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Effects of oxidative degradation on the wear and wear particles of cross-linked UHMWPE

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ABSTRACT – This paper investigated the effects of oxidation and radiation dose on the wear and wear particles of cross-linked Ultra-high Molecular Weight Polyethylene (UHMWPE) by the FT-IR and multi-directional pin-on-plate wear tester. Scanning electron microscopy (SEM) and the necessary software were used for quantitative analysis of wear particles. Results showed that the wear rate and wear particles of cross-linked UHMWPE were not sensitive to the oxidation when the oxidation index (OI) under a certain level. With the increase of OI, the wear and wear particles were strongly affected by oxidation. The wear properties of 1000 kGy cross-linked UHMWPE showed lower sensitivity to oxidation.

1. INTRODUCTION

Highly cross-linked UHMWPE with an improved wear resistance is now widely used as a major bearing material for hip joint prostheses, since wear of UHMWPE has been the main reason to cause the joint failure [1]. However, many of current cross-linked UHMWPEs have a risk of the post-irradiation oxidation caused by residual free radicals and there are concerns about its adverse effects on the wear resistance [2]. In this study, the relationship between the oxidation index (OI), which was defined in ASTM F2102-06 to quantify the degree of polyethylene oxidation, and specific wear rate was examined experimentally for cross-linked UHMWPE specimens, those were shelf-aged for 7 years after cross-linking, and effects of the gamma radiation dose for cross-linking were investigated.

2. METHODOLOGY

2.1 Materials

Compression-moulded UHMWPE (GUR 1050) rods were irradiated with gamma rays to the total doses of 50, 100 and 1000 kGy at a dose rate of 10 kGy/h in air. These rods were subsequently annealed at 110 ℃ for 8 hours inside a vacuum oven. Prior to the machining into the final shape (cylinder: diameter of 6 mm, length of 15 mm), any surface oxidation product that occurred during the irradiation was removed. Finally, all samples without sterilization were shelf-aged in an air-permeable package for 7 years at the lab temperature to carry out the post-irradiation oxidation process. A virgin UHMWPE was used as the control.

2.2 Experiments

Our previous study [3] showed that the oxidation behavior within cross-linked UHMWPE bulk is depth- and dose-dependent. Based on this finding, three representative regions were chosen to check effects of the oxidation on the wear and wear particles: surface region (mild oxidation), subsurface region (severe oxidation) and center region (moderate oxidation). A proper shape of sample was designed for wear testing (Figure 1). Prior to the wear testing, the oxidation level of the testing surface was checked with Nicolet iS5 FT-IR spectrometer (Thermo Scientific, USA).

The wear behavior of cross-linked UHMWPE was evaluated by using the multi-directional pin-on-plate wear tester [3]. Cast CoCrMo alloy with a surface roughness R_a of 0.01μm was used as the mated plate. The wear test conditions were described in our previous work [3]. The specific wear rate k ($mm^3N^{-1}m^{-1}$) was calculated by dividing the wear volume ΔV by with the sliding distance S and applied normal load F.

The 30 vol% fetal bovine serum (FBS) lubricant was collected for the isolation of the wear particles after each wear test. A certain volume of 3 mm^3 of serum was digested and analysed according to the method of Wang et al. [4]. After isolation, at least 200 wear particles per sample were analysed. Area and perimeter measurements were taken in each images to obtain particles size distribution. Equivalent circle diameter (ECD) was calculated to characterize the wear particles.

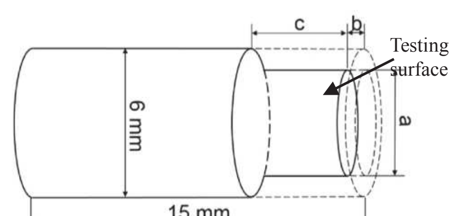

Figure 1 The geometry of pin sample.

3. RESULTS AND DISSCUSSION

The Table 1 shows that the increase of OI value of cross-linked UHMWPE followed the order from surface, center to subsurface regions. The center region of 1000 kGy sample showed a very low OI value compared to the other cross-linked samples.

