PII: S0032-3861(97)00448-5

Polymer Vol. 39 Nos. 8–9, pp. 1545–1553, 1998
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0032-3861/97/$17.00+0.00

Factors affecting near-threshold fatigue crack propagation behavior of orthopedic grade ultra high molecular weight polyethylene

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(Received 18 October 1996; revised 9 May 1997)

It is shown in this work that the manufacturing process, sterilization and aging environment play a critical role on the fatigue threshold and crack propagation rates in medical grade ultra high molecular weight polyethylene (UHMWPE). Two current manufacturing methods were evaluated for each material sample: compression molding and ram extrusion. The role of notch orientation relative to the extrusion direction was investigated in order to elucidate the effect of polymer microstructure on the fatigue fracture behavior of UHMWPE. In order to understand the role of post-sterilization aging, fatigue specimens were sterilized by γ-radiation and aged in an air to simulate shelf aging or in a hydrogen peroxide to mimic a highly oxidative environment. Non-sterile material was used as a control for all studies. Understanding the factors which affect the threshold and fatigue crack propagation behavior of UHMWPE is crucial for the structural integrity of total joint replacements as polymer debris related to cyclic loading of the polyethylene inserts currently limits the life of orthopedic implants. It is found in this work that microstructure and orientation significantly affect the near threshold regime of UHMWPE. Compression molded and extruded polyethylene with notches oriented perpendicular to the extrusion axis offer the greatest resistance to fatigue crack propagation. Further, it is shown that γ-radiation and oxidative aging are highly detrimental to fatigue threshold and crack propagation resistance. The findings from this study have important implications for the fatigue behavior of orthopedic grade UHMWPE as well as other semicrystalline polymers. © 1997 Elsevier Science Ltd. All rights reserved.

(Keywords: fatigue threshold; UHMWPE; sterilization)

INTRODUCTION

The inherent biocompatibility and structural integrity of advanced medical grade polymers have resulted in their widespread utilization in the synthetic biomaterials industry. Many of these applications require not only chemical inertness but also long term mechanical performance. In this respect, surgical grade polyethylenes owing to their high toughness and durability have shown the best mechanical performance in load bearing bio-implantible applications ranging from artificial tendons[1] to the articulating surface of total joint replacements[2]. As with any engineering material used in load-bearing applications, it is imperative to have a fundamental understanding of the material's resistance to cyclic fracture, as fatigue conditions invariably occur in these components owing to repeated loading and unloading. Further, it is likely that these materials contain initial defects or flaws which can propagate under low stress amplitudes over the duration of many load cycles. Hence, understanding the near-threshold fatigue crack propagation is paramount for designing against fatigue failures in these polymers.

While there is a plethora of literature available on the factors affecting near-threshold behavior of engineering alloys, there is little information of near-threshold fatigue behavior of engineering polymers. The fatigue threshold, ΔK_{th}, is defined as the minimum stress intensity range necessary for inception of crack propagation and deals primarily with non-continuum failure processes, where an increment of crack extension is less than 10^{-6} mm/cycle. Studies on fatigue threshold behavior in engineering metals have shown that the fatigue threshold is highly sensitive to microstructural factors and slip characteristics of these alloys[3–6]. While the dislocation models developed for near-threshold fatigue behavior of engineering alloys are not directly applicable to engineering plastics, it is likely that semicrystalline polymers, such as polyethylene, will deform through slip or similar mechanisms and that their near-threshold fatigue behavior will be strongly affected by microstructural factors such as structure and orientation of the crystalline lamellae[7]. Thus, it is expected that any process which alters the microstructure of a given polymer resin will affect its near-threshold fatigue behavior.

An example of the importance of fatigue threshold and defect tolerant design is found in total joint arthroplasty where sterile medical grade ultra high molecular weight polyethylene (UHMWPE) is used as the articulating surface against highly polished alloys. Specifically, the polymer inserts used in tibial components are routinely subjected to cyclic loading with maximum principal stresses ranging from 10 MPa of tension to 40 MPa of compression as the contact area sweeps across the surface during flexion[8]. Further, it is estimated that a million or more stress variations will occur yearly in the routine physical activities of a patient. Designing against fatigue crack inception in this material is of utmost importance as the propagation of

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fatigue cracks in UHMWPE under fatigue loading plays an important role in wear damage and ultimately limits the life of these orthopedic components. In this paper, the factors most likely to affect morphology and structure and hence the near-threshold fatigue behavior for a given starting resin of medical grade ultra high molecular weight polyethylene are investigated: manufacturing method and resulting orientation preference of crystalline lamellae, sterilization process, and aging environment.

For this study, we have chosen the two most common manufacturing methods for orthopedic grade ultra high molecular weight polyethylene: compression molding and ram extrusion[2]. Another variable expected to affect the polymer structure and fatigue behavior of the medical grade polymer is the sterilization treatment employed before surgery. A widely used method used in the orthopedics industry is γ-radiation[2]. This is typically accomplished with 25 kGy of ^{60}Co γ-radiation in an inert environment such as nitrogen. However, it is known that γ-radiation introduces free radicals into polyolefins and these highly reactive free radicals can in turn lead to cross-linking and chain scission of the polymer[9,10]. Over time, as long chains are broken through chain scission mechanisms, the resultant shorter chains are able to pack together more easily, leading to a lower molecular weight material with a higher crystallinity and density[11]. This evolution is further complicated by oxidative degradation, which can stiffen the molecular chains and lead to embrittlement of the polymer[12]. Studies have indicated that oxygen uptake in UHMWPE increases upon irradiation and continues to do so as the material ages[10-13]. For this reason we compare post-sterilization aging in air with a highly oxidative peroxide environment as the structural changes are expected to play a critical role on the fatigue threshold of UHMWPE.

Table 1 Monotonic properties of GUR 415

Property	Value
Molecular weight	> 3 million
Crystallinity	45%–50%
Density	0.931–0.935 g cm^{-3}
Ultimate tensile strength	42–44 MPa
Yield strength (0.2% offset)	20–23 MPa
Elastic modulus	1 GPa
Elongation at break	350%
Shore D hardness	67

It is shown in this work that the processing conditions, γ-sterilization and post-sterilization aging play a critical role in determining structural morphology of the polymer and its coincident fatigue threshold and fatigue crack propagation behavior.

