Investigation of the tribological behavior of amorphous carbon coatings for total knee replacement using a pin-on-disk tribometer

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Great efforts are made to reduce the aseptic loosening of total knee replacements, for example by biotribologically effective surface modifications in order to decrease the wear of polymer inlays. This study focused on the characterization and tribological testing of wear-reducing amorphous carbon coatings with good adhesion to the medical technology materials Co28Cr6Mo and PE-UHMW. Thereby, the present study showed the applicability of coatings to the considered materials and the high potential for wear reduction.

Keywords: Total knee replacement, Biotribology, PVD Coatings, Wear

1. Introduction

The aim of the endoprosthetic replacement of joints is to restore functionality and to provide patients with a painless life [1]. Total knee replacements (TKR) usually consist of a Co28Cr6Mo (CoCrMo) femoral component that rubs against PE-UHMW (PE) inlay. The wear particles removed from TKR are largely responsible for early prosthetic failure [2], primarily due to aseptic loosening [1]. This study focused on the characterization and tribological testing of wear-reducing amorphous carbon coatings with good adhesion to CoCrMo and PE and to analyze wear mechanisms and influencing factors.

2. Methods

Due to promising tribologically effective behavior [3], a tungsten-doped hydrogen-containing amorphous carbon coating (a-C:H:W) was applied to the CoCrMo pins and an a-C:H coating to the PE disks by physical vapor deposition (PVD). A thin adhesive layer of chromium and an intermediate layer of tungsten carbide were used to achieve a high coating-substrate adhesion. In contrast, the a-C:H coating was applied to the polymeric substrate by reactive PVD without intermediate layers. The coating samples were characterized regarding coating thickness and adhesion to substrate using crater-grinding method [4] and scratch testing [5], respectively. Hardness was measured by instrumented indentation test [6].

The tribological behavior of the coated material pairings in comparison to the uncoated pairings was investigated utilizing a climate-controlled pin-on-disk tribometer in rotational sliding mode. Efforts were made to reproduce the boundary conditions in the peri-implant environment, whereby the diluted bovine serum used was tempered to 37 °C in fully flooded lubrication. The wear rates were determined using light and laser scanning microscopy.

3. Results and Discussion

With an indentation hardness of about 13.5 GPa, a-C:H:W coating (thickness of less than 1 µm) was significantly harder than CoCrMo. The coating systems deposited on CoCrMo endured loads of about 54 N in scratch tests without spalling. The a-C:H coating had a thickness of about 1.5 µm and an indentation hardness of about 1.5 GPa, which represented a forty-fold increase compared to substrate hardness while maintaining high adhesion. Thus, no coating applied to PE showed any damage in the form of chipping in the scratch tests.

The wear rates of uncoated and coated disks as well as uncoated and coated pins are compared in figure 1. It was found that a coated sliding combination reduces wear on PE disks by about 66 % and on pins by 57 %. The a-C:H coating was suitable for preventing wear on PE due to its inert character and its favorable H_{IT}/E_{IT} ratio. A similar behavior was observed for the a-C:H:W coated CoCrMo pin compared to the uncoated CoCrMo pin. Despite the pin having permanently been in contact, the magnitude of the wear rate differed between PE and CoCrMo substrates by a factor of 10. This could be attributed to the stiffer and harder character of CoCrMo, which could be supplemented by an additional coating with a-C:H:W to achieve tribologically favorable behavior.

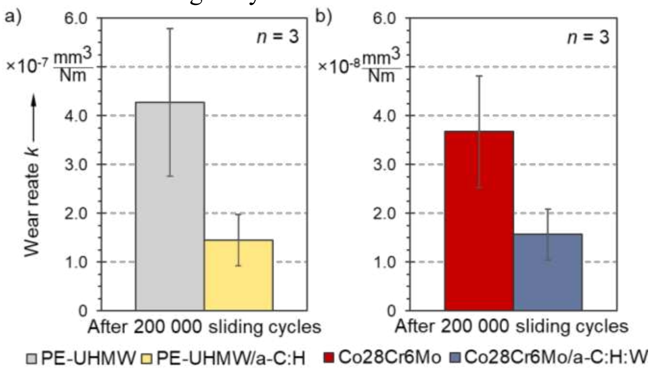

Figure 1: Arithmetic mean and standard deviation of wear rate of PE disks (a) and CoCrMo pins (b).

4. References

[1] Lombardi, A.V. et al., "Why knee replacements fail in 2013: patient, surgeon, or implant?", Bone Joint J., 96-B, 11 Supple A, 2014, 101–104.
[2] Kretzer, J.P. et al., "Wear in total knee arthroplasty – just a question of polyethylene?: Metal ion release in total knee arthroplasty", International orthopaedics, 38, 2, 2014, 335–340.
[3] Hauert, R. "A review of modified DLC coatings for biological applications", Diamond Relat. Mater, 12, 2003, 583–589.
[4] German Institute for Standardization (DIN): DIN EN ISO 26423. Beuth (2016).
[5] German Institute for Standardization (DIN): DIN EN ISO 20502. Beuth (2016).
[6] German Institute for Standardization (DIN): DIN EN ISO 14577-1. Beuth (2015).