Relationship between wear behaviour of ultra-high-molecular-weight polyethylene and surface profile of Co–Cr–Mo alloy in artificial joint

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Abstract: The relationship between the wear behaviour of an ultra-high-molecular-weight polyethylene (GUR1050) pin and surface profile of a Co-28Cr-6Mo alloy (ASTM F-75) disc was investigated. Tribological tests have been performed by pin-on-disc wear testing machine with multi-directional pathways, obtaining the influence of micro-slurry jet erosion (MSE) processed Co–Cr–Mo alloy. The specific wear rate of polyethylene; however, the morphological aspect of polyethylene wear particles was not drastically changed. The wear particles isolated from the lubricating liquid were added to a culture medium, and human monocyte-derived macrophages were incubated by using an upright/inverted method. The production of TNF-α and IL-6 seemed to have a correlation with the amount of wear particles added, however, the influence of particle size on the production of TNF-α and IL-6 was not obvious. This means that the improvements for the incubation method, i.e. upright/inverted method, need further investigation for the accurate analysis.

1 Introduction

Artificial joint replacement is an effective surgical intervention for end-stage arthropathies such as osteoarthritis and rheumatoid arthritis [1, 2]. However, it is usual to perform re-replacement surgery owing to the relaxation of the artificial joint due to osteolysis after 10–20 years of replacement [1–7]. In a polymer-on-hard artificial joint, the bearing part is made of ultra-high-molecular-weight polyethylene (UHMWPE) and an alloy with good corrosion resistance, or polyethylene and a ceramic material. The cause of osteolysis is the discharge of micron or submicron-level fine polyethylene wear particles from the polyethylene part, which stimulates macrophage activity and promotes the development of cytokines [8–12]. Many researchers have reported that when the size of the debris is 1.0 μm or less, the release of inflammatory cytokines increases and bioreactivity becomes significant [13]. There are also reports that the amount of wear particles generated affects biological reactivity [14]. From these results, it is known that the compatibility of the suppression of wear particle size and wear amount leads to the suppression of osteolysis and prolongation of the useful life of artificial joints. The amount of wear should be as small as possible and the wear particle size should be as large as possible.

It is well known that the surface profile of a Co–Cr–Mo alloy may influence not only the amount of UHMWPE wear but also the particles size. A micro-slurry jet erosion (MSE) has been used for processing the surface profile of the Co–Cr–Mo alloy, in which the MSE functioned as a wet blasting using mixed alumina particles and water to spray Co–Cr–Mo alloy surfaces by compressed air [15]. In conventional abrasive processing, such as grinding and polishing, small and hard particles are moved to parallel on the alloy surface and remove the superficial layers.

In MSE processing, abrasive particles with plenty of water (slurry) are sprayed vertically to the alloy surfaces and the collision energy can remove superficial layers of the alloy. A high-precision surface can also be processed by moving an injection nozzle of the slurry so that the alloy surface is able to have a waviness curve from the millimetre to micrometre scale and surface roughness of the nanometre scale. The MSE is thought to be easy to apply for the commercial-based artificial joint surface without modifying its surface material and its geometrical load bearing design.

In this study, the relationship between the surface profile of Co–Cr–Mo alloy and wear behaviour of UHMWPE by using a pin-on-disc wear testing machine with multi-directional pathways was investigated. Furthermore, the production of TNF-α and IL-6 was measured through the incubation of human monocyte-derived macrophages (HMDMs) with polyethylene wear particles.

2 Materials and methods

2.1 Pin-on-disc wear testing machine

The pin-on-disc wear testing machine is shown in Figs. 1–3. The pin made of UHMWPE (GUR1050, diameter of 9.0 mm) was pressed onto a disc made of a Co-28Cr-6Mo alloy (ASTM F-75) at a pressure of 7.0 MPa. The pin was fixed with a holder jig, and the disc was subjected to orbital motion with a diameter of the centre of wear track of 10 mm and a sliding speed of 20.0 mm/s (Figs. 2 and 3), which could demonstrate multi-directional pathways for the pin surface [16–18], because it was reported that polyethylene tends to slide only in the same direction; reorientation of polymer chain occurred, and wear resistance was exhibited [19]. The disc was fixed to a liquid bath with a

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The lubricating liquid of 30 ml. The lubricating liquid was a foetal bovine serum (FBS), in which the total protein concentration of 30.0 g/l was adjusted by adding distilled water [18, 20]. As an antiseptic agent, 0.3 wt% of sodium azide was added. The temperature of the lubricating liquid was adjusted to 37°C, and the liquid was replaced every $5.0 \times 10^3$ m. Every wear test was terminated at the point where the total sliding distance reached $30 \times 10^3$ m.

