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## Characterization of the fatigue threshold behavior of UHMWPE

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### ABSTRACT

Ultra-high-molecular-weight-polyethylene (UHMWPE) has been the material of choice for bearings in total joint replacements (TJRs) for decades as a result of its excellent wear resistance, chemical inertness, energetic toughness, low friction, and biocompatibility. Utilization of this polymer in orthopedic devices requires oxidation, wear, and fatigue resistance. Balancing these important properties by tailoring processing techniques and modulating microstructural features has been an ongoing endeavor in the field. Research into the clinical applications of UHMWPE has primarily focused on the challenges of wear and oxidation while studies into the realm of fatigue have been more limited. Literature gaps exist in fully understanding the fatigue crack initiation near notches or propagation of small existing flaws in UHMWPE used in TJRs. In particular, the characterization of the fatigue thresholds and near-threshold fatigue behavior of orthopedic grade UHMWPE has yet to be thoroughly explored. In this work, we characterized the fatigue crack arrest threshold of clinically-relevant UHMWPE formulations. Correlations between the fatigue thresholds and bulk mechanical properties as well as microstructural properties were examined across these medical resins. The important role played by cross-linking in influencing the fatigue performance of UHMWPE is highlighted in this study. In addition, it is established that J-integral fracture toughness is the best predictor of fatigue thresholds and could possibly be used as a stand-in metric for fatigue performance if thresholds cannot be directly ascertained. Finally, this study corroborates that the true constitutive parameters best describe the mechanical behavior of UHMWPE.

### 1. Introduction

Ultra-high-molecular-weight-polyethylene (UHMWPE) has been the material of choice for the bearing surface of total joint replacements (TJRs) since the 1960's (Charnley, 1973). The choice of UHMWPE arises from an array of unique bio-tribo-mechanical attributes including but not limited to abrasion and wear resistance, chemical inertness, energetic toughness, low friction, and biocompatibility (Kurtz, 2009). Despite its excellent bio-tribo-mechanical performance *in-vivo*, UHMWPE in total knee arthroplasty is subjected to high-amplitude cyclic contact stresses and must endure loading for 20–30 million cycles (Sobieraj and Rinnac, 2009). Such extensive biomechanical demands can culminate in the generation of sub-micron sized wear debris, leading to osteolysis, implant loosening, and eventually, failure of the TJR. In addition to the production of wear debris, catastrophic failure of the implant due to fast fracture from fatigue damage accumulation is also a

potential issue (Ansari et al., 2016a). In order to mitigate these potential failure modes, there is an ongoing effort to develop formulations of UHMWPE that resist the troika of challenges faced in the body – wear, fatigue, and oxidation (Ansari et al., 2016b; Atwood et al., 2011). Though no one specific formulation is ideal for every patient or failure modality, modern implants are typically made of moderately cross-linked UHMWPE which has been remelted with vitamin E additives, to protect it from oxidation while moderately balancing fatigue and wear properties (Bistolfi et al., 2021; Bracco and Oral, 2011). Understanding the interplay between these processing techniques, corresponding microstructures, and concomitant mechanical properties is an ongoing endeavor, even though the existing body of literature about UHMWPE for TJRs is quite extensive (Ansari et al., 2016a; Ansari et al., 2016b; Baker et al., 2000, 2003; Connelly et al., 1984; Furmanski and Pruitt, 2007; Gencur et al., 2006; Patten et al., 2011; Pruitt, 2005; Pruitt et al., 2022; Simis et al., 2005; Sirimamilla et al., 2013a; Sirimamilla and

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Rimnac, 2019). However, there are still literature gaps that exist in understanding the fatigue behavior around crack initiation near notches or propagation of small existing flaws in orthopedic grade UHMWPE used in modern implant designs. In particular, the characterization of the fatigue threshold and near-threshold crack growth behavior across multiple clinically-relevant formulations of UHMWPE has yet to be thoroughly explored.

In linear elastic fracture mechanics (LEFM), the fatigue threshold,  $\Delta K_{th}$ , as a concept, refers to the stress-intensity range below which cracks do not propagate under cyclic loading conditions (Davidson and Suresh, 1984; Ritchie, 1977; Schmidt and Paris, 1973). Determining the threshold experimentally requires careful methodology. The benefit of characterizing fatigue threshold or crack arrest threshold is the determination of a parameter that can be utilized in safety-critical design for orthopedic components known to have notches and elevated cyclic stresses.