EXPERIMENTAL METHODS

Materials

All material in this study was Hostalen GUR 415 (Hoechst Celanese, Houston, TX) surgical grade ultra high molecular weight polyethylene (UHMWPE). Some of the physical and monotonic mechanical properties for the GUR 415 UHMWPE are given in *Table 1*. The polyethylene was supplied in the form of unaged, non-sterile extruded rod and non-sterile compression-molded block. The stock compression molded block and extruded rod material were then machined into compact tension specimens (*Figure 1*) with the following geometry: length $L = 19.05$ mm; height $2H = 19.05$ mm; width from hole center to edge $W = 15.24$ mm; initial notch length $a_0 = 5.334$ mm; thickness $B = 4.75$ mm; notch angle $\theta = 60°$. For the extruded polymer, specimens were machined such that their notch plane was either perpendicular (90°) or parallel (0°) to the processing direction. The non-sterile compression molded specimens were machined in orthogonal planes of the block. In order to study the effect of γ-radiation, a set of the extruded (0°) specimens were sent out for 25 kGy of ^{60}Co γ-radiation in a nitrogen environment (RayChem Corp., Menlo Park, CA). The sterilized specimens were then divided into two aging environments: air to simulate shelf aging and a 3% hydrogen peroxide solution at body temperature (37°C) to

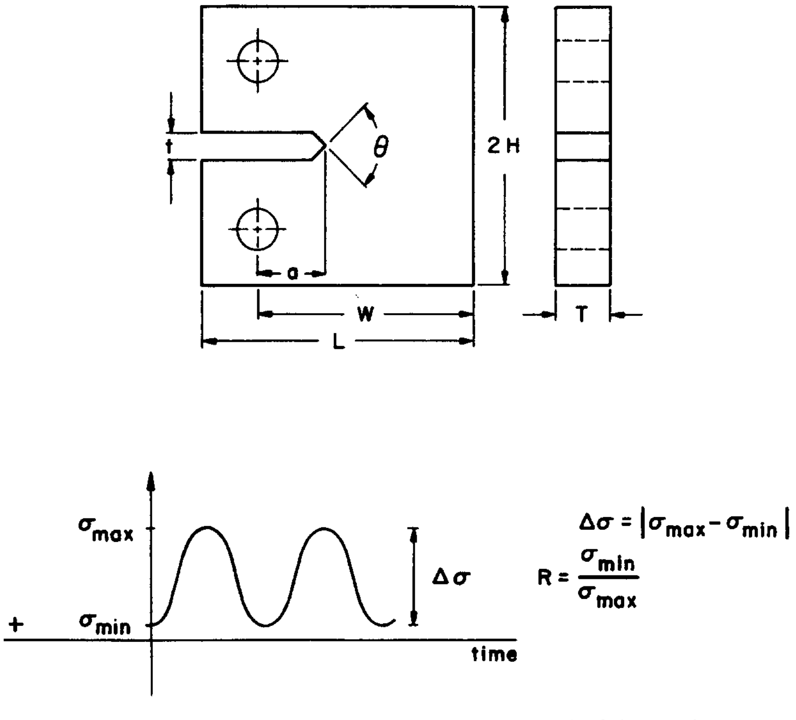

Figure 1 Schematic diagram of the compact tension specimen and definition of the stress ratio for fatigue testing

simulate a highly oxidative environment. The specimens were placed in these environments for 6 months in order to study the effect of oxidative aging. For comparison, γ-radiated compression molded UHMWPE inserts which had previously shelf aged for 5 years (donated by the Hospital for Special Surgery, New York) were machined into the same compact tension geometry and utilized to study the long term aging effects.

Fatigue testing

It is well known that the fatigue threshold can be measured through load shedding techniques where the far-field stress and hence the far-field stress intensity range is reduced incrementally until the crack ceases to propagate, but this technique can result in artificial retardation effects[14,15]. Recent researchers have proposed techniques which utilize self-arresting fatigue cracks which are introduced in notched specimens under fully compressive cyclic loading[15–19]. Cyclic compression loading relies on near-tip residual tensile stresses to introduce a stable mode I fatigue crack in the plane of the notch and has been used successfully in alloys[20], ceramics[21,22], polymers[18,19], and composites[23,24]. Subsequent to compression pre-cracking, the specimen is subjected to cyclic tensile loads at stress intensity factors below the anticipated threshold and the stress intensity range is incrementally increased until the threshold for the onset of fatigue crack propagation, ΔK_{th}, is attained.

For this study, compact tension specimens were first pre-cracked using cyclic compressive loads at an R-ratio, $R = 30$ (R is the ratio of the minimum stress to maximum stress of the fatigue cycle as defined in *Figure 1*) using the method described above. The specimens were loaded in compression platens using a far-field sinusoidal waveform of stress amplitude, $\Delta\sigma = -9.5$ MPa, corresponding to a maximum stress, $\sigma_{\max} = -0.327$ MPa, and a minimum stress, $\sigma_{\min} = -9.8$ MPa, for 50 000 compression fatigue cycles in order to ensure saturation of the crack[19]. Upon completion of pre-cracking, the compact tension specimens were subjected to tensile sinusoidal loading in the near-threshold regime, ΔK_{init} on the order of 1.0 MPa $\sqrt{\text{m}}$. The relation between the far-field loading and near-tip stress intensity is derived from fracture mechanics[25]:

$$\Delta K = \Delta P F(\alpha)/(B\sqrt{W}) \qquad (1)$$

where ΔP is the load amplitude of the fatigue cycle. $F(\alpha)$ is the geometric factor and α is defined as a/W. The geometric factor for the compact tension geometry is defined as follows[25]:

$$F(\alpha) = \frac{(2+\alpha)}{(1-\alpha)^{1.5}}(0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4) \qquad (2)$$

Once threshold is achieved, the test can be continued at constant far field stress amplitude to measure the Paris regime fatigue crack propagation rates where the stress intensity range is linearly related to the crack propagation rate on a logarithmic plot:

$$\mathrm{d}a/\mathrm{d}N = C\Delta K^{m} \qquad (3)$$

where C and m are material constants. Fatigue crack propagation tests were performed at a stress ratio $R = 0.1$, in ambient air conditions using a test frequency of 5 Hz to avoid hysteretic heating. Fatigue crack growth was monitored with a traveling microscope and an Olympus BH-2 optical microscope with a resolution of 0.2 μm. A modified secant formula was used to calculate the crack growth rate or slope at a given number of fatigue cycles.

