Effects of Gamma Irradiation and Accelerated Aging on Wear Properties of UHMWPE Artificial Joint

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Abstract

Oxidative degradation of ultra-high molecular weight polyethylene (UHMWPE; PE), due to gamma irradiation sterilization in air, increases wear rate in artificial joint. Not only adhesive and abrasive wear but also delamination (flaking), a typical wear of the PE component in artificial knee joint, and fracture could be observed. This paper deals with gamma-irradiation effects on severe wear mechanism of PE components. Scanning electron microscope (SEM) observation provided that the freeze-fractured surface of the both of components had a double-layer structure, bordered below 300-700 μm depth from the surface, and at closer observation of subsurface layer below the border, we could find an extremely rough and porous structure. Fourier Transform Infrared (FT-IR) analysis presented that the rough region had the highest extent of oxidation. Wear test result by pin-on-disc machine also demonstrated that this rough region provided the maximum wear volume.

Keywords: UHMWPE, total knee arthroplasty, polyethylene wear, gamma-irradiation

1. Introduction

Wear of UHMWPE tibial insert is a major cause of failure of total knee arthroplasty (TKA). Gamma irradiation in air, the method generally used to sterilize the polyethylene components, has been cited_as a major factor affecting in vivo destructive wear such as delamination and fracture, which could be observed in retrieved PE tibial inserts. (1)(2) (Fig. 1)

We have performed revision surgeries owing to some kinds of PE problems, e.g. delaminations, fractures or a number of forms of wear out, which were clinically presented as pain, joint effusion or joint instability. Those were all sterilized by gamma irradiation in air before implantation. On the other hand, although we have also used that of ethylene oxide sterilization for a number of TKAs, we have never performed any revision surgery on them. A number of reports have focused on the subsurface white band seen on the cross-sections of PE components as oxidative degradation due to gamma sterilization in air.(1)(2)(Fig.2)

This study demonstrated the microstructural features of oxidative degradation of PE. We could determine the main reason for the frequent occurrence of delaminations and fractures with additional result from pin-on-disc wear test .

Fig. 1. Destructive wear of PE tibial insert

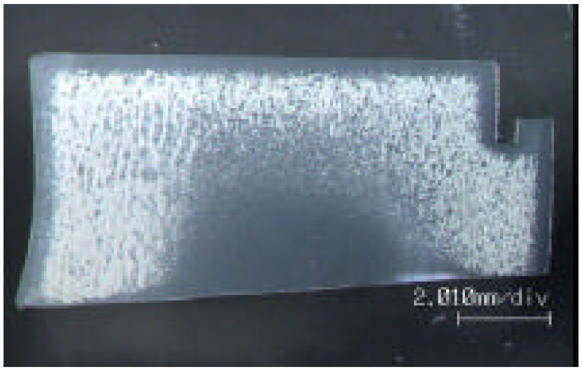

Fig.2. subsurface white band of PE component

2. Experiment

2.1; Materials

2.1.1 Retrieved or stored PE tibial inserts

Retrieved PE tibial inserts (n=29) from five different products, with an average duration after TKA of 5.5 years, and a range of 1-8.1 years (total time from sterilization range 4-12 years), and various kinds of 14 shelf-aged components from four products which were stored for some years after sterilization (range 2-10 years) were prepared for analysis. These components had all been sterilized by gamma irradiation in air.

2.1.2 Accelerated aging of PE discs

As oxidation rate is significantly slow, accelerated aging protocols have already been proposed by earlier reports.(3) Disk specimens which were directly compression-molded from Hoechst GUR1120 by the manufacturer, and sterilized by gamma irradiation at a nominal 25KGy in air. Then those were placed in an oven at a constant temperature of 80°C for 23 days adopting one of these protocols.(3) An oxygen environment of 1 atm was maintained. Test specimens without acceleration controls from the same manufacturing method were used throughout the testing.

2.2 Techniques

2.2.1; SEM

We divided these components into smaller specimens and fractured them at high strain rates in liquid nitrogen in order to analyze the vertical cross sections. SEM observation at 3.0kV accelerating voltage was then performed on these specimens.

2.2.2; FT-IR spectroscopy

Using a Poly Cuts Microtome (Reichert-Jung), we cut the specimens into approximately 50 μm-thickness horizontal sections from the articulating surface to a depth of 3 mm at 20 mm s__ in air at room temperature. The extent of oxidation in each PE components were determined by Fourier Transform Infrared spectroscopy (Perkin Elmer Model 2000 FT-IR). All the spectral resolution were 4 cm__.

2.2.3; Pin on disk wear test

A pin-on-disc wear testing machine (JT-TOHSI INC., Japan) was used to investigate the tribological behavior of the PE discs against Co-Cr-Mo pins with distilled water as a lubricant. A contact stress 10MPa, a constant sliding velocity of 60mm s__ and test durations up to 382166 revolutions (138.9h) were chosen. To determine the friction coefficient (μ=f/F), the friction force f was measured with a load cell.

3. Results

3.1; SEM findings

SEM observation showed that the freeze-fractured surface of the components had a double-layer structure, the border of which was 300-700μm below the surface (Fig. 3). At closer observation, the layer below the border exhibited an extremely rough structure with numerous spikes and cavities (Fig. 4-B), while the upper layer just below the articulating surface showed a relatively smooth and homogeneous structure (Fig. 4-A).

This structure had a tendency to become prominent and expanded broadly in proportion to the total aging time from sterilization. These findings were observed in both retrieved and stored PE components.

Fig.3. Freeze-fractured surface of PE tibial insert which was sterilized 10 years ago by gamma irradiation in air.