In the field of fatigue of metals and alloys, the methods outlined in ASTM E647 (Standard Test Method for Measurement of Fatigue Crack Growth Rates, 2024) are commonly used to measure and determine  $\Delta K_{th}$ . ASTM E647 defines  $\Delta K_{th}$  as the asymptotic value of  $\Delta K$  on a  $da/dN$  vs.  $\Delta K$  log-log plot at which  $da/dN$  approaches vanishingly small rates. The standard further suggests using an operational definition of  $\Delta K_{th}$  as the  $\Delta K$  at which  $da/dN = 10^{-7}$  mm/cycle. To experimentally determine this ASTM-defined  $\Delta K_{th}$ , a load-shedding approach is utilized. This is accomplished by cyclically loading a sample, starting at a  $\Delta K$  value above  $\Delta K_{th}$  - somewhere near the start of the Paris regime as determined from literature - and then decreasing the load in a controlled manner to mitigate fluctuations in stress-intensity factor and concomitant anomalous fluctuations in  $da/dN$  (Saxena et al., 1978).

Fatigue characterization of polymers is generally more complicated than that of conventional metals or alloys. Polymers are viscoelastic and susceptible to hysteretic heating, typically limiting the test frequencies to 5 Hz or less. Specimen geometries can complicate the matter as overly thick specimens can result in internal heating that can alter the microstructure and fatigue behavior (Ansari et al., 2016a; Hertzberg et al., 1978; Pruitt et al., 2022). Much of the UHMWPE fatigue data reported in the literature provides only Paris regime behavior at 5 Hz or less in thermally controlled environments. There remains a paucity of data or literature that focuses on classical fatigue threshold values for UHMWPE. Instead, the orthopedic community has utilized a much less conservative parameter, coined  $\Delta K_{Inception}$  (Baker et al., 2000, 2003; Gencur et al., 2006). This metric is derived empirically from the onset of the Paris regime and is defined as the  $\Delta K$  at which  $da/dN = 10^{-6}$  mm/cycle (Baker et al., 2000, 2003; Pruitt, 2005). One key difference between  $\Delta K_{th}$  as defined previously and  $\Delta K_{Inception}$  is the loading regimen used to find these parameters.  $\Delta K_{Inception}$  is found using only constant or increasing loads, resulting in an increasing  $\Delta K$  due to crack growth throughout the test, limiting the scope of the metric. A more recent study that investigated fatigue crack initiation in UHMWPE (Sirimamilla and Rimnac, 2019) reported the number of cycles to failure for various waveforms and a maximum load of 800 N instead of  $\Delta K_{Inception}$  or  $\Delta K_{th}$ . Our research endeavor intends to expand these concepts by determining  $\Delta K_{th}$  as defined by ASTM E647 for seven different clinically-relevant formulations of UHMWPE. To the authors' knowledge, this is the first study to characterize the fatigue threshold behavior of UHMWPE.

It is essential to enumerate why studying fatigue thresholds and near-threshold crack growth rates is paramount for the orthopedic applications of UHMWPE. All TJRs inherently have stress concentrations or notches built into their locking mechanisms and clinical functionality of the device (Ansari et al., 2016b; Ansari et al., 2016a; Kurtz, 2009; Sirimamilla and Rimnac, 2019). These regions of heightened stress states are prone to crack initiation and crack growth (Furmanski et al., 2009b; Furmanski and Pruitt, 2018; Pruitt and Furmanski, 2009). The majority of a crack's lifetime is spent in initiation rather than in propagation in UHMWPE because the material is fundamentally fatigue-brittle (Barsom

and Rolfe, 1999; Davidson and Suresh, 1984; Furmanski and Pruitt, 2007; Pruitt, 2005). Understanding a crack's initiation behavior or stress state required for initial growth of an existing flaw is clinically important for TJRs, yet the predominant characterization of UHMWPE is based on Paris regime behavior. The Paris regime is important for understanding fatigue but only captures crack propagation behavior at the mid-range of growth rates, typically between  $\sim 10^{-5}$  to  $10^{-2}$  mm/cycle (Barsom and Rolfe, 1999; Hertzberg et al., 2012; Kurtz, 2009; Pruitt et al., 2022). Fatigue thresholds, conversely, are a more relevant fatigue parameter for designing against catastrophic failures and in safety-critical applications, such as TJRs.

