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Modification of joint prosthesis surfaces by ultrashort pulse laser treatment for improved joint lubrication

Abstract: Endoprotheses such as hip replacements are subject to wear. Lubrication of the joint interface plays a key role in the wear process, but the mechanisms of lubrication is challenging to understand. The main issue is the three-body abrasion which leads to a shorter life cycle. In order to improve the life cycle, the surfaces of the articulating components can be modified, for example by pulsed femtosecond-laser microstructuring. By microstructuring of the implant surface, the viscosity of the synovial fluid between the joint can be increased due to the non-Newtonian properties of the synovia. This leads to better lubrication and therefore lower particle abrasion. The objective of this study was to evaluate the impact of different microstructures on the viscosity of a joint fluid substitute. Various microstructures were investigated in a modified rheometer setup featuring a decreased gap size. As a test fluid, a synovial fluid substitute was used. The results show that an increase in the viscosity of the synovial fluid substitute can be achieved by microstructuring. An increase of viscosity of up to 20 % compared to the unstructured reference was observed with ring-structures with a diameter of 100 μm and a depth of 20 μm .

Keywords: joint prosthesis, laser microstructuring, ultrashort pulse laser, wear, synovia, viscosity

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1 Introduction

A common reason for a joint prosthesis to fail is wear. Particles generated by adhesive wear or abrasive wear may act as abrasives and causes damage on the joint interface. Approximately 10% of these implants undergo revisions within a 15-year lifespan per device. [1] Therefore, preclinical wear tests are necessary in order to predict the *in vivo* performance of such prostheses. The surface of the implant plays a vital role in the behavior of the synovial fluid in the joint interface. The synovial fluid of diarthrodial joints has two key functions: the lubrication and the transportation of nutrients to the cartilage. [2] Next to the properties of the joint fluid that affect the tribological properties of prostheses the rheological behavior of the joint fluid plays an important role and needs to be investigated further in the context of total knee arthroplasty. [3] Basically, the changes that arise from knee osteoarthritis can affect the rheological properties of the synovial fluid due to disease progression. [4]

State-of-the-art prosthetic knee joints consist of ultra-smooth bearing surfaces. One of the most common failure mechanisms of prosthetic knee joints are mechanical loosening and instability, caused by osteolysis, which is driven by a biological response to polyethylene wear particles that causes bone resorption. It is well-known that adding a specifically designed patterned microstructure to otherwise smooth bearing surfaces can increase the load-carrying capacity and lubricant film thickness between these bearing surfaces and, thus, reduce friction and wear. [5] Therefore, changing the structure of the articulating implant surface can alter the behavior of the synovial due to the non-Newtonian behavior of the synovia. It is a feasible approach to microstructure implant surfaces in order to advance the functionality of joint prostheses in regards to reduced friction and particle abrasion as well as viscosity adjustment of the synovial fluid. [6,7]

The aim of the current study is to investigate the impact of different microstructures, generated by ultrashort pulse laser technique, on the resulting viscosity of a joint fluid substitute. This approach paves the way to joint prosthesis with reduced wear and finally enhanced longevity.

2 Materials and Methods

The disks for the viscosity measurements were manufactured in accordance to the standard DIN ISO 6476 and have a diameter of 25 mm and a height of 6 mm with a surface roughness of $R_a \leq 0.1 \mu\text{m}$. The material is a medical CoCr alloy type Ergiloy 9.9135HL from the company Zapp Precision Metals GmbH (Ratingen, Germany).

Microstructuring was carried out with a femtosecond fiber laser of the type UFFL_60_200_1030_350_SHG of the manufacturer Active Fiber Systems GmbH (Jena, Germany). A ring area of the disks with an outer radius of 12.5 mm and an inner radius of 5 mm was microstructured (see Fig. 2). A pulse energy of $0.1 \mu\text{J}$ with a pulse duration of 800 fs and a repetition rate of 50 Hz was used.

The surface structure was analysed using a laser scanning microscopy (VK-X200, Keyence Corporation, Osaka, Japan). For measuring the viscosity, the rheometer MCR 702 from the company Anton Paar Germany GmbH (Ostfildern, Germany) was used. In order to be able to measure the effect of the microstructures, the gap between the specimens and the measurement geometry was reduced from $500 \mu\text{m}$ to $100 \mu\text{m}$. To insure the parallelism, a setup was designed that uses adjustable micro screws and an inductive sensor. With this setup, a parallelism of approx. $\pm 5 \mu\text{m}$ is realisable. Fig. 1. shows the setup of the samples with the sensor and the micro screws. The measurements were carried out at a temperature of 21°C and at a constant shear rate of 100 s^{-1} , even though a shear rate dependency of the viscosity of joint fluid is well known. [3] Nonetheless, it was necessary to measure the properties in the chosen range in order to effectively compare the samples.

