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Fatigue crack propagation resistance of virgin and highly crosslinked, thermally treated ultra-high molecular weight polyethylene

Sara J. Gencur[a,*], Clare M. Rimnac[a], Steven M. Kurtz[b,c]

[a] *Musculoskeletal Mechanics and Materials Laboratories, Departments of Mechanical and Aerospace Engineering and Orthopaedics, Case Western Reserve University, 10900 Euclid Ave., Cleveland, OH 44106-7222, USA*
[b] *Exponent, Inc., 3401 Market St., Suite 300, Philadelphia, PA, USA*
[c] *Implant Research Center, Drexel University, 32nd and Market St., Philadelphia, PA, USA*

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Abstract

To prolong the life of total joint replacements, highly crosslinked ultra-high molecular weight polyethylenes (UHMWPEs) have been introduced to improve the wear resistance of the articulating surfaces. However, there are concerns regarding the loss of ductility and potential loss in fatigue crack propagation (FCP) resistance. The objective of this study was to evaluate the effects of gamma radiation-induced crosslinking with two different post-irradiation thermal treatments on the FCP resistance of UHMWPE. Two highly crosslinked and one virgin UHMWPE treatment groups (ram-extruded, orthopedic grade, GUR 1050) were examined. For the two highly crosslinked treatment groups, UHMWPE rods were exposed to 100 kGy and then underwent post-irradiation thermal processing either above the melt temperature or below the melt temperature (2 h—150 °C, 110 °C). Compact tension specimens were cyclically loaded to failure and the fatigue crack growth rate, da/dN, vs. cyclic stress intensity factor, ΔK, behavior was determined and compared between groups. Scanning electron microscopy was used to examine fracture surface characteristics.

Crosslinking was found to decrease the ability of UHMWPE to resist crack inception and propagation under cyclic loading. The findings also suggested that annealing as a post-irradiation treatment may be somewhat less detrimental to FCP resistance of UHMWPE than remelting. Scanning electron microscopy examination of the fracture surfaces demonstrated that the virgin treatment group failed in a more ductile manner than the two highly crosslinked treatment groups.

Keywords: Polyethylene; UHMWPE; Fatigue; Crosslinking; Annealing; Remelting

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) has been used successfully in orthopedic total joint replacements for four decades [1]. However, concerns regarding wear and oxidative degradation of UHMWPE joint components have led to the development and use of radiation crosslinked and thermally treated UHMWPE in both total hip replacements and total knee replacements [2].

In total joint replacements, "conventional" UHMWPE materials have been defined as UHMWPE that is sterilized by any method, other than ionizing radiation (i.e., uncrosslinked) or following sterilization with up to 40 kGy of gamma radiation (i.e., lightly crosslinked) [3]. "Highly crosslinked" UHMWPEs are those that are manufactured by exposing uncrosslinked UHMWPE to an elevated dose of ionizing radiation (e.g., > 40 kGy [1] of gamma radiation), and then typically subjected to post-irradiation thermal processing [4,5]. Thermal processing is conducted on the irradiated UHMWPE to reduce residual free radicals and, thus, minimize the potential for post-irradiation oxidation [4,6]. Post-irradiation thermal processing that occurs below the melt transition is referred to as annealing and thermal processing that occurs above the

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[*] Corresponding author. Tel.: +1 716 456 2326; fax: +1 716 456 2440.
E-mail addresses: sgencur@yahoo.com, sig16@po.cwru.edu (S.J. Gencur).

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melt transition is referred to as remelting [6]. Post-irradiation thermal processing, regardless of temperature, typically occurs at ambient pressure.

Due to the cyclic nature of the loads applied to joint replacements, the fatigue crack propagation (FCP) resistance of UHMWPE materials is of interest. It has been shown that increasing the radiation dose used for crosslinking causes a decrease in the overall ductility of UHMWPE and also a decrease in FCP resistance [7,8]. In addition, post-irradiation thermal treatments above and below the melting temperature, used primarily to quench residual free radicals to reduce oxidation, have been shown to alter the monotonic mechanical properties of UHMWPE [3].

The objective of this study was to evaluate the effects of gamma radiation-induced crosslinking with two different post-irradiation thermal treatments on the FCP resistance of UHMWPE. In addition, the effect of specimen thickness on FCP behavior was also examined.

2. Materials and methods

Three treatment groups, two highly crosslinked and one virgin (as-received), of ram-extruded, orthopedic grade, GUR 1050 UHMWPE (Ticona, Bayport TX) were examined in this study. For the two highly crosslinked treatment groups, UHMWPE rods were exposed to 100 kGy. After irradiation, the two highly crosslinked treatment groups underwent post-irradiation thermal processing either above the melt temperature (remelted, 150 °C) or below the melt temperature (annealed, 110 °C). To accomplish the post-irradiation thermal processing, the highly crosslinked materials were placed in an air-circulating oven and heated until the center of each stock rod reached the required temperature and were held at that temperature for 2 h. The materials were then cooled to room temperature over a 24-h period. Selected material and monotonic properties of each treatment group have been previously reported (Table 1).