The fatigue threshold is pertinent as it reveals the minimum stress-intensity range at which a flaw will commence propagation before it traverses through the Paris regime and culminates in fast fracture. However, little is known regarding the UHMWPE threshold even though other aspects of its fatigue properties are well-researched. Fatigue threshold values have never been measured directly for the UHMWPE resins utilized in TJRs. One reason for the paucity of this data may be the time investment needed for the load-shedding methodology (Nibur and Somerdar, 2025).

The purpose of this study is to determine the crack arrest threshold and fatigue crack propagation behavior across seven clinically-relevant formulations of UHMWPE. This study also examines the relationships between fatigue threshold and known mechanical and microstructural properties for these clinically-relevant formulations. To the authors' knowledge, this is the first study to characterize the fatigue threshold of UHMWPE and to use the load-shedding method to accomplish that.

## 2. Materials and methods

Seven different clinically-relevant formulations of UHMWPE were analyzed in this study (comprehensively tabulated in Table 1). Specifically, two medical grade resins, GUR 1020 and GUR 1050, with varying amounts of vitamin E (VE) and crosslinking were examined. All resins were manufactured following industry specifications. The 1050 75 kGy resin was ram extruded and the balance of the resins were compression molded. For the VE samples, the antioxidant was blended into the GUR 1020 base resin before consolidation at 0.1 wt%. Two levels of crosslinking in 1020 (0 kGy and 35 kGy), three levels of crosslinking in 1020 VE (0 kGy, 100 kGy, and 125 kGy), and two levels of crosslinking in 1050 (0 kGy and 75 kGy) were included in the scope of this investigation. All sample groups were sourced from Orthoplastics (Lancashire, UK) except 1050 75 kGy which was sourced from Quadrant EPP (Fort Wayne, IN). At least 3 samples for each group were analyzed for statistical relevance. These clinically-relevant UHMWPE formulations were sourced from the same base materials used in our previously published studies investigating microstructure as well as bulk mechanical properties and fracture toughness (Malito et al., 2018, 2019). A summary of relevant properties is provided in Table 1.

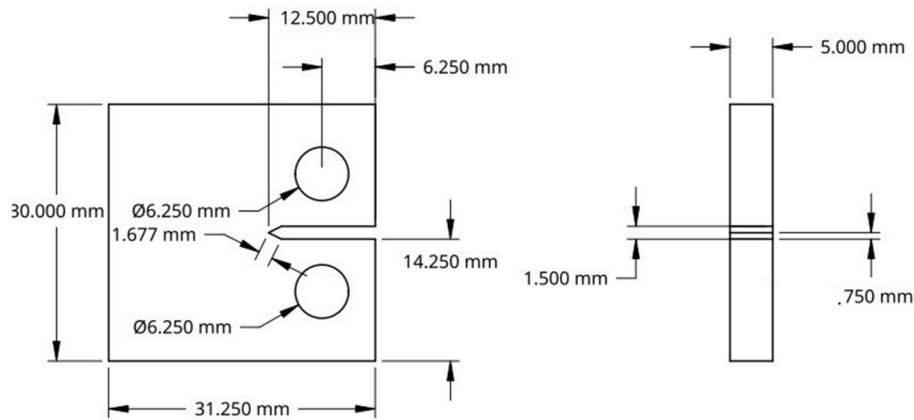
Compact tension (C(T)) specimens were machined from stock materials with dimensions adhering to ASTM E647 (Standard Test Method for Measurement of Fatigue Crack Growth Rates, 2024). It is important to state here that while ASTM E647 prescribes a set of dimensions and dimensional ratios and proportions for the specimens used for fatigue testing, the standard was originally developed for ductile metals and alloys. An upgrade to the ASTM E647 standard is needed for full relevance to the fatigue testing of polymeric materials.

C(T) samples had a width ( $W$ ) of 25 mm, a thickness ( $B$ ) of 5 mm, and a length ( $L$ ) of 31.8 mm (Fig. 1). To ensure a sharp notch, pre-cracking was performed with a clean razor blade to achieve an initial crack length ( $a_0$ ) of 7–8 mm.