Upon completion of the fatigue tests, the specimens were overloaded to fracture. The fracture surfaces were then sputter coated with Au–Pd to be examined by scanning electron microscopy (SEM). Further, transmission electron microscopy (TEM) specimens were prepared from the stock material to study any initial morphological differences due to compression molding or ram extrusion (details of TEM sample preparation are published elsewhere[11]). For the extruded morphology, the TEM samples were taken oriented parallel to the extrusion axis.

RESULTS

The effect of manufacturing on the near-threshold fatigue behavior

The effects of manufacturing and notch orientation have a pronounced effect on the fatigue crack growth behavior of UHMWPE. The relationship between the crack growth rate, da/dN, and the applied stress intensity range, ΔK, for the GUR 415 UHMWPE for the two manufacturing methods

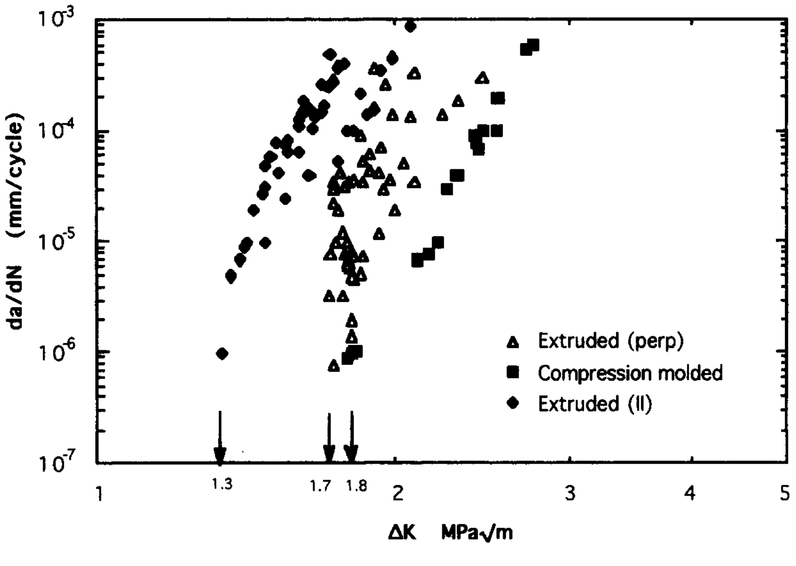

Figure 2 Plot of crack propagation rate as a function of the applied stress intensity range for compression molded and extruded GUR 415 UHMWPE demonstrating the effect of notch orientation

(compression molded and extruded for both notch orientations) is shown in *Figure 2*. The compression molded specimens did not show an orientation sensitivity and exhibited the greatest resistance to crack inception with a threshold value of 1.8 MPa$\sqrt{m}$. While in the extruded UHMWPE specimens, notch orientation had a pronounced effect. For the ram extruded UHMWPE with the crack propagating perpendicular to the extrusion direction, the threshold is 1.7 MPa$\sqrt{m}$ but this is reduced to 1.3 MPa$\sqrt{m}$ for the case where the crack propagates parallel to the extrusion direction. The effect of manufacturing process and notch orientation not only affected the threshold but also resulted in a shift of the linear crack growth regime. For the specimens with the crack propagating parallel to the extrusion direction, the stable crack growth regime spans from 1.3 MPa$\sqrt{m}$ to 1.9 MPa$\sqrt{m}$; for the perpendicular orientation the stable regime spans from 1.7 MPa$\sqrt{m}$ to 2.3 MPa$\sqrt{m}$; the compression molded polyethylene offers the best fatigue crack propagation resistance with a stable crack growth regime spanning 1.8 MPa$\sqrt{m}$ to 2.8 MPa$\sqrt{m}$ (as summarized in *Table 2*).

The effect of sterilization and aging on the near-threshold fatigue behavior

As discussed earlier, a critical concern for bio-implantible polymers is the effect of sterilization and post-sterilization aging on the structure and concomitant fatigue properties. For this set of experiments, all specimens were taken from the batch of 0° orientation extruded GUR 415 UHMWPE. Non-sterile specimens were used as a control and compared to γ-radiated specimens which have aged either in air or in a highly oxidative peroxide solution to accelerate oxidative degradation.

Table 2 Fatigue threshold and Paris regime for GUR 415

GUR 415	ΔK_{th} (threshold) (MPa$\sqrt{m}$)	Paris regime (MPa$\sqrt{m}$)
Compression molded	1.8	1.80–2.8
Compression molded γ-air	1.2	1.20–1.8
Extruded 90° orientation	1.7	1.70–2.3
Extruded 0° orientation	1.3	1.30–1.9
Extruded 0° γ-air	1.01	1.01–1.7
Extruded 0° γ-peroxide	1.12	1.12–1.3

Figure 3 is the logarithmic plot of the crack growth rate, da/dN, as a function of the applied stress intensity range, ΔK, for the γ-radiated specimens (with non-sterile plotted as a control). The γ-radiation had a detrimental effect on the fatigue behavior of UHMWPE. The fatigue threshold dropped from 1.3 MPa$\sqrt{m}$ for the non-sterile control to 1.01 MPa$\sqrt{m}$ for the γ-radiated specimens aged in air.

For the γ-radiated specimens aged in peroxide, the fatigue threshold was found to be slightly higher than the air-aged specimens with $\Delta K_{th} = 1.12$ MPa$\sqrt{m}$. The higher threshold associated with the oxidative peroxide environment is believed to be the result of surface microcracking, as shown in *Figure 4*. The microcracking at the crack tip initially shields the crack-tip from the full intensity of the far-field stresses, as is known to happen in microcracking ceramic systems[26], and results in an artificially high fatigue threshold. It should be noted, however, that the peroxide aging embrittled the polymer and resulted in a steep increase in the Paris regime slope and premature onset of fast fracture, as shown in *Figure 3* and summarized in *Table 2*.

Long term aging results are shown in *Figure 5* which plots the crack growth rate as a function of stress intensity for the non-sterile and γ-radiated, air aged compression molded UHMWPE. This plot shows the detrimental effect of post-sterilization aging on the near threshold and stable crack growth regime of the compression molded polyethylene. It should be noted from *Figure 5* that the γ-radiated material results in a drop of fatigue threshold from 1.8 MPa$\sqrt{m}$ to 1.2 MPa$\sqrt{m}$ and that the onset of fast fracture is reduced to 1.8 MPa$\sqrt{m}$ in comparison to 2.8 MPa$\sqrt{m}$ for the non-sterile material (as summarized in *Table 2*).

