

Wear Characteristics of Ultra High Molecular Weight Polyethylene (UHMWPE) in Cyclic Impingement Test

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Abstract

A series of impingement wear tests on the three kinds of ultra-high molecular weight polyethylene (UHMWPE), namely conventional, cross-linked and vitamin E-doped UHMWPE has been performed. Water uptake of UHMWPE was measured first, and then the impingement wear tests were performed. An amount of wear in terms of weight change of UHMWPE with the cyclic impingement was not able to be determined, so the volume change in the wear section was alternatively measured. As a result, the vitamin E-doped UHMWPE clearly showed the smallest wear volume among these three UHMWPEs.

Key words

Total Hip Arthroplasty (THA), Ultra-High Molecular Weight Polyethylene (UHMWPE), Impingement Wear Test, Cross-linked and Vitamin E-doped Polyethylene, Water Uptake

1. Introduction

Recently, coxarthropathy due to aging has been major clinical issue in the world. Particularly, femoral neck fracture related to hip osteoarthritis (OA) is remarkably getting increased. Total hip arthroplasty (THA) is used as one of the main surgical treatments for such joint diseases. In THA, ultra-high molecular weight polyethylene (UHMWPE) is usually used as bearing material for acetabular cup. However, the problem is that the wear particles of UHMWPE often cause the osteolysis after THA [1]. The wear particles are attributed to not only sliding surface, but also impingement between the UHMWPE acetabular cup and metallic femoral stem [2]. Therefore, UHMWPE with higher resistance to wear and impingement has to be required.

According to such background, two kinds of UHMWPE, namely cross-linked and vitamin E-doped UHMWPE have been newly developed in addition to conventional UHMWPE currently and widely used. The cross-linked and vitamin E-doped UHMWPE are thought to have superior resistance to wear and oxidation, respectively.

A lot of studies concerning the wear tests on UHMWPE have been reported so far [3-5], however, no clear interpretation of most suitable UHMWPE for the acetabular cup has been given yet. Some studies looked at the weight change in wear due to impingement in bipolar hip arthroplasty (BHA) [6], and the other studies paid carefully no attention to such weight change. Furthermore,

no wear characteristics of UHMWPE acetabular cup due to cyclic impingement has been found.

In this study, a series of impingement wear tests on the three kinds of UHMWPE has been performed. The commercially available acetabular cups made of conventional, cross-linked and vitamin E-doped UHMWPE were used as specimens. The impingement wear testing machine specially designed and developed by us was used. Before wear test the variation of water uptake of the UHMWPE cup under a constant dead load with time was measured so as to obtain the real amount of wear, and then the impingement wear test on it was performed. Both the water uptake and the amount of wear were determined first in terms of the change of weight. However, it was a little bit difficult to get the consistent manner of wear by the weight change. Therefore, the amount of wear was additionally or alternatively evaluated by the volume reduction in the wear section using the laser displacement meter other than by the measurement of weight change. In addition, the surface morphology of the damaged area was observed in terms of scanning electron microscopy.

2. Materials and Method

2.1 Materials

The specimens used in this study were the three kinds of UHMWPE acetabular cups with inner diameter of 28mm, namely made of conventional, cross-linked and vitamin E-doped UHMWPE (Biomet Japan Inc., Japan). Cross-linked and vitamin E-doped UHMWPE have been especially improved in wear resistance and oxidation resistance, respectively. Metallic shells were attached to all acetabular cup specimens and then tested in combination with the femoral stem made of Ti-6Al-4V (Biomet Japan Inc., Japan) [7].

2.2 Experimental apparatus

The experimental apparatus specially designed for simulating human walking was developed by us (Fig. 1). Although a real human hip joint can freely or three-dimensionally move and rotate, this experimental apparatus only thought about extension and flexion. The apparatus gave us the swing angle of 100° under a dead load of 100N and an impingement force of 50N. The apparatus was once used for impingement wear tests on BHA [8], and has been improved for the similar tests on THA in this study.

