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Wear behavior and wear debris distribution of UHMWPE against Si_3N_4 ball in bi-directional sliding

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Abstract

Four kinds of wear tracks possibly occurred in the wear of artificial hip joints, including uni-directional sliding, oval curvilinear sliding, double-elliptical sliding, triple-elliptical sliding, were simulated on the UMT wear tester by using of a Si_3N_4 ball sliding on the UHMWPE disc under bi-directional sliding motion. The wear behavior and wear particle distribution of UHMWPE in plasma solution lubrication were studied for these sliding motions. The experimental results indicate that the wear mass loss in uni-directional reciprocating sliding is much smaller than those in bi-directional sliding modes. The wear rates of UHMWPE in bi-directional sliding modes are linearly inverse proportional to the defined frequency factor, as agreed with the cross-shear theory. This result suggests that cross-shear movement with larger intersection angles is a significant factor influencing the wear rate of UHMWPE, and the bi-directional sliding path at direction reversals will play an important role on the increasing of UHMWPE wear compared to uni-directional sliding motion. In bi-directional sliding modes, the wear particle distribution range decreases when direction reversal path increases in the sliding motions. So, the complex wear tracks are harmful to the implant joint due to the higher wear and more active wear particles. The particles sizes follow a lognormal distribution. The central size and the peak accumulation of UHMWPE particles decreases and increases against the frequency ratio, respectively, besides the uni-directional reciprocating sliding. These suggest that the intersection angle increasing on sliding path will contribute to the size decreasing of UHMWPE wear particle. Also, cross-points on sliding track will produce wear particles in smaller size. The radius of curvature of the curvilinear paths may be dictating the size reducing of UHMWPE wear particles. The main wear mechanisms are ploughing in uni-directional reciprocation, while plastic deformation, adhesion and fatigue in the bi-directional sliding modes.

Keywords: UHMWPE; Wear; Sliding modes; Wear particles; Size distribution; Wear mechanism

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) is a well-known biomaterial having low friction [1]. Owing to its superior mechanical toughness and wear resistance, UHMWPE has been used as an acetabular cup in total artificial hip joints since the early 1960s. The wear of UHMWPE components implanted in human body produces wear debris. As the service time of artificial joints prolongs, the aseptic losing and the osteolysis induced by UHMWPE wear becomes the main cause of long-term failure of hip joint replacements [2–4]. It has been known that the wear particles generated at the prosthetic surface enter the peri-prosthetic tissue where they are phagocytosed by macrophages. The macrophages release pro-inflammatory cytokines and eventual loosening of the prosthesis, which results in the failure of total hip replacement. In tribological aspect, the goal of biotribological research of total hip replacement is to develop a new hip joint having “low wear and less harm” property, in order to reduce UHMWPE debris generation and control their bioactivity in human body [5].

A number of researchers investigate the wear mechanism of UHMWPE in total joint replacements. Linear elastic stress analysis using finite element methods [6] shows that the maximum principal stress within the UHMWPE during normal walking is usually less than 10 MPa for the total joint replacement. But it has not led to any significant understanding of the wear mechanism of UHMWPE in total joint replacement for that the wear of UHMWPE is not an elastic process in the hip component. When

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acetabular cup/femoral head are put into contact, their microscopic asperities are plastically deformed, although the overall, or nominal, contact is elastic. An incremental residual plastic strain is built for that every contact asperity experiences repeating cyclic deformation during walking. Failure will occur when the ductility of material within each unit contact spot comes to the limit. Based on the critical strain criterion model, wear particle will be produced when the accumulated plastic strain reaches the critical strain. Although this theory is validated by experimental results, the wear rate of UHMWPE in this experiment is lower than clinical results [2]. The low-wear phenomenon is normally encountered when the artificial joint material is measured with the conventional simple wear tester [7,8]. However, the joint simulators have received limited success in reproducing clinical wear rates [9–12].

Some papers have attempted to explain the low-wear phenomenon observed on simple wear test machines. Mckellop [13] proposes that the conventional wear testers are overly simplistic in motion and loading configurations, and low UHMWPE wear may be closely associated with their linear motion. Bragdon et al. [14] further proposes that higher clinical wear rates in UHMWPE acetabular cups may be associated with multi-directional motion of the hip joint. Wang et al. suggests that the motion-dependent behavior of UHMWPE wear is attributed to the unique molecular structure of UHMWPE, which molecules orient preferentially in the direction of sliding [15,16,18]. In linear-tracking motion, molecular orientation leads to strain-hardening of the wear surface, which results in wear resistance enhancement as sliding proceeds. In multi-directional motion, the UHMWPE wear surface experiences both shear and tensile stresses in multiple directions. Strengthening in one particular direction will result in weakening in the perpendicular direction—a phenomenon that is often observed in oriented linear polymers [16,19]. Recent computer simulation of the human joint kinematics has indeed indicated that stresses experienced by the surface in both the hip and knee joints are multi-directional [16,17,20].