Scanning electron microscopy

Scanning electron microscopy of the compression molded and the ram extruded UHMWPE with the notch in the perpendicular orientation demonstrated the classic diamond-like criss-cross patterns documented for the ultra high molecular weight polyethylenes[27]. *Figure 6a–c* is a collection of scanning electron micrographs for the extruded polyethylene with the notch oriented perpendicular to the extrusion axis. *Figure 6a* is a low magnification image which depicts the whole fracture surface of the compact

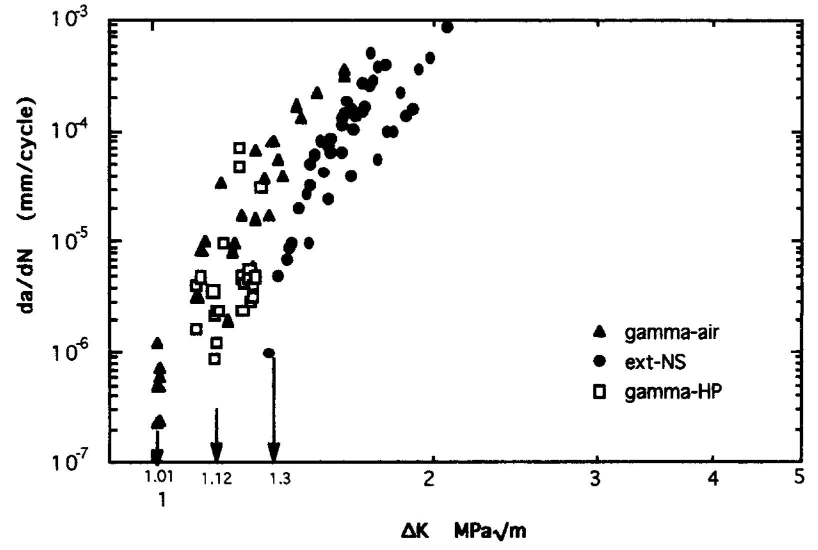

Figure 3 Plot of crack propagation rate as a function of the applied stress intensity range for γ-radiated air aged and peroxide aged extruded GUR 415 UHMWPE showing the effect of sterilization and aging. Non-sterile is plotted as a control

tension specimen and clearly exhibits the criss-cross pattern which lies in the plane of the crack (fatigue crack growth is right to left). A higher magnification image of these features reveals lineage which is perpendicular to the crack growth direction and whose spacing (about 5–7 μm on average) is independent of the stress intensity factor range. Another important feature is the buckling and shear associated with ductile failure mechanisms observed on these diamond crosses (*Figure 6c*). These characteristics are believed to be related to the breakdown of crystallites or lamellae–amorphous boundaries of the UHMWPE where disentanglement and drawing of the tie molecules can provide ductility and toughness to the polymer structure[28].

The ram extruded UHMWPE with the notch in the parallel orientation exhibits very limited features in fractography. *Figure 7a–c* is a collection of scanning electron micrographs for the extruded polyethylene with the notch oriented parallel to the extrusion axis. *Figure 7a* is a low magnification image of the fracture surface whose criss-cross features are sparse in comparison with the perpendicular and compression molded specimens. A higher magnification image of these features (*Figure 7b* and *c*) reveals lineage which is perpendicular to the crack growth direction and whose spacing is similar to the perpendicular orientation. There is very little buckling or remnants of fibril drawing found in the parallel orientation. However, the higher magnification fractography revealed a shear-like mechanism in the plane of the advancing crack front (*Figure 7c*).

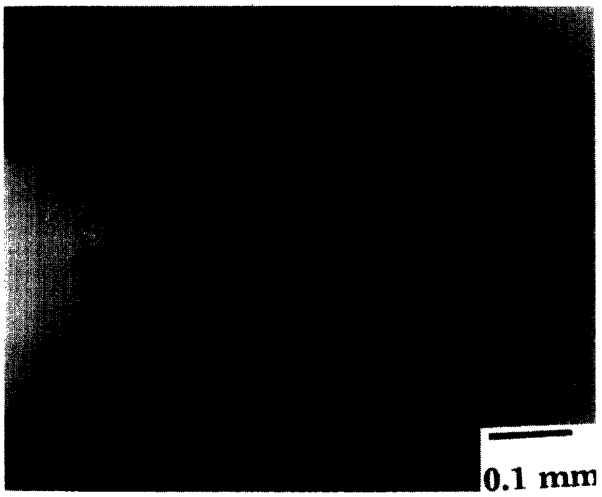

Figure 4 Optical micrograph of the near-tip microcracking observed for the oxidative peroxide aging of the UHMWPE

Gamma-radiation sterilization results in substantial changes to the fracture mechanisms and failure features. *Figure 8a–c* is a collection of scanning electron micrographs for the γ-radiated, air aged extruded polyethylene with the notch oriented parallel to the extrusion axis. *Figure 8a* is a low magnification image of the fracture surface; note the criss-cross features have been replaced with 'scallop' markings, which are more pronounced at higher magnifications (*Figure 8b* and *c*). The fractography reveals lineage which is predominantly perpendicular to the crack growth direction but additionally follows the contours of the 'scallop' markings (*Figure 8c*). Fractographic features for γ-radiated UHMWPE are consistent with previous work which characterized aged, γ-radiated UHMWPE[29,30].

Post sterilization aging in a peroxide environment resulted in further changes to the fracture mechanisms and failure features. *Figure 9a–c* is a collection of scanning electron micrographs for the γ-radiated, peroxide aged extruded polyethylene with the notch oriented parallel to the extrusion axis. *Figure 9a* is a low magnification image of the fracture surface where the scallop markings are more pronounced than for the air aging (*Figure 9b*). Further, the fractography reveals that the oxidative degradation is more strongly pronounced in the near-surface regime along the edges of the specimen, as shown in the low magnification image (*Figure 9a*) and the higher magnification of the near-edge regime (*Figure 9c*).