Circular compact tension specimens were machined from transverse cross-sections of the rod stock from all three treatment groups (Fig. 1). Specimen dimensions were selected with guidance from ASTM E 399 [9] and ASTM E 647 [10]. To examine the effect of specimen thickness on FCP behavior, specimens were made with two thicknesses: 10 mm ($n = 5$/material) and 20 mm ($n = 2$/material) (Fig. 1). After notching, specimen surfaces were polished to better visualize crack growth. Immediately prior to testing, the specimens were thawed and razor sharpened at room temperature. A 3 mm long extension of the notch was introduced by slowly and manually pressing a fresh razor blade into the notch of each specimen such that the initial ratio of crack length, a, to width, W, was 0.3 or 0.39 [10].

The compact tension specimens were tested to failure with guidance from ASTM E 647 [10]. Testing was conducted on a servo-hydraulic, closed-loop testing machine (Instron 8874, Canton, MA). Specimens were tested with an R-ratio of 0.1, a sinusoidal waveform, and a frequency of 3 Hz. Specimens were air-cooled during testing to minimize hysteretic heating. Tests were performed at room temperature (22–24 °C).

Fatigue crack growth was monitored with a traveling microscope (10 × objective-Gaertner, Skokie, IL) and the total crack length (a) was recorded (±0.01 mm) approximately every 0.2 mm of growth (0.1 mm when the number of cycles <100). To reduce the influence of the razor-sharpened notch on the crack growth behavior, the first data point was not taken until 0.2 mm of crack growth occurred (>0.2 × notch root radius [11]). The number of cycles (N) for each growth period was also recorded. Specimens were cycled until catastrophic failure occurred or until the specimen deformed such that the crack tip moved past the range of view of the microscope. The crack growth rate (da/dN) was calculated using the secant method [10].

The cyclic stress intensity (ΔK) was calculated according to [10]:

$$\Delta K = \left(\frac{\Delta P}{B\sqrt{W}}\right) f(a/W), \tag{1}$$

where ΔP is the load range, B the specimen thickness, W the specimen width, and $f(a/W)$ is a geometrical correction factor for a circular compact tension specimen.

The cyclic stress intensity (ΔK) and the average crack growth rate (da/dN) for each specimen were plotted. Linear regression analysis was performed on a portion of the Paris region ($10^{-4} < da/dN < 10^{-2}$ mm/cycle) of each resulting curve. The slope and intercept obtained from the linear regression analysis were used to determine the exponent, m, and the coefficient, C, of the Paris relationship for each specimen [12]:

$$da/dN = C(\Delta K)^m. \tag{2}$$

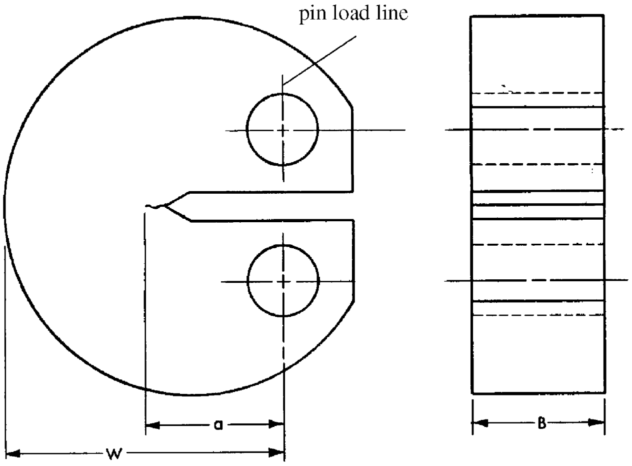

Fig. 1. Circular compact tension specimen used in fatigue crack propagation testing. Dimensions were: $W = 40$ mm, $B = 10$ and 20 mm, $a_n = 12$ and 15.7 mm.

Table 1
Selected material and tensile properties for the three UHMWPE treatment groups (mean ± std. dev., $n = 15$/treatment group)

	Virgin	100 kGy Annealed	100 kGy Remelted
Crystallinity (%)[a]	50.4±3.3	60.8±0.9	45.7±0.3
True ultimate stress (MPa)[a]	238±53	163±12	133±14
True ultimate strain (%)[a]	1.65±0.07	1.25±0.03	1.21±.03
True yield strength (MPa)[a]	26.9±0.4	27.94±0.1	24.47±0.24
K_c (MPa $\sqrt{m}$)[b]	4.0±0.5	2.8±0.4	3.0±0.6

Data reported previously [a][3], [b][22].
Note that K_c is an estimated fracture toughness.