Tension-tension loading-based fatigue tests were conducted on an electro-servo-hydraulic MTS Elastomer Test System Model 831 machine (Eden Prairie, MN). Crack propagation rates ( $da/dN$ ) were measured using the aforementioned compact tension specimens. Crack measurements were taken by pausing the load cycle at the midpoint load and

**Table 1**  
Properties of the UHMWPE resins utilized in this study (Malito et al., 2018, 2019).

Sample Group Name	Amount of Crosslinking radiation (kGy)	wt.% VE (%)	Percent Crystallinity (%)	Lamellar Thickness (nm)	Elastic Modulus $E$ (MPa)	Ultimate True Tensile Strength $\sigma_{UTS \text{ true}}$ (MPa)	J-integral Fracture Toughness $J_{Ic \text{ true}}$ (kJ/m <sup>2</sup> )	Plane-strain Mode I Fracture Toughness $K_{JIC}$ (MPa $\sqrt{m}$ )
1020	0	0	57.7	26.3	799.5 ± 26.2	188.2 ± 17	40.6	6.41
1020 35 kGy	35	0	57.8	26.1	758 ± 39.4	184.3 ± 16.1	N/A	N/A
1020 VE	0	0.1	60.0	29.3	921.2 ± 13.6	229.1 ± 9.7	32.5	7.07
1020 VE 100 kGy	100	0.1	60.7	27.0	1008.5 ± 36.6	146.4 ± 13.6	19.7	5.03
1020 VE 125 kGy	125	0.1	60.8	28.1	865.4 ± 56.3	158.8 ± 9.7	19.5	4.63
1050	0	0	55.8	28.0	810.6 ± 26.2	202.8 ± 29.9	36.1	6.42
1050 75 kGy	75	0	55.8	27.7	762.3 ± 32.0	127.9 ± 12.8	20.2	4.60



**Fig. 1.** Dimensions of the C(T) sample used for this study, inspired by ASTM E647 (Standard Test Method for Measurement of Fatigue Crack Growth Rates, 2024).

measuring the crack length using an Olympus micromechanical stage (Tokyo, Japan) and a corresponding image from a microscope (with a resolution of 0.1  $\mu\text{m}$ ). Crack propagation rates ( $da/dN$ ) were then calculated using a secant method outlined in ASTM E647 and reported in units of mm/cycle. The stress-intensity range ( $\Delta K$ ) was calculated using the standard long crack in C(T) specimens, as formulated in the ASTM E647 standard:

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} f(\alpha), \quad (1)$$

where  $\Delta P$  is the maximum applied load minus the minimum applied load,  $B$  is the sample thickness,  $W$  is the sample width,  $a$  is the crack length, and  $\alpha = \frac{a}{W}$  is the ratio of crack length to width.  $f(\alpha)$  is formulated as follows:

$$f(\alpha) = \frac{(2 + \alpha)}{(1 - \alpha)^{1.5}} (0.866 - 4.64\alpha - 13.32\alpha^2 - 14.72\alpha^3 - 5.6\alpha^4) \quad (2)$$

Fatigue crack propagation tests were performed to determine the fatigue thresholds for the aforementioned UHMWPE formulations using  $\Delta K$  decreasing tests, while the subsequent near-threshold growth rates and higher growth rates were determined under increasing  $\Delta K$  tests (Barsom and Rolfe, 1999; Hertzberg et al., 2012). The  $\Delta K$  increasing tests were load-controlled with a frequency of 5 Hz and a sinusoidal waveform. All tests were performed at room temperature with a fan system to avoid hysteretic heating (Sobieraj and Rimnac, 2009). A load ratio of  $R = 0.1$  (ratio of minimum to maximum load) was maintained

throughout testing, and the load applied was increased when necessary, to ensure  $\Delta K$  concomitantly increased.

For the  $\Delta K$  decreasing tests, a stepped force-shedding approach was utilized (Saxena et al., 1978; Standard Test Method for Measurement of Fatigue Crack Growth Rates, 2024). The initial load began well above the implied stress-intensity range for crack arrest from the  $\Delta K$  increasing tests and was then decreased at a rate consistent with ASTM E647 in order to limit abnormal data from reductions in stress-intensity factor. To do this, the normalized  $K$ -gradient  $C'$  was kept above  $-0.08 \text{ mm}^{-1}$  according to:

$$C' = \frac{1}{K} \left( \frac{dK}{da} \right) > -0.08 \text{ mm}^{-1} \quad (3)$$