Transmission electron microscopy

Transmission electron microscopy was performed on the two manufacturing processes to assess the orientation effects induced by processing. Transmission electron micrographs (*Figure 10*) revealed a subtle texture in the ram extruded UHMWPE resulting in alignment of polymer lamellae along the extrusion direction while the

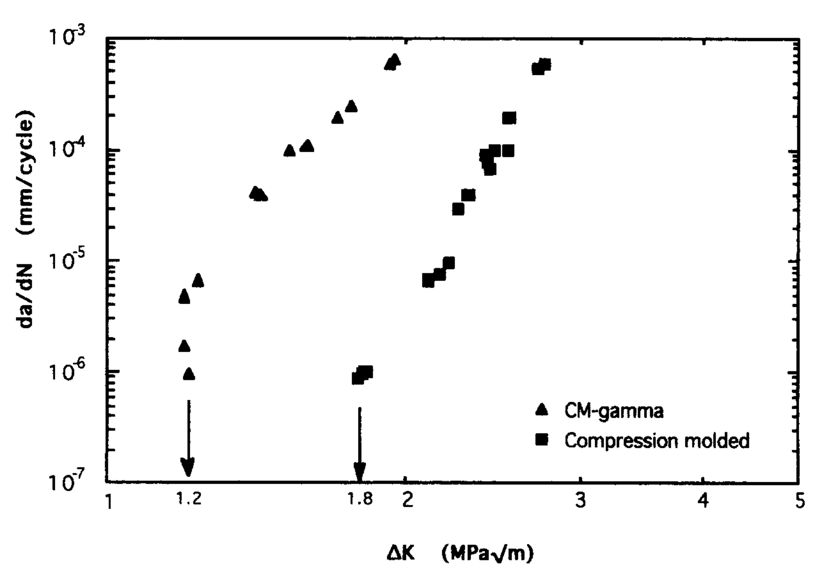

Figure 5 Plot of crack propagation rate as a function of the applied stress intensity range for γ-radiated air aged (for 5 years) compression molded GUR 415 UHMWPE showing the effect of sterilization and aging. Non-sterile is plotted as a control

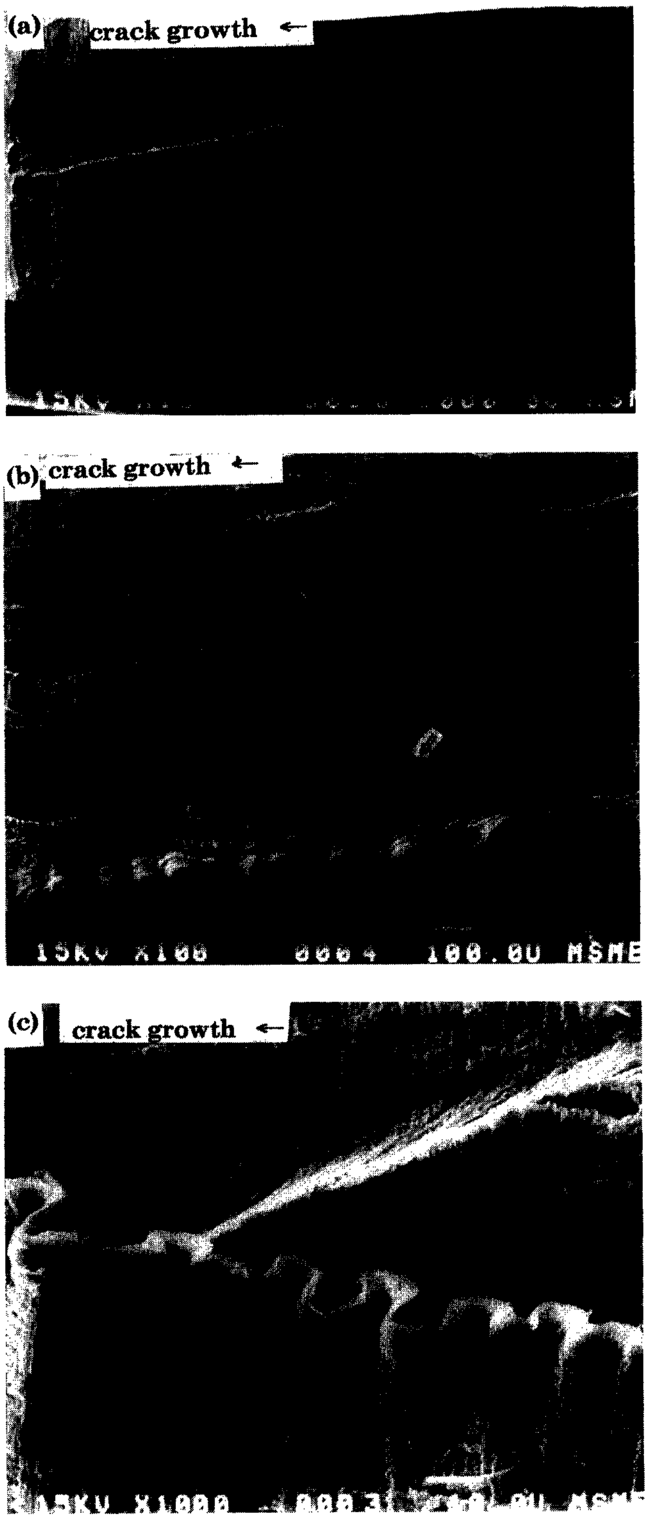

Figure 6 (a–c) Scanning electron micrographs of the fracture surface of the extruded UHMWPE in the perpendicular notch orientation. Arrow denotes crack propagation direction. Smaller arrows denote enlargement regions (b and c). Note the classic 'criss-cross markings', see text for details

compression molded morphology revealed random orientations of the crystalline lamellae. Note that the compression molded specimen shows no preferred orientation. This lack of lamellae preference can aid in crack deflection and benefit threshold and rates of crack propagation rates for the compression molded UHMWPE. This finding is consistent with the fatigue results for the extruded and compression molded ultra high molecular weight polyethylene[29].