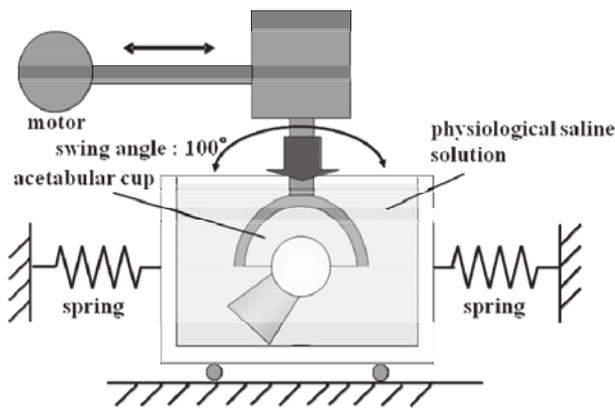


Fig. 1 Schematic of experimental apparatus for impingement wear test in this study

2.3 Experimental method

2.3.1 Water uptake experiment

The increase of the weight of UHMWPE could be observed under no cyclic impingement since UHMWPE itself has water uptake characteristics. In order to look at the weight reduction of UHMWPE acetabular cup only due to cyclic impingement, water uptake experiments were performed in advance before impingement wear test. The each kind of UHMWPE cup was held on the apparatus under a dead weight of 100N and in physiological saline solution of 37°C. Water uptake was evaluated in terms of the increment of the weight, and its variation with time up to 370 hours, correspondent to one million cycles of the impingement, was obtained. The first five measurements were performed every 18.5 hours and the next four measurements every 74 hours.

2.3.2 Impingement wear experiment

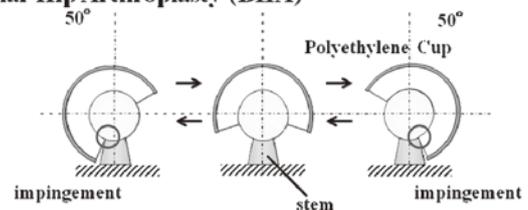
The range of motion of the femoral stem in THA is known to be bigger than that in BHA, and therefore impingement hardly occurs in THA in comparison with BHA. Bone cement is clinically used in THA to rigidly place the UHMWPE cup on acetabulum, and no rotation of the cup can be allowed. This can lead to the repeated point contact between the neck of femoral stem and the rim of UHMWPE cup in very limited area (nearly same point), namely impingement (Fig. 2). Impingement wear experiment was performed with the consideration of in vivo situation mentioned above, that is, bone cement was used to rigidly fix the UHMWPE cups to the apparatus and the femoral stem was properly inclined to make sure of the cause of the impingement. The experiment was performed up to one million cycles in physiological saline solution of 37°C. The rate of cyclic impingement was chosen to be 0.75Hz. The magnitude of impingement force and the dead load were 50N and 100N, respectively. The weight and volume reduction of each UHMWPE acetabular cup were measured every 200,000 cycles. Before measurement, the cup was washed for 15 minutes in distilled water using an ultrasonic cleaner and then dried out for 20 minutes at a constant temperature using an electric oven. Circumferential surface profiles partly damaged due to

cyclic impingement were measured on the same cup using laser displacement meter (LK-030, KEYENCE Corp., Japan) (Fig. 3). The measurements were performed at the three different points of every 0.84mm in radial direction. The volume reduction due to impingement wear was derived from the surface profile (Fig. 4) using Eqs. (1) and (2):

$$S = \int_{x_1}^{x_2} \{f_1(x) - f_2(x)\} dx \tag{1}$$

$$V = \int_{r_1}^{r_2} S dr \tag{2}$$

Bipolar Hip Arthroplasty (BHA)



Total Hip Arthroplasty (THA) in this study

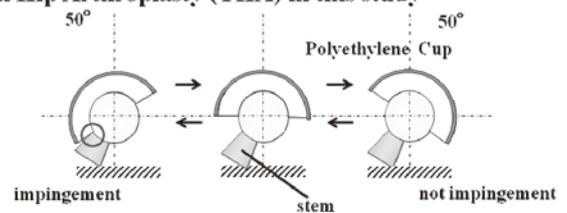


Fig. 2 Difference in impingement mechanism between BHA (above) and THA (below) in this study