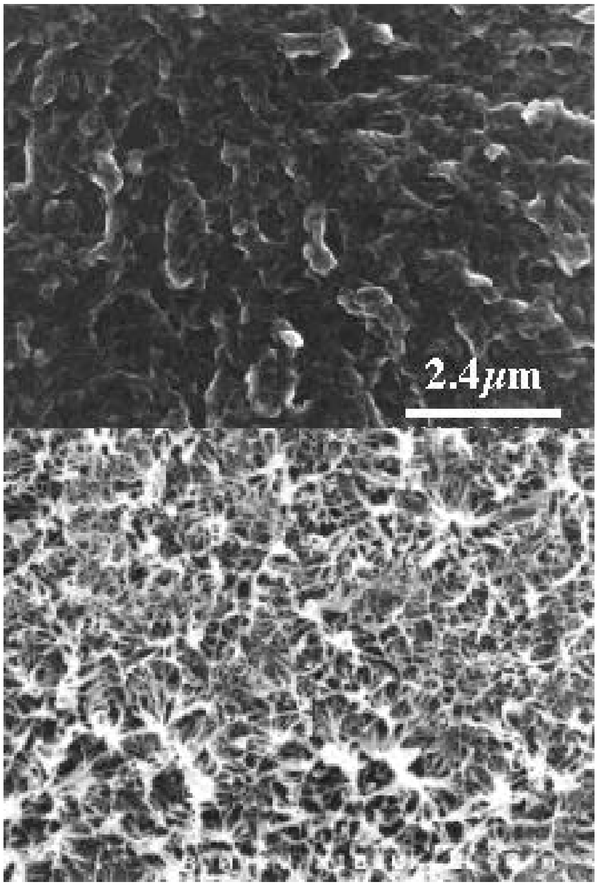

Fig. 4-A and 4-B: closer observation of each layer in Fig.3. Both are same magnification.

3.2; FT-IR analysis and oxidation index

The IR peak at 1716cm__ corresponds to carbonyl functional groups, which is seen for the oxidized sample, but not for the virgin UHMWPE sample. Carbon-oxygen functional groups can exist in various forms (ketone, ester or hydroxylic acid); in general, the IR oxidation peaks appear in the range of 1660cm__ to 1800cm__. The integrated peak area in this range can be used to quantify the extent of oxidation. To have a valid comparison from sample to sample, the oxidized peak area is divided by the 1464cm__ (CH_2 group) peak area, using the range of 1400cm__ to 1560cm__, to give an oxidation index. The highest oxidation peak according to FT-IR was found to take place at the subsurface region showing the rough structure by SEM. We could find the greatest degree of crystallization and the highest density in that region.

3.3; Pin on disk wear test

Figure 5 shows, after 382166 cycles, oxidatively accelerated discs had the maximum average total wear volume (0.0823g) followed by the control discs having the average total wear volume(0.0413g). The gamma irradiated samples without acceleration had the minimum total wear (0.0249g). There were no significant volume loss or remarkable wear marks in the pins, except for slight polyethylene transfer which was evidently confirmed by optical microscopy. After the start of the test, there was a immediate increasing trend of the friction coefficient in each sample. While the average friction coefficient in control discs gradually increased during the testing, that of oxidatively accelerated discs had a tendency to decrease.

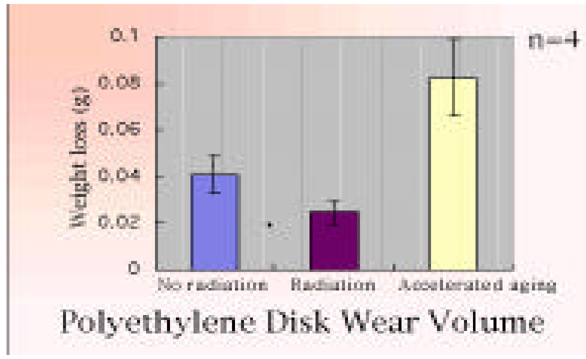

Fig.5. Wear volume comparison of UHMWPE

4. Discussion

Examination of the morphology of freeze-fractured surfaces by a SEM offered a new approach for assessing the nature and characteristics of the internal structure of PE components, especially when they contain oxidatively degraded areas in which delaminations or other manifestations of wear are present. Some researchers already revealed that the visible subsurface white band is a zone of highly oxidized, embrittled material with reduced ultimate tensile strength and elongation, resulting from gamma irradiation in air. (1)(2)

The oxidation index by FT-IR techniques in both the retrieved PE and stored one for years after gamma irradiation showed a subsurface maximum. The SEM findings showed that the subsurface highly-oxidized region which has been generally called the white band, has an extremely rough structure with many spikes and cavities. Togethering with the results of IR and the results of other papers (4)(5), high extent of oxidation, increased crystallization and high density at the region, we could comprehend the dynamic morphological changes by the oxidative effect after gamma sterilization in air. It seems reasonable to suppose that the main cause of delaminations and fractures is due to that subsurface structural weakness by shrinkage of material. The results of our pin-on-disk wear test indicated not only the weakness at the rough structure, considering its high wear rate despite its low friction coefficient, but also the possibility that such a structural change might has a correlation with delaminations. It was shown by Bartel (6) that the repeated stresses by weight bearing result in increased maximum shear stresses occurring 1 to 2 mm below the surface. If there are such increased stress concentrations to the brittle region of subsurface rough structure, the delamination and the fracture easily occur.

5. Conclusion

This study demonstrated the microstructural features of oxidative degradation after gamma irradiation in PE components.

The mechanisms of destructive wear could be elucidated by observing freeze-fractured surfaces using a SEM.

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