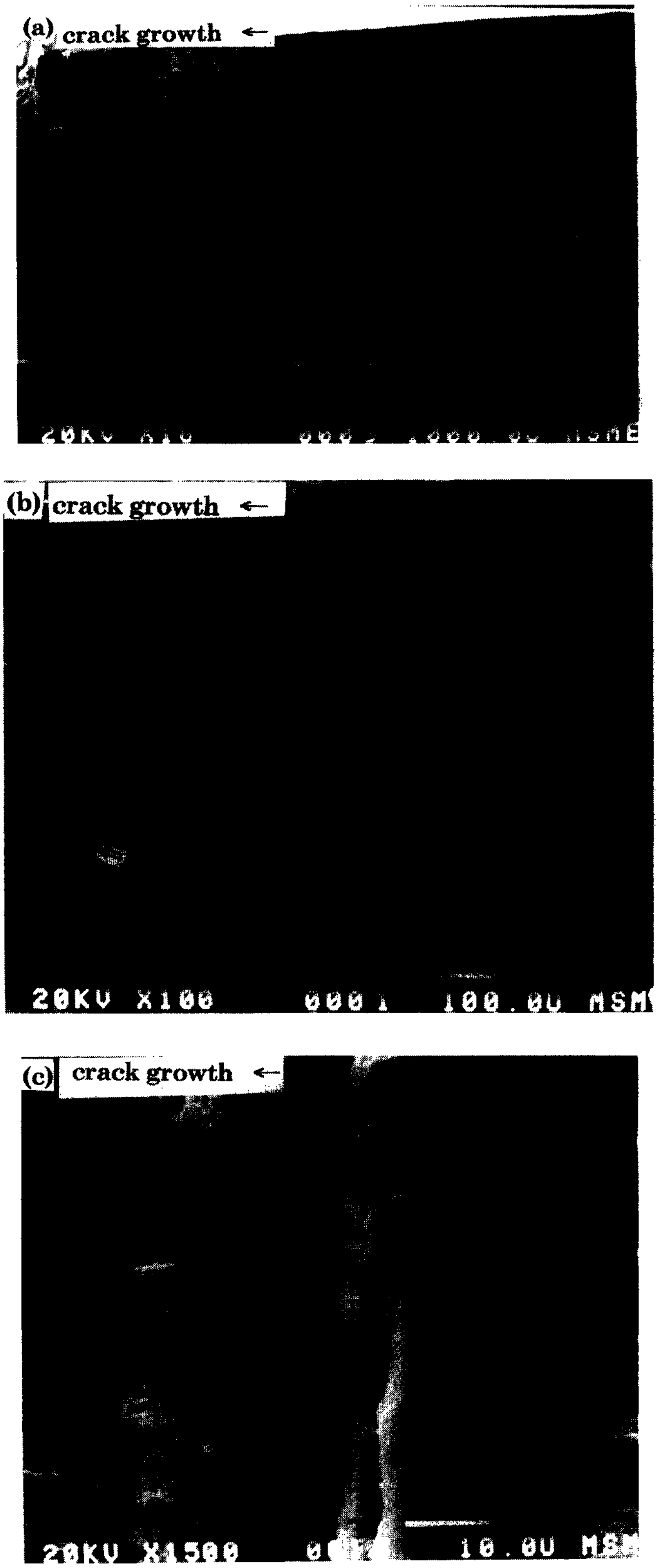

Figure 7 (a–c) Scanning electron micrographs of the extruded UHMWPE in the parallel notch orientation. Arrow denotes crack propagation direction. Smaller arrows denote enlargement regions (b and c). Note that 'criss-cross markings' are much subtler than the orthogonal orientation

DISCUSSION

The results of this study clearly indicate that the manufacturing process and resulting preferred orientation of the crystalline lamellae, γ-sterilization and post-sterilization aging affect the near-threshold fatigue behavior and fracture mechanisms of UHMWPE. The threshold and Paris regime

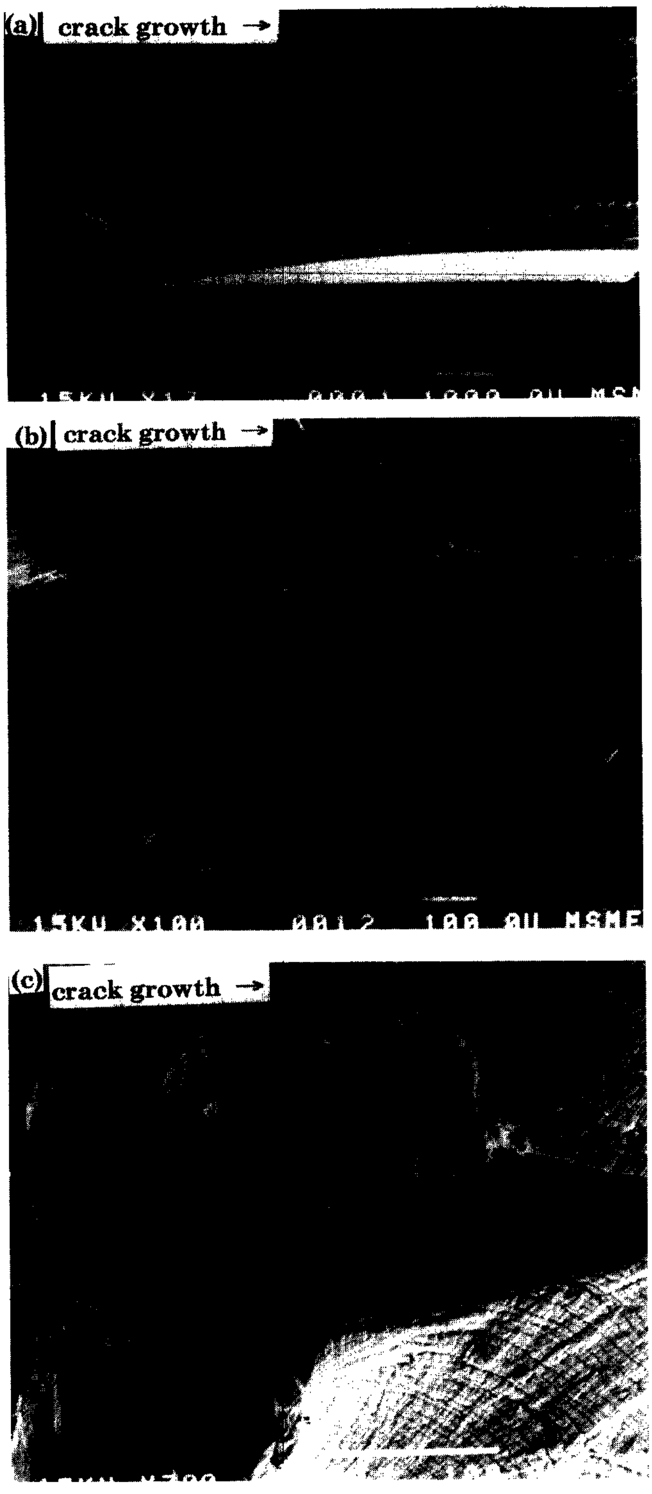

Figure 8 (a–c) Scanning electron micrographs of the γ-radiated UHMWPE which has aged in air for 6 months. Arrow denotes crack propagation direction. Smaller arrows denote enlargement regions (b and c). Note the scallop markings and transformation in fracture mode