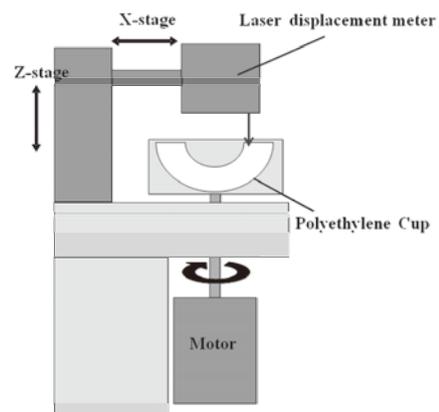


Fig. 3 Schematic of measurement of volume reduction in damaged part due to impingement wear using laser displacement meter

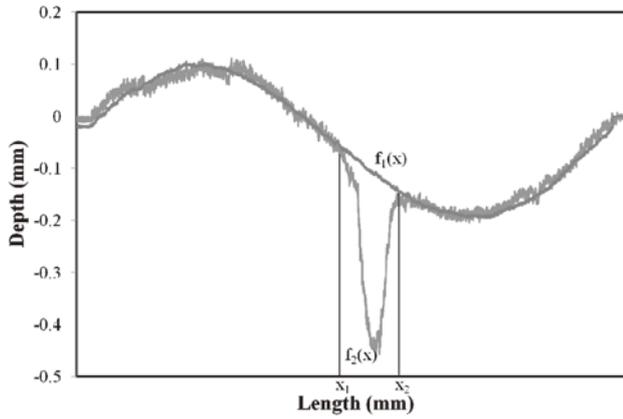


Fig. 4 Circumferential surface profiles of non-damaged, f_1 , and partly damaged, f_2 , due to cyclic impingement

2.3.3 Scanning Electron Microscopy

After impingement wear test, the UHMWPE acetabular cups were observed using a scanning electron microscope (SEM; JSM-6400, JEOL Inc., Japan). The morphology of the impingement wear surface coated with carbon was examined.

3. Results and Discussion

The water uptake was evaluated in terms of the increment of the weight of UHMWPE acetabular cup, and its variation with soaking time for each UHMWPE is shown in Fig. 5. All UHMWPEs showed the reduction of water uptake at initial 18.5 hours (correspondent to 50,000 impingement cycles), and then the weight increased. The initial reduction of the weight appears to be unnatural behavior and this is probably due to coming water-insoluble gases out or falling small debris off from the UHMWPE surface.

The change in weight of each UHMWPE cup only due to cyclic impingement was derived from the results of Fig. 5 and the measurement of the weight of UHMWPE cup. That is, the amount of impingement wear in terms of the weight was equal to be the difference between the weight of UHMWPE cup simply measured and water uptake (Fig.5).

Figure 6 shows the results of the weight change with number of impingement cycles. All UHMWPE cups appeared to show the decrease of their weights with an increase of number of impingement cycles, but conventional and cross-linked UHMWPE showed the positive change of the weight. This unnatural wear manner is probably due to that the water uptake could be more effective under cyclic impingement load than under static or dead load. Consequently it is difficult to evaluate amount of wear by weight, so the amount of wear was evaluated in terms of volume reduction (designated wear volume) as an alternative method of the weight measurement (Fig. 7). The wear volume due to cyclic impingement was clearly observed, namely less volume in cross-linked and the least one in vitamin E-doped UHMWPE.

Both the volume reduction due to wear and the plastic deformation due to high stresses at the contact point of the impingement were, strictly speaking, included in the wear volume in this study (Fig. 7). However, the plastic deformation was not thought to be significant since the

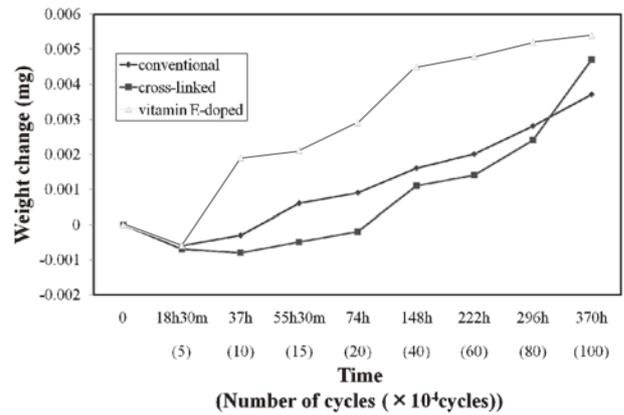


Fig. 5 Weight change in water uptake experiment as a function of soaking time. Correspondent number of impingement cycles to soaking time is also shown in abscissa

