Journal of the Mechanical Behavior of Biomedical Materials 79 (2018) 314–323

Contents lists available at ScienceDirect

Journal of the Mechanical Behavior of Biomedical Materials

journal homepage: www.elsevier.com/locate/jmbbm

Mechanical wear and oxidative degradation analysis of retrieved ultra high molecular weight polyethylene acetabular cups

Dipankar Choudhury[a,b], Matúš Ranuša[c,*], Robert A. Fleming[a], Martin Vrbka[d], Ivan Křupka[d], Matthew G. Teeter[e], Josh Goss[a,b], Min Zou[a,b,**]

[a] Department of Mechanical Engineering, University of Arkansas, Fayetteville, AR, USA 72701
[b] Center for Advanced Surface Engineering, University of Arkansas, Fayetteville, AR, USA 72701
[c] Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic
[d] Central European Institute of Technology (CEITEC), Brno University of Technology, Brno, Czech Republic
[e] Medical Biophysics and Surgery, Schulich School of Medicine & Dentistry, Western University, 339 Windermere Road, London, Ontario, Canada, N6A 5A5

ARTICLE INFO

Keywords:
Retrieved prosthesis
Wear
Oxidative degradation
Plasticity index
Micro-CT
Raman spectroscopy
Nanoindentation

ABSTRACT

The number of revision joint replacements has been increasing substantially over the last few years. Understanding their failure mechanism is extremely important for improving the design and material selection of current implants. This study includes ten retrieved and four new mildly cross-linked ultra-high molecular weight polyethylene (UHMWPE) acetabular liners. Among them, most of the prostheses (n = 5) were reported to be revised and replaced due to aseptic loosening, followed by painful joint (n = 2), dislocation (n = 1), intra articular ossification (n = 1), combination of wear (liner) and osteolysis (stem) (n=1). Surface deviations (wear, material inflation and roughness), oxidative degradation and change of material properties were measured using micro-computed tomography (micro-CT) scan, 3D laser scanning microscopy, raman spectroscopy and nanoindentation, respectively. Prostheses having eccentric worn areas had much higher linear wear rates (228.01 ± 35.51 μm/year) compared to that of centrically worn prostheses (96.71 ± 10.83 μm/year). Oxidation index (OI) showed similar trends to the surface penetration depth. Among them, sample 10 exhibited the highest OI across the contact area and the rim of the cup liner. It also had the lowest hardness/elasticity ratio. Overall, wear and creep, oxidative degradation and reduced hardness/elasticity ratio all contributed to the premature failure of the UHMWPE acetabular cup liners.

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) is a common bearing material in the acetabular components used in total hip arthroplasty (2017; Steinberg, 2014). It contributes to the good performance features such as absorbing impact loadings and giving low frictional sliding (Ge et al., 2009; Kurtz, 2009). Typically, a UHWMPE liner is placed in a titanium alloy shell to form the acetabular cup component of the implant. The stiffness of the acetabular cup component, when measured by rim compression, is less than when a metal or ceramic cup liner is used. It has been suggested acetabular cup components with lower stiffness provide a more uniform load distribution on the pelvis compared with that of stiffer components and this is a possible further advantage of using UHMWPE (Small et al., 2013).

Cup liners made from UHMWPE can suffer from higher wear rates than when other liner materials are used (such as metals or ceramics). These wear rates are still low enough to avoid immediate problems after hip replacement surgery. However, as found in one wear simulator study (Goldsmith et al., 2000), they can be as much as 100 times higher than that of metal-on-metal hip implant systems. Over time, these UHMWPE wear rates change the overall conformity of the articular joint and affect the contact mechanics and wear mechanisms (Dowson et al., 2004; Goldsmith et al., 2000). Also, more significantly, this wear rate results in an accumulation of wear particles into the periprosthetic tissues. The contacting surface of the UHMWPE components also suffers from creep. Creep is a permanent deformation, which occurs due to rearrangement of the positions of the polyethylene molecules and could result in an increasing hardness, stiffening and embrittlement.