2.2 Surface profile of Co–Cr–Mo alloy disc

A schematic illustration of MSE is shown in Fig. 4. It was used for processing the surface profile of the Co–Cr–Mo alloy disc. MSE is a type of wet blasting, which uses alumina particles (WA #8000, the average particle size of 1.2 μm) as an abrasive medium with compressed air and water (slurry). A high-precision surface can be processed by controlling the concentration of alumina particles, the pressure of the slurry flow, and feed speed (v) and feed pitch (p) of the nozzle. In this study, the slurry concentration was 3.2 wt%, and the injection pressure was 0.31 MPa. Since the motions of the nozzle were applied by a precise robotic control, in some cases, the same trace pattern of the nozzle was repeated at several times in order to increase the mechanical removal volume on the surface material. Table 1 presents the feeding conditions of the injection nozzle. Three types of processed surfaces by MSE and a mirror-finished surface by a conventional lapping method were prepared.

A non-contact three-dimensional surface profile-measuring device (NewView 7000, manufactured by Zygo) was used for the measurement of each surface profile. Parameters used for evaluation are shown in Fig. 5. $R_a$ is defined as the surface roughness at the top area, $D_p$ is the depth from the bottom area to top area, and $W_i$ is the width between the top or bottom area.

2.3 Polyethylene wear

The polyethylene pin was removed from the pin-on-disc testing machine every $10 \times 10^3$ m, and the gravimetric wear was measured. Before measurement, the pin was cleaned in an ultrasonic bath sonicor with an aqueous solution of 5 vol% polyoxyethylene octylphenyl ether for 10 min [21], with deionised water for 30 min, and with ethanol for 5 min. After these cleaning processes, the pin was dried for 24 h in a vacuum dryer at a
temperature of 60°C. The gravimetric wear of polyethylene was measured. Based on the gravimetric wear measured at $10 \times 10^3$, $20 \times 10^3$, and $30 \times 10^3$ m, the mean specific wear rates from 0 to $10 \times 10^3$, $10 \times 10^3$ to $20 \times 10^3$, and $20 \times 10^3$ to $30 \times 10^3$ m, were calculated. The specific wear rate can be expressed as follows:

$$\text{Specific wear rate} = \frac{V}{(W \times D)}$$  (1)

where $V$ (mm$^3$) is the volumetric wear of polyethylene, $W$ is the applied load of 445.3 N, and $D$ is the sliding distance of $10 \times 10^3$ m. $V$ was estimated through the gravimetric wear and density of polyethylene.

2.4 Wear particles of polyethylene

The polyethylene wear particles were isolated from the lubricating liquid FBS, purified, and investigated for their morphological aspects. Fig. 6 shows the procedures. The protein contained in the lubricating liquid after the test was digested with trypsin at 37°C for 24 h. The lipid contained in the liquid was extracted by mixing chloroform and methanol at a ratio of 2:1, followed by centrifugation at 2000 g for 720 s. Subsequently, the supernatant containing wear particles was extracted. After repeating the lipid extraction process three times, an equal volume of absolute ethanol was added and the remaining contaminated proteins were precipitated while stirring at 4°C for 24 h. Finally, the protein was removed by centrifuging the supernatant at 2000 g for 1.5 h.

The purified wear particles were filtered by using cellulose membranes (Millipore filter, Merck Millipore, Germany) with different pore sizes of 10, 1.0, and 0.1 μm, in sequence. In order to evaluate the wear particles, referring to the method by Tipper et al. [21, 22], a cellulose membrane was sputter-deposited with gold and observed with an abrasion powder using a scanning electron microscope (SEM; JSM-6390LV, JEOL, Japan). The long-axis length ($L_l$) and short-axis length ($L_s$) were measured for all isolated particles on 3 × 3 mm square strips of cellulose filters of 10, 1.0, and 0.1 μm (Fig. 7). The equivalent circle diameter ($L$) was calculated from $L_l$ and $L_s$ by (2). The distributions of the equivalent circular diameter ($L$) were estimated.

$$L = \sqrt{(L_l \times L_s)}$$  (2)

The production of inflammatory cytokine against the wear particles isolated was examined. The wear particles on the cellulose filters were released into phosphate-buffered salts, hereinafter referred to as PBS (-), by adding ultrasonic waves. The concentration of wear particles generated from the conventional surface in PBS (-) was adjusted to 200 μg/ml. The concentration of wear particles generated from the MSE-processed surface was adjusted based on the gravimetric wear result, which had a relation to the gravimetric results from the conventional surface.