Practically, this means that each  $\Delta K$  after the initial  $\Delta K_0$  was determined by the following exponential decay equation:

$$\Delta K_n = \Delta K_0 \exp[C'(a_{n-1} - a_0)] \quad (4)$$

Here,  $\Delta K_0$  is the initial  $\Delta K$  selected to be far above the threshold,  $a_0$  is the initial crack length,  $a_{n-1}$  is the crack length measured, the normalized  $K$ -gradient  $C' = -0.08$ , and  $n$  is an index beginning at 2 (2,3,4, etc.). Each  $\Delta K$  was calculated using the crack length preceding it, so the first two data points in each test were excluded. The crack arrest threshold ( $\Delta K_{th}$ ) was defined as the  $\Delta K$  at which the growth rate,  $da/dN$ , was less than  $10^{-7}$  mm/cycle for at least 3 steps down the force-shedding regimen. After reaching the threshold, the sample would then be subject to the  $\Delta K$  increasing test to ensure the  $da/dN$  rates matched both

going up and down for a given  $\Delta K$ . Consequently,  $da/dN$  vs.  $\Delta K$  was traced on a log-log plot.

After experimentally ascertaining the  $da/dN$  and calculating the  $\Delta K$  values, the Paris regime constants  $C$  and  $m$  were calculated in the range of  $da/dN$  from  $10^{-6}$  to  $10^{-5}$  as outlined in ASTM E647. By fitting a line using the least squares method to the log-log plot of  $da/dN$  vs.  $\Delta K$ , one can determine the values of  $C$  and  $m$  using the following equation:

$$\log\left(\frac{da}{dN}\right) = m\log(\Delta K) + \log(C). \tag{5}$$

In addition, relationships between the threshold ( $\Delta K_{th}$ ),  $J$ -integral fracture toughness ( $J_{Ic \text{ true}}$ ), plane-strain mode I fracture toughness ( $K_{JIC}$ ), elastic modulus ( $E$ ), and ultimate true tensile strength ( $\sigma_{UTS \text{ true}}$ ), as well as percent crystallinity and lamellar thickness were analyzed using a non-parametric Spearman rank correlation coefficient (Atwood et al., 2011; Malito et al., 2018). Spearman rank correlation is an appropriate test to run because we expect monotonic relationships between the variables explored in this study. Average values were used for the correlations.  $J_{Ic \text{ true}}$ ,  $K_{JIC}$  as well as the bulk mechanical and microstructural properties for the specific material groups in this work were experimentally measured in previous studies published from our lab (Malito et al., 2018, 2019).

### 3. Results

The  $da/dN$  vs.  $\Delta K$  curves for the seven clinical formulations of UHMWPE are comprehensively compiled and illustrated in Fig. 2. On this logarithmic plot of crack propagation rate (mm/cycle) as a function of stress-intensity range (MPa $\sqrt{m}$ ), we illustrate both near-threshold and Paris regime fatigue resistance of the UHMWPE resins spanning a range of crosslinking and antioxidant dosages. Two distinct groups emerge in Fig. 2 based on the amounts of crosslinking. The sample groups with little or no crosslinking (1020, 1020 VE, 1020 35 kGy, and 1050) are more fatigue resistant as their curves lie further to the right of the overall plot, indicating that it requires more crack driving force to advance the flaw at the same crack growth rate. The  $da/dN$  vs.  $\Delta K$  curves also overlap significantly, indicating that the resins without substantial crosslinking exhibit comparable fatigue performance. The sample groups with less resistance to fatigue are the resins with moderate to high degree of crosslinking (1050 75 kGy, 1020 VE 100 kGy, and 1020 VE 125 kGy) and their curves are located further to the left of the  $da/dN$  vs.  $\Delta K$  plot. Their curves overlap significantly as well, demonstrating similar fatigue performance for resins with crosslinking dosages ranging from 75 to 125 kGy. Further analysis of these plots indicates that the highly crosslinked materials have lower crack arrest thresholds and reduced fatigue crack propagation resistance than do formulations with

