loading crack propagation power law fit (ie, Paris equation) to quantitatively evaluate the relative crack propagation velocities between materials under a given applied condition obtained by each loading approach. Normalized failure times were also compared to the

normalized velocities to evaluate its potential utility as a material performance ranking metric. No statistical tests were performed due to the limited number of available test specimens (two to three specimens per group).

Results

Crack propagation readily occurred under the applied static loading for all irradiated materials, but stable propagation did not initiate for the unirradiated material (Material A). The static load crack propagation velocity for all irradiated formulations increased with radiation dose from 7.16×10^{-5} to 4.99×10^{-4} mm per second (Table 1). The crack velocity in the irradiated materials was approximately constant during the first 1 mm of crack growth but continuously decelerated in the unirradiated group (Fig. 2). Crack propagation commenced without a substantial delay in the irradiated materials, indicating crack initiation occurred rapidly and crack initiation effects could be neglected from the analysis.

The normalized static load crack velocities (a'/a'_D) agreed well with the normalized cyclic power law coefficients for these materials (C/C_D), and both methods generally produced the same material performance rankings (Table 1). However, Material C registered a difference in the normalized power law coefficient between the two methods; C_C/C_D was slightly lower than C_B/C_D despite the overall higher crack velocity of Material C with respect to Material B (Fig. 3). The performance of Material A could not be compared because the static load experiment did not result in stable crack propagation.

After the first 1 mm of crack growth under static loading, the crack accelerated to failure in the irradiated material groups (Fig. 4). The failure time for the irradiated materials ranged from 2160 to 19,000 seconds (increasing

with decreasing radiation dose) (Table 1), while the unirradiated material did not fail after 2 weeks under load. Normalized failure times ($t_{f,D}/t_f$) (Table 1) were nearly identical to the normalized static load velocities and accordingly also corresponded well with the normalized cyclic crack propagation coefficients.

Discussion

Crack propagation in UHMWPE is dominated by noncyclic phenomena [7], although it is typical to quantify the crack propagation resistance of the material under cyclic loading conditions [3, 7, 8, 12]. We asked whether (1) cracks would

Fig. 3 Fatigue crack propagation data for 5-Hz sinusoidal loading are shown. Dashed lines indicate respective power law correlation fits (Eq. 3). The velocity at $K_{\max} = 1 \text{ MPa m}^{1/2}$ corresponds to the value of the coefficient power law fit C.

Fig. 2 Crack propagation rate increases with radiation dose and is approximately constant for the first 1 mm of growth for the irradiated materials. Apparent propagation decelerated continuously in the unirradiated material. The different symbols for each group denote individual specimen results.

Fig. 4 Crack propagation velocity increased after 1 mm of growth in the four irradiated groups, accelerating to failure. Failure time (t_f) for the materials ranged from 2160 to 19,000 seconds in a dose-dependent manner. The unirradiated specimen group did not fail.

initiate from acute notches and stably propagate under static loading with a velocity dependent on crosslinking radiation dose, (2) crack propagation under static loading would result in quantitatively similar material crack propagation resistance data to those obtained under cyclic loading conditions, and (3) specimen failure time under a static load would yield a similar evaluation of material crack propagation resistance as crack velocity under a static or cyclic applied load.

Our study is subject to certain limitations. First, only two to three specimens were tested under static loading conditions for each material, as these were all that were available after completing the cyclic loading experiments. Material property data for synthetic materials tend to be repeatable, and crack propagation results in engineering materials are often reported with a limited number of specimens and consequently without statistical evaluation. Thus, while our findings in this pilot study are encouraging, a future study with increased statistical power is warranted to more rigorously evaluate the efficacy of static loading crack propagation protocols. Second, the loss of remaining ligament was used to infer crack growth rate, as tracking the crack tip leads to substantial error, particularly early in a test where the crack tip typically moves in a retrograde manner toward the load line [16]. However, there is also some reduction in the ligament due to gross elastic and inelastic deformation of the specimen. The observed ligament loss in the unirradiated material under static loading may be due to creeping deformation in the absence of any production of new crack surface at the crack tip. No substantial creep contribution to ligament reduction was noted in the irradiated materials, which indicates true crack growth dominated confounding contributions from gross specimen deformation, except in the case of Material A, which appeared to only undergo gross specimen deformation.

Static loading applied to a clinically relevant acute notch in crosslinked UHMWPE resulted in stable crack propagation and ultimately fracture, as also occurs in experiments run under applied cyclic load waveforms. The resulting crack velocity rankings obtained under static loading were similar to those under sinusoidal loading for identical specimens from the same material batches. Normalized measures of crack velocity for static and cyclic loading (a'/a'_D and C/C_D , respectively) showed good agreement for Materials B and E (Table 1) (Material D was not evaluated as the baseline for normalization and Material A did not initiate a crack under static loading). Such a similarity between static and cyclic crack propagation velocities is expected due to the dominance of static mode crack growth mechanisms, which has been previously reported for UHMWPE [7, 11]. The result for Material C, however, appears to not fit this trend. The cause for the lack

of agreement seen for Material C is unclear and may be attributed to the relatively small number of samples ($n = 2-3$) used in the static load experiments and uncertainty from the power law fit to the cyclic loading experimental data.

The normalized time to failure ($t_{f,D}/t_f$) for all the formulations matched the static loading crack velocity results and, hence, the fatigue crack propagation results as well (Table 1). Such a close agreement between the relative time to failure and crack velocities implies time to failure under a static load could be a sufficient indicator for ranking the crack propagation resistance of various formulations of UHMWPE when crack initiation occurs rapidly. As mentioned, the static loading experiment was inspired by ASTM F1473, a testing standard that quantifies the time to failure for various grades of polyethylene for specified static load and notched specimen geometry [1]. Our results seem to support the use of failure time as a simplified crack propagation resistance assay for UHMWPE, where only the time to failure under a static applied load is recorded, since the failure time results are in direct correspondence with crack velocity when crack initiation is rapid. Such an approach would substantially reduce the complexity of quantifying the intrinsic resistance to crack propagation, which ordinarily requires dedicated servohydraulic load frames for cyclic loading, is labor intensive, and demands substantial technical expertise.

The static mode character of crack propagation in UHMWPE predicts crack propagation experiments under an applied constant tensile load will achieve similar results to those run under cyclic tensile loading conditions. While cyclic tensile crack propagation experiments have been widely adopted as a screening method for the introduction of new UHMWPE formulations into clinical use [3, 8, 12], with considerable technical merit, there has been little analysis of the intrinsic validity or quantitative utility of such data. Our data suggest static load crack growth experiments may be used in place of the typical sinusoidally loaded fatigue crack propagation experiments and also the time to failure under a static load may be a sufficient metric of the relative crack propagation resistance of a given set of UHMWPE materials. Furthermore, static loading conditions may probe the material in a more mechanistically appropriate manner than cyclic experiments; cyclic fatigue data might be falsely interpreted to imply static mode crack growth does not occur, and cyclic loading can result in testing artifacts such as hysteretic heating or error from poor waveform tracking. Therefore, we propose examining crack propagation velocity and failure time under a constant applied load is an appropriate approach for quantifying the relative fatigue performance of UHMWPE materials and in fact may be preferable to cyclic loading approaches.

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