Figure 1: Measurement setup for the disk samples

Instead of using synovial fluid, a substitute fluid exhibiting comparable non-Newtonian behavior was used [8]. The substitute fluid consists of bovine calf serum from the company Bio&Sell GmbH (Feucht, Germany) with a protein

content between 32 - 37%. Hyaluronic acid (HA) with a molecular weight of $2 \times 10^6 \text{ Da}$ was added to a ratio of 3 g/L in order to resemble synovial fluid. The concentration of HA in the synovial fluid is in the range of 2%–3% with molecular weights of 10^6 – 10^7 Da . [9] The HA was purchased from the company Sigma-Aldrich Chemie GmbH (Taufkirchen, Germany). Four different microstructures as well as an unstructured specimen for reference were investigated in regards to their effect on the viscosity of the synovial substitute fluid. The microstructures have the following specifications:

- Square: $50 \times 50 \times 1 \mu\text{m}$ at a distance of $50 \mu\text{m}$
- Net: $15 \times 20 \mu\text{m}$ (w/d) at a distance of $100 \mu\text{m}$
- Web: $20 \times 10 \mu\text{m}$ (w/d) at a radial distance of $200 \mu\text{m}$ and an angle of 1.15° between the radial lines
- Rings: $100 \times 10 \times 20 \mu\text{m}$ at a radial distance of $200 \mu\text{m}$ for distance of $200 \mu\text{m}$ between circular tracks
- Reference: no micro structures

At least 5 viscosity measurements of each specimen were carried out for statistical reasons.

3 Results and discussion

All disks have been successfully laser structured and analysed. A ring structured specimen is depicted in Fig. 2.

Figure 2: Femtosecond-lasers-structured CoCr specimen for viscosity investigations. The specimen features a ring microstructure at the outer ring area of the disk.

Fig. 3 shows laser scanning microscopy scans of the different microstructures that were applied to the disk samples. No expulsion of melt could be observed and the resulting cavities and structures feature sharp edges due to the minimal thermal impact of the ultrashort laser pulses.

Figure 3: Different microstructures of the disk samples (top left: square, top right: net, bottom left: web, bottom right: rings)

The results of the viscosity measurements demonstrate that the microstructures on the surface lead to a significant increase of the viscosity of the synovial fluid substitute. As seen in Fig. 4, the structures in net and ring form have the biggest effect on the viscosity of the fluid. The viscosities show an increase of approx. 20 % compared to the unstructured reference specimen.

Figure 4: Results of the viscosity measurements of the synovial fluid substitute on different microstructures measured at a constant shear rate of 100 s⁻¹.

Considering that the microstructures have different shapes and sizes, it is imperative to investigate and understand the main impact factors of the structures, such as structure density, symmetry or depth. Qiu et al. recommended that the largest minimum lubricant film thickness in the bearing occurs with a texture area density between 20 % and 40 % and an aspect ratio of 0.025. [5] One observation implies that the depth of the structure, for example, has a bigger impact on the viscosity increase than the structure width. The net structure as well as the rings have the deepest pits, which could cause the fluid to

change its flow behaviour to a higher degree than the other structures. The fluid can flow into the pits, whereby the shear rates are lowered and the viscosity increases. The smallest increase can be seen in the square structure, which have a depth of only 1 μm . This structure was investigated, because it showed promising wetting behaviour in a hydrodynamic lubrication study. [10] However, the good lubrication behaviour did not result in a high viscosity behaviour. Therefore, it is of great interest to see if a rise of viscosity due to the microstructures also increases the lubricant film thickness. Thus, an increased portion of the bearing load is carried by the lubricant film, resulting in reduced contact and friction. [11]

Deeper microstructures are helpful with regard to the collection of particles since more particles can fit in the larger structure volume. This is a positive indicator that third-body abrasion can be reduced. Surface textures may act as lubricant reservoir, providing lubricant to the contact in cases of starved lubrication, and entrap wear debris, minimizing third-body abrasion.

4 Conclusion

A lot of research has been aimed at finding optimal texturing parameters for best enhancement results. Although some general guidelines exist, it has become clear that in most cases textures need to be designed in regard to the given operating conditions. This further underlines the need for accurate and robust models that allow the evaluation of future texture designs. It shows great promise that a patterned microstructure optimized for a prosthetic knee bearing will reduce friction and wear by means of improved lubrication. This study has already shown an increase of viscosity up to approx. 20 % at femtosecond-lasers-structured surfaces. Further investigation of different microstructures will help find optimal parameters for knee joint lubrication in the context of total knee arthroplasty.

Author Statement

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