Table 1 Oxidation index of the testing surfaces.

Regions	0 kGy	50 kGy	100 kGy	1000 kGy
Surface	0	0.20	0.15	0.35
Subsurface	—	4.32	5.14	4.65
Center	—	1.97	2.06	0.59

The Figure 2 shows that the specific wear rate of surface region of all samples maintained low values and decreased with radiation dose. This result indicated that under a certain of OI, the wear rate of UHMWPE is not sensitive to oxidation and still dominated by the crosslinking. At center and subsurface regions which having higher OI, the wear were observed to increase significantly. These phenomenon were due to the high sensitivity of the resulting material to oxidation. In addition, at surface and subsurface regions, 1000 kGy sample showed lower wear rates compared to 50 kGy sample even under the higher OI conditions, presumably due to the higher cross-linking density caused by the higher irradiation dose.

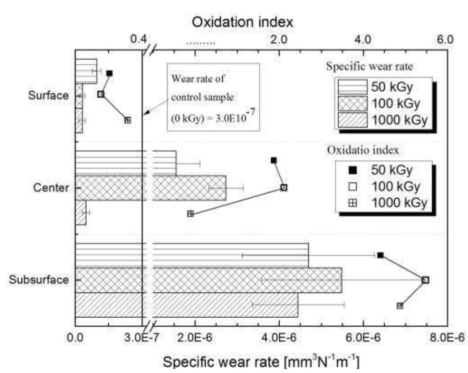

Figure 2 Specific wear rate of all testing surfaces.

The wear particles analysis results showed that the subsurface region of 50 kGy generated large amount of wear particles of smaller size (Figure 3), while the 100 kGy and 1000 kGy samples showed different results. As seen in Figure 4, the median values of ECD showed that the surface region of these two samples generated the smaller size particles.

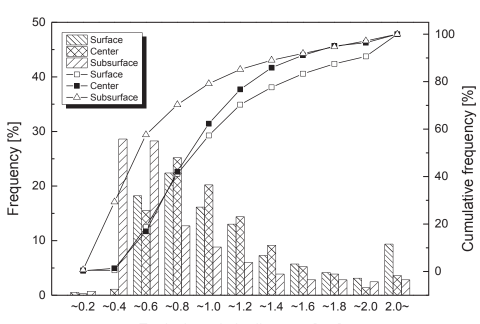

Figure 3 Size distribution of wear particles of 50 kGy cross-linked UHMWPE.

The wear behavior of surface region with low OI is controlled by crosslinking. Higher cross-linking density with increased radiation dose could reduce the plastic deformation of UHMWPE and subsequently decreased the size of wear particles. However, the material became brittle with increased of OI, which would cause the deterioration of wear and mechanical properties of the material [4]. Some large size wear particles came off at the subsurface regions due to the fatigue fracture. 1000 kGy sample showed the smallest size wear particles compared to the other samples at the same region due to the unique structure after 1000 kGy crosslinking.

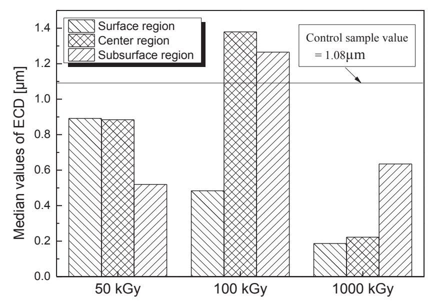

Figure 4 Median values of ECD of wear particles of all testing samples.

4. CONCLUSION

The wear rate and wear particles of cross-linked UHMWPE were not sensitive to the oxidation when the OI was under a certain level and was still controlled by the crosslinking. With the increased of OI, the wear behavior was strongly affected by oxidation. 1000 kGy sample showed lower sensitivity to the oxidation due to the unique microstructure with highly cross-linking established by extremely high radiation dose.

5. REFERENCES

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