To improve the wear resistance of virgin UHWMPE, cross-linking of its microstructure can be performed. In the retrieved and new cup liners of the present study, this was done by a γ-irradiation process in a nitrogen atmosphere (25–45 kGy/N_2 sterilized). The nitrogen atmosphere

* Corresponding author.
** Corresponding author at: Department of Mechanical Engineering, University of Arkansas, Fayetteville, AR, USA 72701.
E-mail addresses: Matus.Ranusa@vut.cz (M. Ranuša), mzou@uark.edu (M. Zou).

https://doi.org/10.1016/j.jmbbm.2018.01.003
Received 1 December 2017; Accepted 3 January 2018
Available online 06 January 2018
1751-6161/

prevents oxygen from combining with the free radicals at the ends of the chains that were cut by the irradiation process, and thus cross-linking occurs without oxidation. However, the oxidative process can initiate after the irradiation process; and in the presence of the lipids in the body fluid, the oxidation accelerates. It is to be noted that, the extent of cross-linking is considered to be mild when 25–45 kGy irradiations are applied.

Current literature (Peers et al., 2015; Xiong and Xiong, 2012) reports that using highly cross-linked polyethylene (HXLPE, 50–100 kGy γ-irradiated with various strategies for reducing free radicals) significantly reduces wear (Kurtz et al., 2010). Bragdon et al. (2007) reported that the use of “HXLPE substantially improved the prognosis of patients after THA (total hip arthroplasty) up to 13 years as judged by clinical scores, incidence of osteolysis, and polyethylene wear measurements”. Furthermore, a recent study of total knee arthroplasty by de Steiger et al. (Steinberg, 2014) found a lower revision rate when cross-linked polyethylene (≥ 50 kGy with various strategies to reduce free radicals) was used compared with the mildly cross-linked polyethylene (≤ 50 kGy versions identified above), but noted that this was only for a smaller subset of implant designs and patient groups. In addition, HXLPE cup liners that were infused with vitamin E demonstrated further improvements against oxidation (Puppulin et al., 2016). However, very long term clinical data for HXLPE are still not available. Moreover, the older versions of UHMWPE ($25 - 45$ kGy/N_2 sterilized) may still find some applications in knee replacements (Sakellariou et al., 2013) and a large number of patients still have older version of polyethylene in acetabular and tibia liners (Fulin et al., 2016; Pokorny et al., 2012). Hence, the wear and degradation of the older version of polyethylene remains a topic of interest.

The wear and surface degradation of acetabulum component of an artificial hip joint have very complex mechanisms, where mechanical wear, creep and oxidative degradation could happen simultaneously and also accelerate each other. A comprehensive mapping (locations and level) of wear, creep and oxidation of the retrieved prosthesis might provide insight into the mechanisms and processes of surface degradation. Besides surface degradation, changing mechanical properties, such as hardness and modulus of elasticity, are key indicators for contact and wear mechanisms. For example, a higher ratio of hardness and modulus of elasticity with lower wear when surface coatings are applied to orthopaedics implants (Ching et al., 2014). For the retrievals of the present study, oxidation causes hardening and embrittlement of UHMWPE and so the, ratio of hardness to modulus of elasticity changes over time. The changed mechanical properties can be precisely measured using nanoindentation (Briscoe et al., 1998; Cakmak et al., 2012).

Radiographic, gravimetric, volumetric and optical techniques are available for mapping mechanical wear and creep. A few examples of the techniques involved are: a) 3D profiler (Govind et al., 2015; Ranusa et al., 2017; Ranuša et al., 2016), b) coordinate measuring machine (CMM) (Spinelli et al., 2009; Uddin et al., 2016) and c) micro–computer topography (micro-CT) (RAD, 2015; Teeter et al., 2011). These techniques can map wear/creep volume and the measurement accuracy is related to the number of detected points. Micro-CT is a non-destructive technique (NDT) that can provide precise and accurate volumetric measurements along with quantifiable three-dimensional surface deviation maps for the entire retrieved prosthesis surface (Teeter et al., 2011).