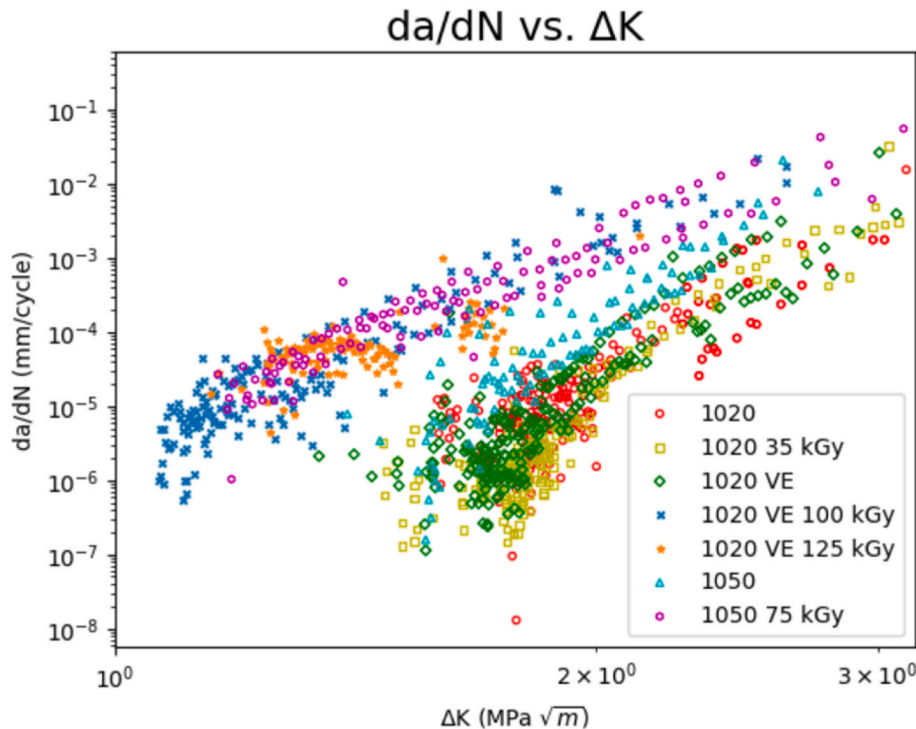


Fig. 2. Crack propagation rate ( $da/dN$ ) as a function of stress-intensity range ( $\Delta K$ ) plots for the clinical formulations of UHMWPE tested in this study.

**Table 2**  
Paris regime constants ( $C$ ,  $m$ ) and fatigue thresholds ( $\Delta K_{th}$ ) for the clinical formulations of UHMWPE tested in this study.

UHMWPE Group	Paris regime constants		$\Delta K_{th}$ (MPa $\sqrt{m}$ )
	Exponent ( $m$ )	Coefficient ( $C$ ) ( $\frac{mm}{cycle}/(MPa \sqrt{m})^m$ )	
1020	11.77	$5.5 \times 10^{-9}$	$1.76 \pm 0.16$
1020 35 kGy	14.63	$3.9 \times 10^{-10}$	$1.66 \pm 0.15$
1020 VE	13.55	$1.7 \times 10^{-9}$	$1.61 \pm 0.05$
1020 VE 100 kGy	9.84	$1.8 \times 10^{-6}$	$1.15 \pm 0.12$
1020 VE 125 kGy	4.82	$1.1 \times 10^{-5}$	$1.17 \pm 0.07$
1050	13.74	$8.8 \times 10^{-9}$	$1.58 \pm 0.04$
1050 75 kGy	6.75	$8.6 \times 10^{-6}$	$1.22 \pm 0.13$

little to no crosslinking.

The average crack arrest fatigue thresholds ( $\Delta K_{th}$ ) and the Paris regime constants (coefficient and exponent) are reported in Table 2. Similar to the trends seen in Fig. 2, the less crosslinked samples have coefficients that group together on the order of  $10^{-9}$  and  $10^{-10}$  and the samples with significant crosslinking have coefficients that group together around values ranging from  $10^{-6}$  to  $10^{-5}$ . The fatigue thresholds also group together based on the amount of crosslinking, *i.e.*, the crosslinked sample groups have lower fatigue thresholds. Both sets of results reported in Table 2 indicate that crosslinking is detrimental to fatigue performance in the UHMWPE groups tested.

Table 3 displays the Spearman rank correlation coefficients with their respective p-values between crack arrest threshold ( $\Delta K_{th}$ ) and mechanical properties as well as crystallinity and lamellar thickness. Our findings indicate that there are no statistically significant correlations between  $\Delta K_{th}$  and the microstructural properties of the UHMWPE formulations. However, the findings show a statistically significant ( $p < 0.05$ ) correlation coefficient between  $\Delta K_{th}$  and  $J$ -integral fracture toughness ( $J_{IC \text{ true}}$ ). If  $p < 0.1$  is considered to be statistically significant, then correlations also exist between  $\Delta K_{th}$  and ultimate true tensile strength ( $\sigma_{UTS \text{ true}}$ ) and plane-strain mode I fracture toughness ( $K_{JIC}$ ).

