Numerical Contact Model of Delaminating Destruction in Ultra-high Molecular Weight Polyethylene (UHMWPE) Knee Component

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Introduction
Recently, flaking-like destruction so-called “delamination” has been reported in retrieved ultra high molecular weight polyethylene (UHMWPE) knee components (Collier et al., 1991; Walker et al., 1996). The debris generated through delamination may enter the periprosthetic tissue, leading in many cases to periprosthetic osteolysis and loosening of implants often necessitating revision surgery. In order to extend the longevity of artificial knee joints, it is necessary to elucidate the initiation mechanism of delaminating destruction in UHMWPE. The authors developed a new numerical contact model based on the discrete element method (DEM (Cundall et al., 1979)), which enabled us to analyze nonlinear deformation and ultimate destruction in inhomogeneous material such as UHMWPE (Shibata et al., 2000). In this study, a DEM-based numerical contact model was proposed and a two-dimensional numerical simulation on sliding fatigue test was performed as the first step to examine the microscopic behavior of delaminating destruction of a UHMWPE knee component.

Methods
The UHMWPE component (5 mm in thickness and 20 mm in length) as agglomerate of polyethylene grains was discretized with discrete and pore elements as shown in Fig. 1. The pore elements, which were supposed to act equivalently to deformation resistance as a pseudo-continuous body, were embedded in apertures between the rigid discrete elements. The circular discrete elements with the unit thickness were used, the size of which was empirically determined as 70 microns in radius by taking both the accuracy of solution and computing time into consideration. Grain boundary was arranged randomly based on the Voronoi decomposition. The hemispherical head of an indenter (titanium alloy: Ti-6Al-4V) 3 mm in curvature radius was assumed to be rigid, compared with the UHMWPE component, and was represented by one rigid discrete element.

Figure 1: Discretization of the UHMWPE specimen with discrete and pore elements and modeling of interactive forces between them

All the discrete and pore elements in the UHMWPE component constituted a networked system connecting them mechanically with each other. As shown in Fig.1, the interactive forces, which act between these elements as internal reactive forces to external loads, were modeled by simple mechanical elements: an elastic spring, a damper, a coupling and a friction slider to represent the viscoelastic characteristic, peculiar to polymer materials such as UHMWPE.
UHMWPE has microscopic material discontinuity caused by the existence of grain boundaries due to its processing method, which makes microscopic material constants at grain boundaries different from those in intra-granular portions (Tomita et al., 1999). In this study, microscopic material constants at grain boundaries and those in intra-granular portions were determined as summarized in Table 1. Microscopic destruction in UHMWPE was assumed to occur by given criteria of destruction, tensile strength in tension and Mohr-Coulomb’s law of yielding in shear.

\[
k_n = \frac{\pi (1 - \mu)}{4(1 + \mu)(1 - 2\mu)} E, \quad k_t = \frac{\pi}{8(1 + \mu)} E
\]

\([E] : \) Macroscopic Young’s modulus of a bulk UHMWPE ( = 500 MPa)

\([\mu] : \) Poisson ratio of a bulk UHMWPE ( = 0.4)

subscript \(n\): normal component \(t\): tangential component

\((k_n)_{\text{boundary}}, (k_n)_{\text{in}}, (k_t)_{\text{boundary}}, (k_t)_{\text{in}}\) were determined by calculation based on experiments of dynamic micro-indentation (Shibata et al. 2000).

\[
\begin{align*}
\eta_n &= C \cdot 2\sqrt{m k_n}, \quad \eta_t = C \cdot 2\sqrt{m k_t} \\
(\eta_n)_{\text{boundary}} &= C \cdot 2\sqrt{m \cdot (k_n)_{\text{boundary}}}, \quad (\eta_n)_{\text{in}} = C \cdot 2\sqrt{m \cdot (k_n)_{\text{in}}} \\
(\eta_t)_{\text{boundary}} &= C \cdot 2\sqrt{m \cdot (k_t)_{\text{boundary}}}, \quad (\eta_t)_{\text{in}} = C \cdot 2\sqrt{m \cdot (k_t)_{\text{in}}}
\end{align*}
\]

\([m] \): equivalent mass of two circular discrete elements \(m_1\) and \(m_2\) defined as:

\[
\frac{1}{m} = \frac{1}{m_1} + \frac{1}{m_2}
\]

\([\zeta] = 6\pi \eta r\]

\((\zeta)_{\text{boundary}} = 6\pi \cdot (\eta_n)_{\text{boundary}} \cdot r, \quad (\zeta)_{\text{in}} = 6\pi \cdot (\eta_t)_{\text{in}} \cdot r)

\([r] \): radius of circular discrete elements

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<thead>
<tr>
<th>spring constant</th>
<th>(k_n, k_t)</th>
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<th>damper coefficient</th>
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<th>friction coefficient</th>
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Table 1: Summary of parameter setting

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<thead>
<tr>
<th>(F_z)</th>
<th>(F_0)</th>
<th>(V_x)</th>
<th>(V_0)</th>
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<tr>
<td>stationary period</td>
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Figure 2: Time-course changes of the load and motion imposed on the indenter

A metallic pin on a UHMWPE plate sliding fatigue test was conducted by a two-dimensional numerical simulation in this study. Figure 2 shows time-course changes of the load and motion imposed on the pin (titanium alloy: Ti-6Al-4V). Prior to reciprocating movement, 10 minutes of stationary period \(t_0\) in Fig. 2) was given because of relaxation of creep deformation in UHMWPE. Subsequently the reciprocating sliding movement was imposed at a speed of \(V_0\) ( = 0.1 m/s) under a constant load of \(F_0\) (= 196 N).

Results & Discussion
As shown in Fig. 3, stress concentration was observed to occur at grain boundaries in a subsurface layer ranging from
the sliding surface to 3 mm in depth. The values of von Mises stresses backward to the contact center were higher than those forward. As the number of sliding increased, a decrease in von Mises stresses was obtained showing stress softening in the subsurface layer (Fig. 4). When friction force acts on the sliding surface, a friction coefficient more than 0.11 results in maximum shear stresses at the contact surface (Smith et al., 1953). Moreover, whenever the indenter head runs on an arbitrary point on the surface, the point can be periodically exposed to dynamic tension-compression stress condition in a direction parallel to the sliding surface. As surface grain boundaries suffer dynamic periodical stresses under the stress-concentrated condition, microscopic cracks can be initiated at the surface grain boundaries. Our numerical result also suggests that microscopic crack initiation can be occurred at subsurface grain boundaries. This coincides with the result of experimental observation on the sliding fatigue test of UHMWPE specimens (Ohashi et al. 1996). Therefore stress concentration at surface and subsurface grain boundaries can be one of the important factors that triggers microscopic crack initiation as the initial stage of delamination.

However, influences of other unknown factors on stress concentration at grain boundaries have to be examined because it has been reported that simple sliding reciprocation does not possibly result in wear and delamination (Bragdon et. al., 1995). To accomplish the study, further research is needed by three-dimensional numerical analysis simulating multi-directional sliding fatigue conditions in in vivo articular knee joints, the investigation of which is now under way.

![Figure 3](image1.png)  
**Figure 3**: Depth profile of von Mises stress in the UHMWPE component for various pin position $x$ (number of sliding: N=100)

![Figure 4](image2.png)  
**Figure 4**: Depth profile of von Mises stress in the UHMWPE component for various number of sliding $N$ (on the plane $x=0$)

References