On the other hand, advanced NDT for measuring oxidation are: scanning electron microscopy (SEM) with Energy Dispersive Spectroscopy (EDS) (Costa et al., 2002; Salahshoor and Guo, 2014), Raman spectroscopy (Puppulin et al., 2016), transmission electron microscopy (TEM) (Hellmann et al., 2015), and Fourier transform infrared spectroscopy (FTIR) (Pezzotti et al., 2007). Raman spectroscopy is a very powerful tool, easy to operate and affordable compared to EDS and TEM. Moreover, Raman can also assess the complex microstructural changes at the microscopic scale giving the fraction of crystalline phase in the polyethylene (Pezzotti et al., 2007). This enables Raman spectroscopy to detect chemical distortion caused by creep deformation and oxidation, which cannot be achieved by FTIR.

Pezzotti et al. (2007, 2011) developed and validated a protocol for separately measuring the contributions to the dimensional change in acetabular cups arising from creep and wear without any destructive sample manipulation. They considered the integrating peaks around I_{1293}, I_{1305} and I_{1414} cm^{-1} as the main Raman spectra for measuring oxidation index and orthorhombic crystalline phase fraction. Puppulin et al. (2016) conducted a similar study which included various cross-linked UHMWPE cups. The study mapped oxidation indices and crystalline fraction in the depth direction and along the material subsurface. The results revealed the effects of γ-ray irradiation and vitamin E blended on the oxidation indices of HXLPE cups for total joint replacement.

One of the key limitations of these published NDT studies on wear and oxidation analysis was their reliance on a single measurement technique and the lack of surface mapping. For example, almost all of the wear studies only considered mechanical wear rate and the remaining studies considered only Raman spectra based studies. As noted by Kumakura et al. (2009) and Pezzotti et al., (2017), orthopaedics implants undergo both mechanical and chemical wear, and it is essential to conduct a combined study to map wear and creep followed by an oxidation and crystalline study. Puppulin et al. (2016) and Pezzotti et al. (2007) predicted an ideal wear-zone and conducted their Raman analyses, but Jasty et al. (1997) showed that the wear at the articulating surface was characterized by a highly worn polished area superiorly and a less worn area inferiorly, separated by a transition ridge, in all components, depending on the host patient gait patterns, surgical technique and accuracy. Thus, it is important to identify the wear-zone through mapping to accurately measure wear rates and relate them to wear mechanisms.

The main purpose of the present study was to examine the relationships between hip implant failures and features of their retrieved polyethylene cups such as the location of the wear and creep on the cup along with chemical and mechanical changes in material properties. Therefore, we measured surface deviations (material added to or removed from the original surface), roughness, oxidation indices and ratios of hardness to elastic modulus of the retrieved polyethylene liners along with the same measurements of new polyethylene liners to provide a baseline. Following clinical observations, the reasons for retrieval were classified into three subgroups (Table 1): group-1: aseptic loosening, group-2: pain in the joint, and group-3: other (variety of other reasons). The surface deviations were mapped with micro-CT because of its time-efficiency, easy post-processing of the measurement data and precision. Based on the surface deviation map, the targeted areas were identified and Raman analyses were conducted. Finally, nanoindentation was utilized for measuring the hardness and modulus of elasticity of selected samples, which were also used to provide some validation for the crystalline outcomes from the Raman spectra.

2. Materials and methods

2.1. New and retrieved prostheses

A total of four new and ten retrieved polyethylene cup liners from Bicon-plus acetabular cup components (Plus Endoprothetik AG, Rotkreuz, Switzerland; later Smith and Nephew, USA) were studied. All of the cup liners were made from compression molded GUR 1020 UHMWPE according to International Organization for Standardization (ISO-5834-2) and American Society for Testing and Materials (ASTM-F648). The irradiation dose (applied in a N_2 environment) was between 25 and 37 kGy (Milosev et al., 2012). All the cup liners had inner surface radius of 14 mm. The cup components were implanted using cementless fixation.