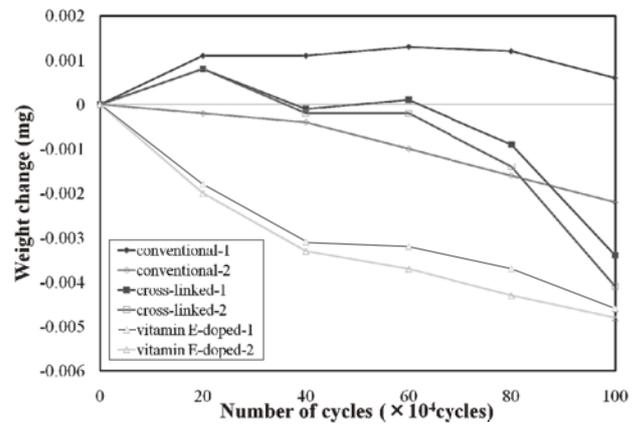


Fig. 6 Weight change in impingement wear experiment as a function of number of impingement cycles

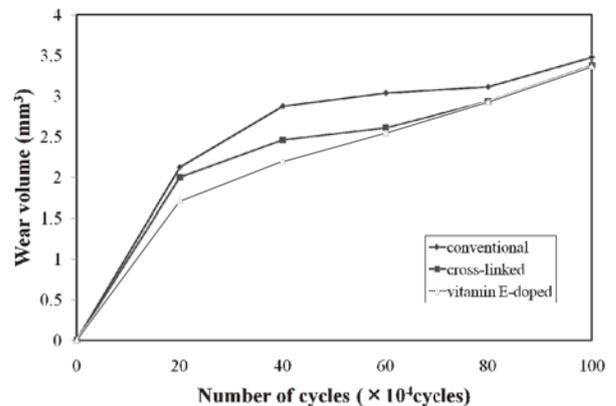


Fig. 7 Wear volume in impingement wear experiment as a function of number of impingement cycles

SEM micrographs clearly showed the fracture aspects similar to spalling typically observed in contact fatigue [9] (Fig. 8). Detailed features of the flakes broken off due to

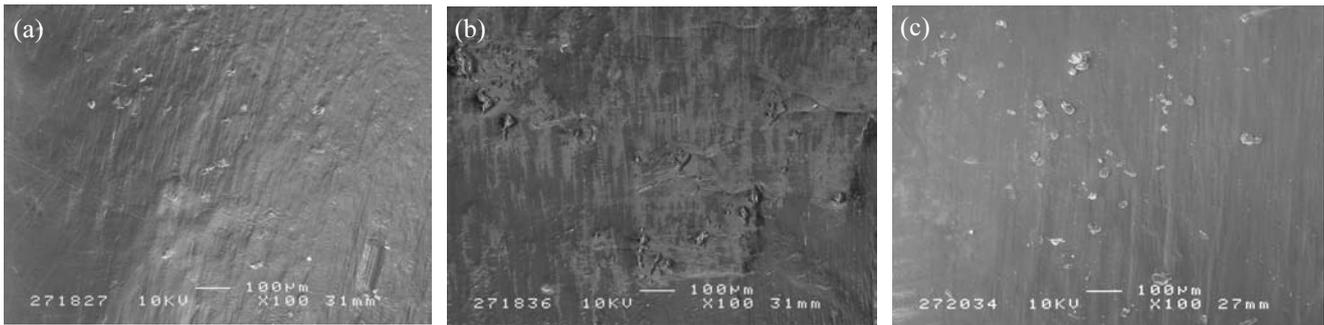


Fig. 8 SEM micrographs of the UHMWPE surface due to impingement wear. (a) conventional, (b) cross-linked, and (c) vitamin E-doped UHMWPE