It has been proved that there are different modes of multi-directional sliding in not only real hip but also various simulators [21,22]. Most of the gait slide tracks are oval figures, but there are also tracks with very high aspect ratio and small tracks similar to HUT-3 simulators. The tracks on acetabular cup, produced by BRM simulator, include figures of eight line, straight line, nonsysmmetric oval and elliptic figures. Because the wear of the most common acetabular cup material, UHMWPE, has been found to be highly sensitive to the motion modes [10,16,23], it is important to investigate the influence of motion patterns on the wear of UHMWPE. Up to now, we knew little about the effect of these sliding tracks on the wear of UHMWPE. Turell et al. [24] studied the effect of elongated and closed rectangular motion patterns on the wear of UHMWPE. Their results obey the orientation softening theory.

The purpose of this paper is to study the wear behavior of UHMWPE under different sliding motions with varied bi-directional shear rates and find the most significant factor influencing the wear rates and wear particle distribution of UHMWPE material. In this paper, we designed four kinds of sliding patterns, including straight line, oval shape, double-elliptical (butterfly-like) figure and triple-elliptical (double butterfly) figure to carry out the wear tests of UHMWPE disc against Si_3N_4 ceramic ball on a ball-sliding-on-disc machine, which represents the sliding tracks of a single contact point between the femoral head of an orthopaedic implant and the acetabular cup during testing. The wear behaviors of UHMWPE under these sliding modes and their quantitative characterization are studied. Naturally, there are an infinite number of tracks on hip cup, and wear of the hip cup is the wear summation of all tracks. The research of single type of wear track will be helpful for deep understanding of the wear mechanism of acetabular cups.

2. Experimental details

2.1. Test materials

The UHMWPE samples were prepared using a hot-press molding method. The molecular weight of UHMWPE is 5,000,000 g/mol. UHMWPE powder was pre-pressed in a molder under pressure of 5 MPa at room temperature for 15 min. Then the molder was heated to 190–200 °C without applied pressure for 2 h. Afterward, UHMWPE sample was pressed under 15 MPa pressure until it cooled to 50 °C in atmosphere. The UHMWPE sample was prepared in disc shape with diameter of 30 mm and thickness of 10 mm. The friction surface of UHMWPE sample was polished to the average roughness of $R_a = 0.2–0.4\ \mu m$. Before testing, UHMWPE samples were cleaned in acetone in ultrasonic bath. A Si_3N_4 ball was selected as the counterpart of UHMWPE to simulate the wear of artificial joints consisting of UHMWPE cup and ceramic head. The diameter of all Si_3N_4 balls is 4 mm and their surface roughness locate at 0.01–0.03 μm. Two samples were tested for each wear track and the mean of wear mass loss was taken as the testing results.

2.2. Wear tests

The ball-on-disc wear tests were performed on an UMT tester developed at CETR (Campbell, CA). This tester can produce synchronized combinations of linear and rotary motions with in situ measurements of tribological parameters, including friction forces and coefficient, wear depth, contact acoustic emission, etc. The schematic of contact between Si_3N_4 ball and UHMWPE is shown in Fig. 1. The Si_3N_4 ball mounted to the three-dimensional force sensor reciprocates in X direction, and the UHMWPE disc driven by an eccentric rotator reciprocates in Y direction. We set the UHMWPE disc reciprocating at fix frequency of 0.5 Hz, however, the Si_3N_4 ball at varied frequency of 0 Hz, 0.5 Hz, 1 Hz and 1.5 Hz. As a result, four kinds of wear tracks are formed with different frequency ratio, as shown in Table 1, which are plotted by the X and Y position data recorded during wear tests. The reciprocating amplitudes of disc and ball are 12 mm. The sliding distance per cycle in Table 1 is approximately calculated by

$$l = \sum_{i=1}^{n} \sqrt{(X_i - X_{i+1})^2 + (Y_i - Y_{i+1})^2} \qquad (1)$$