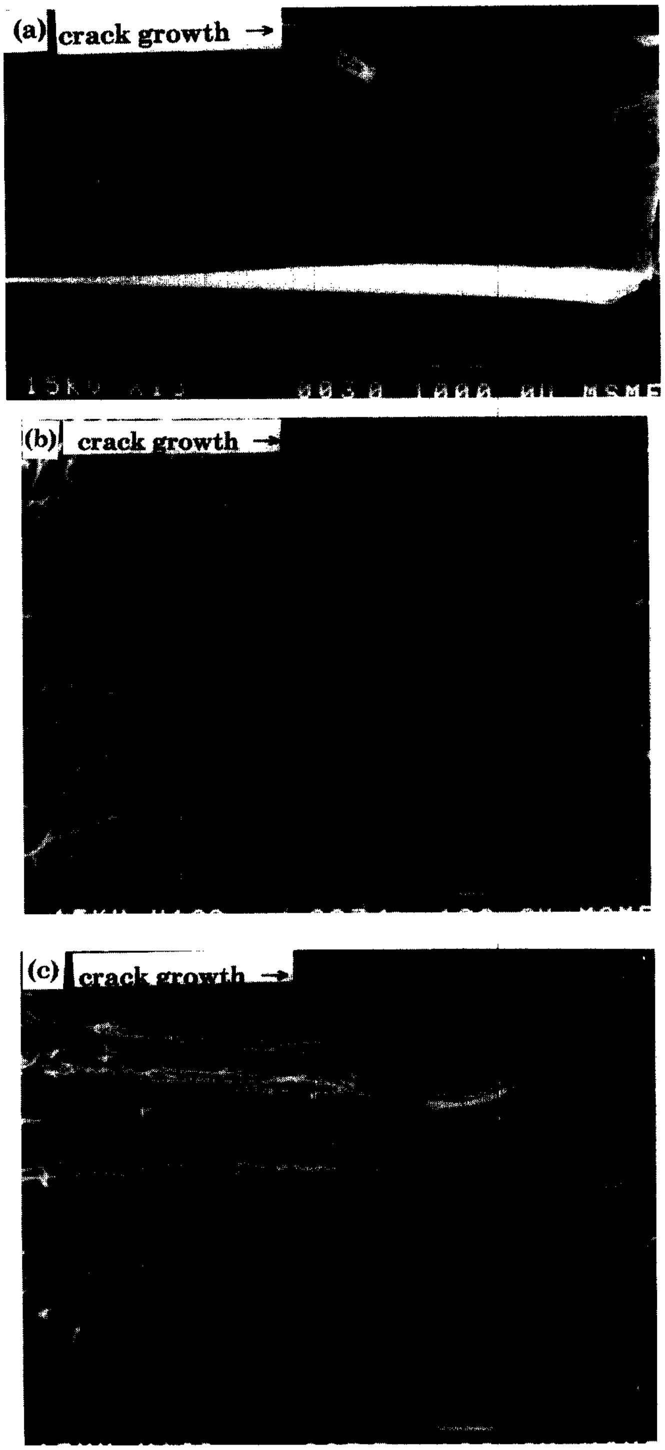

Figure 9 (a–c) Scanning electron micrographs of the γ-radiated UHMWPE which has aged in body temperature hydrogen peroxide for six months. Arrow denotes crack propagation direction. Smaller arrows denote enlargement regions (b and c). Note the deeper scallop markings and transformation in fracture mode near the edge of the specimen

of the extruded polyethylene is strongly affected by the notch orientation with the 90° orientation providing superior resistance to crack growth inception and subsequent crack propagation. This behavior is attributed to the arrangement of crystalline lamellae and tie molecules (schematically depicted in *Figure 11*). In the 90° orientation, the near tip peak tensile stresses will result in disentanglement of connecting tie molecules and, at sufficient strains, unfolding of the crystalline lamellae[31,32]. This is consistent with the ductile failure and fibril drawing remnants observed in fractography. In the parallel orientation, the lamellae are expected to have preferential alignment in the extruded direction (as shown in TEM) and hence preferential alignment in the plane of the advancing crack. In this arrangement, chain disentanglement of the tie molecules is restricted owing to rigid constraints of the crystalline lamellae so that the displacements are limited within the amorphous–crystalline interface. This results in little drawing and ductility of the polyethylene, as observed in the fractography, and a reduced value of stress intensity

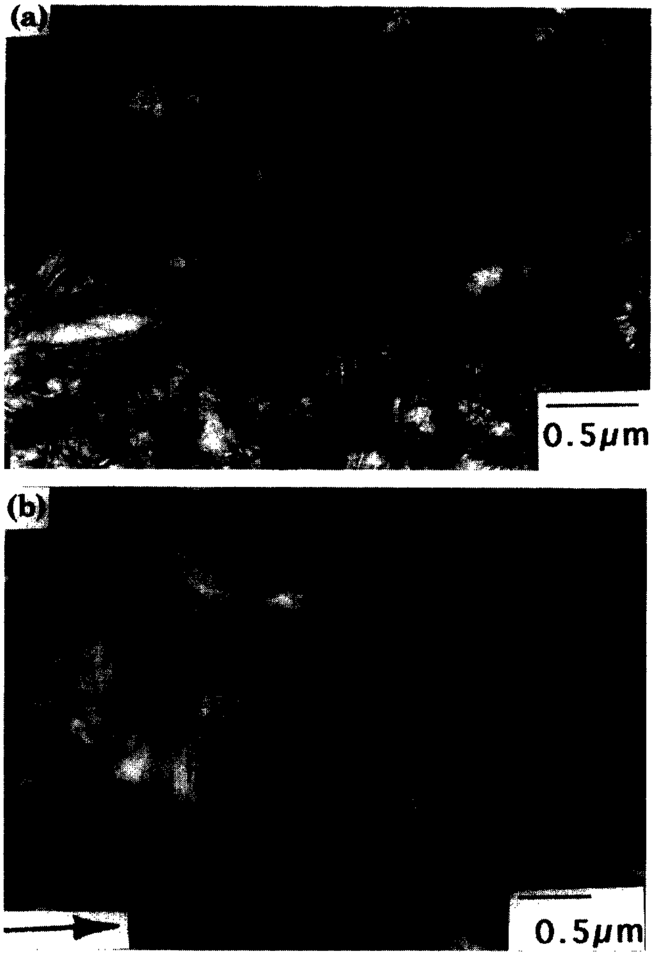

Figure 10 Transmission electron micrographs of the two manufacturing methods: (a) compression molded and (b) ram extruded (arrow denotes extrusion orientation). Note that the compression molded specimen shows no preferred orientation, while the extruded UHMWPE reveals subtle texture of the crystalline lamellae. This lack of lamellae preference can aid in crack deflection and reduce crack propagation rates for the compression molded UHMWPE