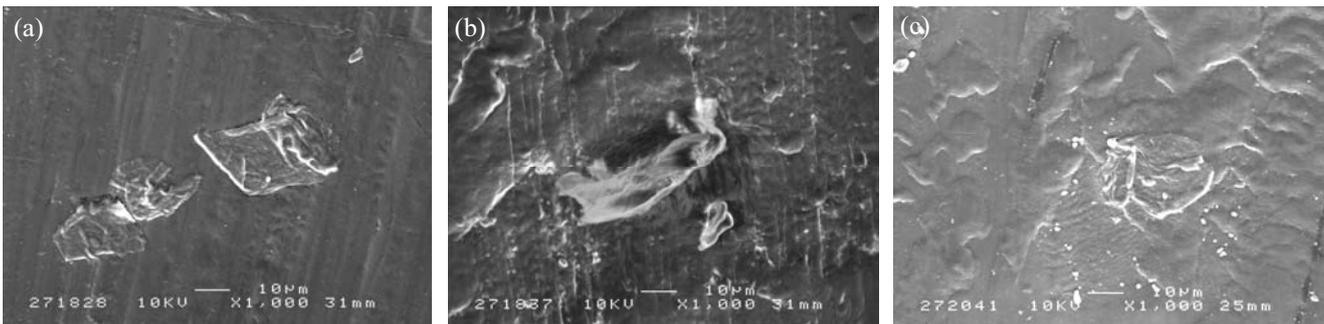


Fig. 9 SEM micrographs of the chips on the UHMWPE surface due to spalling in impingement wear. (a) conventional, (b) cross-linked, and (c) vitamin E-doped UHMWPE

spalling are shown in Fig. 9, and the smallest chip was observed in vitamin E-doped UHMWPE among the three UHMWPEs (Fig. 9). Larger amount of the chips was observed in cross-linked UHMWPE compared to the other two UHMWPEs (Fig. 8 (b)), and therefore the hardness on the surface appeared to be higher than that inside UHMWPE. In other words, the gamma-irradiation was effective only in the surface region of UHMWPE acetabular cup. Further discussion concerning the hardness distribution from the surface to bottom of the acetabular cup should be required so as to improve the wear resistance.

On the other hand, the previous study concerning the mechanical properties of these three UHMWPEs under various strain rates revealed that dynamic Young's modulus was small in conventional, larger in cross-linked and largest in vitamin E-doped UHMWPE [10]. Therefore, the amount of wear was supposed to be related to the magnitude of elastic modulus. There have been many factors to affect the elastic modulus of UHMWPE [11-14]. The gamma-irradiation made the level of cross-linking in UHMWPE stronger, and the elastic modulus consequently became larger [11]. Larger elastic modulus improved the resistance to wear as well as the surface hardness as a result. The other factors such as melting temperature [12], annealing [13], manufacturing process [14] are also important as the factors to control the mechanical properties of UHMWPE. Addition of vitamin E to UHMWPE gave it higher elastic modulus, but this strengthening mechanism has not been well investigated. Several methods of the addition of vitamin E to UHMWPE, for instance vitamin E-infused and vitamin E-blended UHMWPE, have been proposed [15],

and so the appropriate method which gives UHMWPE better mechanical properties or higher resistance to wear should be further discussed.

4. Conclusion

The impingement wear characteristics of the three kinds of UHMWPE acetabular cups clinically used for THA have been experimentally investigated. The amount of wear was not able to be evaluated in terms of the increment of the weight due to the considerable water uptake under cyclic impingement. The wear volume derived from the circumferential surface profiles with the inclusion of wear section was successfully evaluated. The least and less wear volume were observed in vitamin E-doped and cross-linked UHMWPE, respectively. The conventional UHMWPE showed the most inferior resistance to the impingement wear. The SEM observation clearly showed the damage similar to spalling in contact fatigue and severely damaged aspects in conventional and cross-linked UHMWPE. The magnitude of elastic modulus was supposed to be related to the wear characteristics, but the detail of strengthening mechanism should be further discussed.

Nomenclature

- f_1 original surface profile, mm
- f_2 damaged surface profile due to impingement wear, mm
- r distance in radial direction, mm
- r_1 outer point of interest in radial direction, mm
- r_2 inner point of interest in radial direction, mm
- S damaged area, mm²

- V volume reduction or wear volume, mm^3
- x distance in circumferential direction, mm
- x_1 onset of damage in circumferential direction, mm
- x_2 end point of damage in circumferential direction, mm

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