The same amount of FBS as wear particle containing PBS (-) was mixed by inversion at 4°C for 24 h. From a Dulbecco’s modification of Eagle medium containing 2% FBS and 100 U/ml penicillin, 100 μg/ml was added to prepare the administration medium. In this study, cell experiments were carried out using cells differentiated into HMDMs from blood collected from healthy volunteers. HMDMs (1.0 × 10^4 cells/well) were seeded on the cell plate and cultured for 1 to 2 days for cell adhesion. The medium was removed and a medium containing 2.0 μg of wear particles per well was administered. The method of culturing macrophages after wear particle administration is shown in Fig. 8. Cultivation was carried out with respect to two conditions of erect culture and those in which the plates were covered with paraffin and subjected to an inverted culture. The cultivation time was 24 h. A normal culture, serving as a negative control, was used as a positive control by culturing in a medium containing lipopolysaccharide (0.1 μg/ml LPS). The culture supernatant of each well after culturing was recovered and the production amount of

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**Fig. 6** Separation of polyethylene wear particles in lubricating liquid for evaluating morphological aspects of particles and macrophage activation from particles

**Fig. 7** Definition of morphological parameters, $L_l$ and $L_s$ in polyethylene wear particles
inflammatory cytokine IL-6 was measured using the sandwich method of ELISA.

3 Results and discussion

3.1 Surface profile of Co–Cr–Mo alloy

The conventional surfaces processed by using conventional lapping methods are shown in Fig. 9. Three specimens were processed at the same conditions (Discs 1–3). For these surfaces, the surface roughness \( R_a \) ranged from 9.91 to 18.2 nm, and mirror-finished surfaces were obtained.

The processed surfaces by MSE are shown in Figs. 10–12. The surface roughness \( R_a \) of each processed surface was lower than that of the conventional surface. The MSE process is a type of mechanical removal process, where abrasive particles are injected vertically into the Co–Cr–Mo alloy with plenty of water in the slurry. In this process, the abrasive wear, which was induced by scratching with hard particles, was in low level in comparison to

![Fig. 8 Incubation methods for evaluating macrophage activations from polyethylene wear particles](image)

![Fig. 9 Surface profiles of Co–Cr–Mo alloy (conventional surface) processed by conventional lapping method. Errors indicate standard deviations (N = 10 at each surface)](image)

![Fig. 10 Surface profiles of Co–Cr–Mo alloy (surface 1) processed by MSE methods according to Table 1. Errors indicate standard deviations (N = 10 at each surface)](image)

![Fig. 11 Surface profiles of Co–Cr–Mo alloy (surface 2) processed by MSE methods according to Table 1. Errors indicate standard deviations (N = 10 at each surface)](image)

![Fig. 12 Surface profiles of Co–Cr–Mo alloy (surface 3) processed by MSE methods according to Table 1. Errors indicate standard deviations (N = 10 at each surface)](image)
that in the conventional lapping process, so that the surface roughness was thought to be lower. It was confirmed that a larger $D_p$ could be obtained with the increase in repeated MSE processes at the same path (Figs. 10 and 11, Table 1).

3.2 Polyethylene friction and wear

Fig. 13 shows the frictional coefficient during testing. The frictional behaviour seemed not to be influenced by the surface profile with or without the processing by MSE. Although a high frictional coefficient was recorded at the first stage, the frictional coefficient was decreased in accordance with the sliding distance tested, and finally showed the constant value of about 0.1.

Fig. 14 shows the total amount of gravimetric wear of polyethylene at the sliding distance of $30 \times 10^3$ m. It was elucidated that the processed Co–Cr–Mo alloy surface influenced the specific wear rate of polyethylene. Surface 2 could reduce the wear, whereas the others increased the wear in comparison to the conventional surface. Fig. 15 shows the specific wear rate of polyethylene. For all the Co–Cr–Mo alloy surfaces, the specific wear reduced in accordance with the sliding distance tested.