range necessary for inception of crack propagation and a decreased resistance to crack growth. Further, this behavior is consistent with the crack tip opening displacement which can be calculated from fracture mechanics using the relationship:

$$\Delta\delta_t = \Delta K^2/2E\sigma_y \quad (4)$$

It was found that the ratio for the crack tip opening displacement of the perpendicular orientation to the crack tip opening displacement for the parallel orientation at the inception of crack propagation is 1.71. This correlates to the ratio of the square of their fatigue thresholds, as the modulus $E = 1$ GPa, and yield strength $\sigma_y = 23$ MPa, is the same for these two materials. The near-threshold crack opening displacements are tabulated for all materials in *Table 3*. An interesting finding is that extruded ultra high molecular weight polyethylenes have shown consistent densities and crystallinities in their bulk materials and correlating values of properties such as elastic modulus and yield strength (as shown in *Table 1*)[32]. However, the role of microstructure, such as lamellae and tie molecule orientation, which are averaged out in the monotonic mechanical properties, play a critical role in fatigue fracture processes where increments of crack growth are on the microstructural size scale.

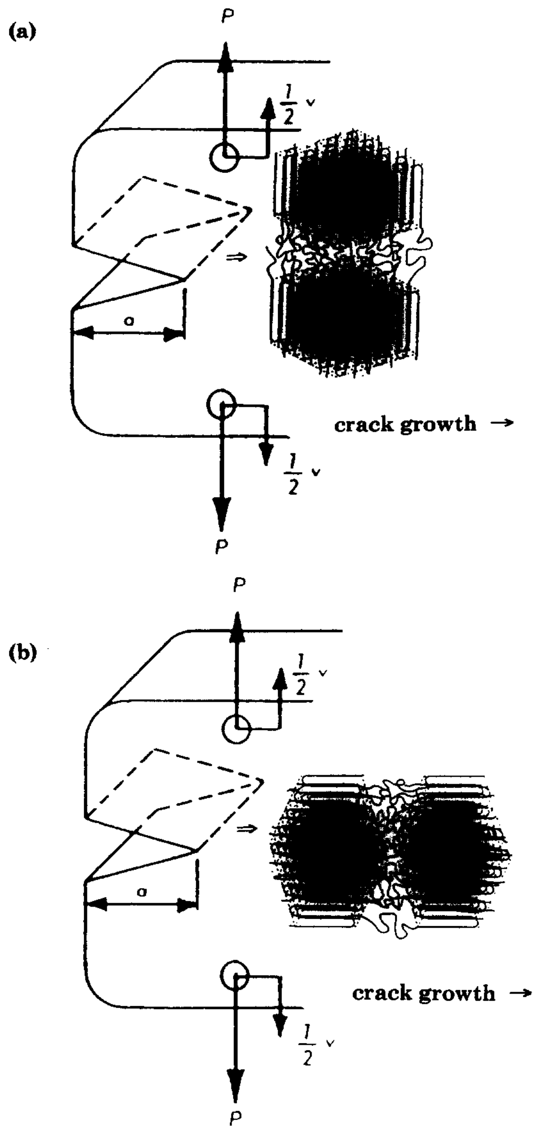

Figure 11 Schematic diagram of the arrangement of crystalline lamellae and tie molecules for the (a) perpendicular and (b) parallel orientations. (Lamellae modified from[32])

Gamma-radiation also had a detrimental effect on fatigue threshold and fracture mechanisms of UHMWPE. The ratio of the crack opening displacement for the extruded nonsterile to the γ-radiated extruded polyethylene was found to be 1.66. For comparison, the ratio of the crack tip opening displacements for the non-sterile compression molded specimens to the γ-radiated, air aged compression molded specimens is 2.25, as summarized in *Table 3*. This latter increase is believed to be the result of greater embrittlement due to the longer aging time for the compression molded specimens. The effect of γ-radiation and subsequent air aging is a reduction in near tip displacements and extension associated with reduced chain disentanglement. From previous work, it is known that the γ-radiation results in an increase in density, crystallinity (due to chain scission), and oxidation index (due to free radical reaction with oxygen species)[11]. Further, it has been shown using small angle X-ray scattering that the distance between crystalline regions decreases as a result of post-radiation aging[11]. This finding is consistent with the reduction in crack tip opening displacements and reduction of fatigue threshold found in this study. Recent findings

Table 3 Crack-tip opening displacements at the inception of crack propagation

GUR 415 UHMWPE	$\Delta\delta_t$ (μm)	$\Delta\delta_t$ (ratio)
Compression molded	70.4	2.25
Compression molded γ-air	31.3	
Extruded 90° orientation	62.8	1.71
Extruded 0° orientation	36.7	
Extruded 0° orientation	36.7	1.65
Extruded 0° γ-air	22.2	

have shown that the oxidative degradation is substantially enhanced by the peroxide environment and is consistent with the findings of this study[33]. In summary, the structural changes associated with γ-radiation and oxidative aging embrittle the polymer and reduce the ability to accommodate plastic strain. This was evident in the decreased thresholds and reduction in the stress intensities necessary to induce fast fracture in comparison to the non-sterile UHMWPE.

CONCLUSIONS

The fatigue threshold of UHMWPE is a critical design factor for orthopedic implants as this value serves as a criterion for fatigue crack growth inception. In this regime, the fatigue resistance is highly sensitive to local microstructure and it is believed that this behavior is linked to orientation of the lamellae and tie molecules relative to the advancing crack front. This study found a decrease in fatigue threshold for the specimens whose notch was oriented parallel to the extrusion direction. Further, the effects of γ-radiation sterilization and oxidative aging resulted in embrittlement of the polymer and further degradation of the fatigue fracture resistance of the medical grade UHMWPE. These results indicate the importance of understanding the effect of processing, sterilization and aging on the fatigue fracture mechanisms of engineering polymers.

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation under grant 442444-22178 to the University of California, Berkeley. Ms R. Ranganthan is gratefully acknowledged for the compression molded UHMWPE fatigue data and the TEM micrographs. The assistance of Ms N. Parekh and Mr R. Nassiri in the fatigue studies is appreciated.

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