#### 4. Discussion

This study offers a number of technical findings, some of which follow the well-established and classical understanding of UHMWPE fatigue behavior while others differ from the “norms” of the field. This work is the first to report experimental  $\Delta K_{th}$  values and to examine correlations across a volley of microstructural and mechanical properties. In terms of expected results, our fitted values for  $C$  and  $m$  in the Paris regime are consistent with those reported previously for similar formulations of UHMWPE in the literature (Baker et al., 2003; Furmanski and Rinnac, 2011; Gencur et al., 2006). Though the fatigue thresholds were not examined in prior studies, it is reassuring to note that the Paris regime behavior results are in consonance across the literature.

Another encouraging result is that crosslinking is the defining factor that influences the fatigue performance of the formulations considered in this study. Four of the seven sample groups (*viz.* 1020, 1020 VE, 1020 35 kGy, and 1050) have  $\Delta K_{th}$  values that are statistically the same, *i.e.*, fall within the standard error margin of each other. The sample groups that have significantly different  $\Delta K_{th}$  from these (namely, 1050 75 kGy, 1020 VE 100 kGy, and 1020 VE 125 kGy) have undergone higher doses of crosslinking. Similar trends in  $C$  and  $m$  values are observed as well, with the former UHMWPE groups with little-to-no crosslinking having similar orders of magnitude for  $C$  ( $10^{-10}$  to  $10^{-9}$ ) *vis-a-vis*  $C$  values between  $10^{-6}$  to  $10^{-5}$  for the highly crosslinked groups (Furmanski and Rinnac, 2011). These also exhibited higher  $m$  values than the latter groups as was observed in another study (Baker et al., 2003). Crosslinking significantly reduces fatigue crack propagation resistance which is congruous with the trends reported in the literature (Ansari et al., 2016b; Atwood et al., 2011; Baker et al., 2003; Cole et al., 2002; Gencur et al., 2006; Medel et al., 2007; Sobieraj and Rinnac, 2009). Conclusively, crosslinking, which is typically undertaken to improve the wear resistance of UHMWPE in orthopedic medical devices, comes at the

expense of its fatigue resistance.

Interestingly, no correlation was found to exist between elastic modulus ( $E$ ) and  $\Delta K_{th}$ , even though  $E$  has been successfully related to fatigue crack propagation in the past (Hertzberg et al., 1970, 1978). Specifically, in ductile materials where a fatigue crack propagates by crack-tip blunting followed by resharpening over the loading cycle, a high elastic modulus tends to reduce the crack-opening displacement which should then lower the crack extension each cycle. Since different deformation mechanisms govern fatigue crack propagation *vs.* fatigue crack initiation/arrest, it is possible that parameters correlating with one have little to no correlation with the other, thus explaining why  $E$  did not correlate with  $\Delta K_{th}$  in the present study. Previous work has shown that fatigue crack growth in UHMWPE follows a fatigue-brittle mechanism and as such more tightly correlates with fracture toughness rather than modulus (Furmanski et al., 2009a; Pruitt and Furmanski, 2009).

On a similar note, there was also no correlation between  $\Delta K_{th}$  and percent crystallinity. Previous studies have shown that higher crystallinity should result in higher resistance for both fatigue crack initiation and propagation due to crystalline regions impeding crack growth by means of crack deflection (Ansari et al., 2016a; Atwood et al., 2011; Baker et al., 2003; Niinomi et al., 2001; Oral et al., 2006). This trend was not observed in the present study. The percent crystallinity values for all seven sample groups in our study were only marginally different, ranging from 55.8 % to 60.8 %. This narrow range of crystallinities is likely insufficient to directly influence the fatigue properties.