The results (Figs. 13–15) showed that the polyethylene wear shifted from a running-in regime to a static regime. Under the tribological condition provided in these tests, the lubrication mode between the pin and disc would be in the mixed or boundary lubrication, which means that direct contact between the pin and disc at asperity levels occurred. The strategies for designing the processed Co–Cr–Mo surfaces by MSE in order to reduce the amount of wear of polyethylene were as follows: (1) minimisation of surface roughness to minimise abrasive wear, (2) minimisation of real contact areas between the pin and disc surfaces to minimise adhesive wear, and (3) minimisation of waviness curves to minimise plowing wear. Strategy 1 was easy to achieve because a reduction in $R_a$ can be realised by using the latest precision machining processes. However, strategies 2 and 3 were difficult to achieve, because the surface condition (profile) on the Co–Cr–Mo alloy by adjusting of $D_p$ and $W_t$ in order to minimise the real contact against polyethylene, which has a 'rough surface at micrometre level (not at $R_a$ level)', induces plowing wear. On the other hand, the lowest value of $R_a$ with no $D_p$ and $W_t$ such as a super-smooth and flat surface would reduce the wear. However, the particle size of polyethylene would be smaller, because this surface would promote adhesive wear, which should be avoided based on previous studies.

3.3 Wear particles of polyethylene

Fig. 16 shows an example of the wear particles isolated in this test. According to the SEM observation, the morphological aspect of the polyethylene wear particles was not drastically changed. Distribution of the equivalent circle diameter of polyethylene particles at each condition showed that the processed surface did not change the particle size clearly (Fig. 17).

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Fig. 13  Frictional coefficient during testing

Fig. 14  Total amount of gravimetric wear of polyethylene. The total sliding distance was $30 \times 10^3$ m

Fig. 15  Specific wear rate of polyethylene from 0 to $10 \times 10^3$, $10 \times 10^3$ to $20 \times 10^3$, and $20 \times 10^3$ to $30 \times 10^3$ m

Fig. 16  Examples of wear particles isolated from lubricating liquid
Fig. 18 shows the production of TNF-α and IL-6. The concentration of wear particles added to the culture medium is presented in Table 2, which had a correlation to the generated wear of polyethylene (Fig. 13, second testing). For the upright incubation, both TNF-α and IL-6 were slightly decreased by using surface 2, which could be due to the low concentration of wear particles in the culture medium. Although the concentration of particles was low, surface 1 increased both TNF-α and IL-6 at both upright and inverted incubations. In the series of tests conducted, the change of a morphological aspect of wear particles was not obvious (Figs. 15 and 16). The density of polyethylene is lower than that of water, so that the particles may move upward into the culture medium. That is the reason why inverted incubation should be performed, where the macrophages attached to the top ceiling might capture the floating polyethylene particles. However, the proteins contained in the culture medium might be adsorbed onto the polyethylene particles, and the hydrated polyethylene particles might be promoted. In this case, the particles could stay into the culture medium or go down to the bottom of the culture plate. That is the reason why upright incubation should be performed. From these discussions, the production of TNF-α and IL-6 seemed to have a correlation with the amount of wear particles added; however, the incubation method, i.e. upright/inverted method, needs further investigation for an accurate analysis.

![Fig. 17 Distribution of equivalent circle diameter of polyethylene particles. Number of particles measured under each condition is shown in figure](image)

**Table 2** Concentration of wear particles added at each test

| Surface Type     | Concentration, μg/ml |
|------------------|----------------------|
| Conventional     | 200                  |
| surface 1        | 169                  |
| surface 2        | 104                  |
| surface 3        | 281                  |

Concentrations were referred to wear results in each second test (Fig. 13).
4 Conclusion

The surface of a Co–Cr–Mo alloy disc was processed by MSE. The wear behavior of UHMWPE (Co-28Cr-6Mo) pin was tested by using a pin-on-disc wear testing machine. The alloy disc surface processed by MSE influenced the specific wear rate of polyethylene, however, the morphological aspect of polyethylene wear particles was not drastically changed. HMDMs were incubated with the particles generated in the wear tests by using an upright/inverted method. The production of TNF-α and IL-6 seemed to have a correlation with the amount of wear particles added, however, the influence of particle size on the production of TNF-α and IL-6 was not obvious. This means that the improvements for the incubation method, i.e. upright/inverted method, need further investigation for the accurate analysis.

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