The most important result derived from this study is that  $J$ -integral fracture toughness ( $J_{IC \text{ true}}$ ) is the best predictor of  $\Delta K_{th}$  and could possibly be used as a stand-in metric for fatigue crack arrest/initiation if  $\Delta K_{th}$  cannot be ascertained for the groups of UHMWPE examined in this study. This is in agreement with findings from another study where  $\Delta K_{Inception}$  was found to correlate with  $J_{IC \text{ true}}$  (Furmanski and Pruitt, 2007, 2018; Sirimamilla et al., 2013a).  $\Delta K_{th}$  correlates with  $J_{IC \text{ true}}$  possibly due to plastic deformation being the prevailing mechanism in both cases. Other relevant predictors of  $\Delta K_{th}$  are ultimate true tensile strength ( $\sigma_{UTS \text{ true}}$ ) and the plane-strain mode I fracture toughness ( $K_{JIC}$ ), though  $J$ -integral remains the most significant with a p-value less than 0.05. Recently, arguments have been made to use true stress instead of engineering stress when analyzing the behavior of UHMWPE (Malito et al., 2019), and our results strongly support this argument of using true constitutive behavior. These findings also support the idea that UHMWPE fatigue behavior is best modelled by the viscoelastic fracture theory (Williams, 1977), an idea which is gradually gaining traction in the UHMWPE community (Furmanski and Pruitt, 2018; Sirimamilla et al., 2013b).

It is noteworthy to mention here that UHMWPE is a viscoplastic polymer and consequently, all of the results reported herein are influenced by a multitude of factors including but not limited to the frequency, waveform, and temperature. Our findings in this article are thus limited to 5 Hz, sinusoidal waveform, and room temperature, and capture the results within the snapshot of the experimental conditions under which these samples were tested. Further, the result correlating  $\Delta K_{th}$  with  $J_{IC \text{ true}}$  is stated only in the context of the UHMWPE resins tested in this study and should not be generalized to all polyethylenes nor to all polymers.

**Table 3**

Spearman rank correlation coefficients between crack arrest thresholds and microstructural as well as mechanical properties (Malito et al., 2018, 2019).

Crack Arrest Threshold p-value significance	Percent Crystallinity (%)	Lamellar Thickness (nm)	Elastic Modulus $E$ (MPa)	True Ultimate Tensile Strength $\sigma_{UTS \text{ true}}$ (MPa)	$J$ -integral Fracture Toughness $J_{IC \text{ true}}$ (kJ/m <sup>2</sup> )	Plane-strain Mode I Fracture Toughness $K_{JIC}$ (MPa $\sqrt{m}$ )
$\Delta K_{th}$ (MPa $\sqrt{m}$ )	-0.198	-0.0714	0.00	0.714	0.829	0.771
p-value	0.67	0.89	0.88	0.052	0.042	0.072
Significant ( $p < 0.05$ , $p < 0.1$ )	No	No	No	Yes, $p < 0.1$	Yes, $p < 0.05$	Yes, $p < 0.1$

## 5. Conclusions

In summary, this is the first study to fully characterize the fatigue crack (arrest) threshold behavior and to correlate measured  $\Delta K_{th}$  values to bulk mechanical and microstructural properties across a wide range of clinically-relevant UHMWPE formulations. Paris regime parameters for the mid-range of growth rates ( $\sim 10^{-5}$  to  $10^{-2}$  mm/cycle) were also experimentally determined and were found to be consistent with the literature. There are two major takeaways from our findings. First, crosslinking, which is typically undertaken to improve the wear resistance of UHMWPE for use in total joint replacements, comes at the expense of fatigue resistance. Our study demonstrates that increased crosslinking decreases the fatigue threshold and reduces fatigue crack propagation resistance in UHMWPE. Secondly, the best predictor of fatigue performance for the UHMWPE resins tested in this study is the  $J$ -integral fracture toughness with a Spearman correlation coefficient of 0.829. Other less statistically significant but still relevant predictors of fatigue threshold include the ultimate true tensile strength (Spearman correlation coefficient of 0.714) and plane-strain mode I fracture toughness (Spearman correlation coefficient of 0.771). While the fatigue threshold,  $J$ -integral fracture toughness, ultimate true tensile strength, and plane-strain mode I fracture toughness are experimentally more challenging to determine than many engineering parameters, the authors contend that it is worth characterizing the true behavior of UHMWPE to make better design decisions in the orthopedic medical device realm and support the idea that true constitutive behavior is ultimately the best descriptor for UHMWPE.

## CRedit authorship contribution statement

**Bethany B. Smith:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anurag Roy:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Robert O. Ritchie:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition. **Lisa A. Pruitt:** Writing – review & editing, Supervision, Software, Resources, Project administration, Funding acquisition, Conceptualization.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

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