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Wear-reducing surface functionalization of implant materials using ultrashort laser pulses

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Abstract

The aim of the project called "EndoLas" is the development of a reproducible and reliable method for a functionalization of articulating surfaces on hip joint endoprostheses due to a reduction of abrasion and wear by the generation of micro structures using ultrashort laser pulses. On the one hand, the microstructures shall ensure the capture of abraded particles, which cause third-body wear and thereby increase aseptic loosening. On the other hand, the structures shall improve or maintain the tribologically important lubricating film. Thereby, the cavities serve as a reservoir for the body's own synovial fluid. The dry friction, which promotes abrasion and is a part of the mixed friction in the joint, shall therefore be reduced. In experimental setups it was shown, that the abrasive wear can be reduced significantly due to micro-structuring the articulating implant surfaces.

To shape the fine and deterministic cavities on the surfaces, an ultra-short pulsed laser, which is integrated in a high-precision, 5-axes micro-machining system, was used. The laser system, based on an Yb:YAG thin-disk regenerative amplifier, has an average output power of 50 W at the fundamental wavelength of 1030 nm, a maximum repetition rate of 400 kHz and a pulse duration of 6 ps. Due to this, a maximum pulse energy of 125 μJ is achievable. Furthermore external second and third harmonic generation enables the usage of wavelengths in the green and violet spectral range.

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Keywords: *ultrashort laser pulses; wear reducing; surface functionalization; mirco-structuring*

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1. Motivation and Aims

Worldwide about 1.5 million implantations of artificial hips or knees are performed every year (Baumann 2008). 8.3% of these surgical procedures are revision operations, which are primary induced by the aseptic implant loosening (Wirtz 2009). In turn, the aseptic implant loosening is induced by abraded wear particles in the most cases (Talmo (2011).

The aim of SLV's project "EndoLas" is to develop a reproducible and reliable method for a functionalization of articulating surfaces on hip joint endoprostheses due to a reduction of abrasion and wear by the generation of micro structures using ultrashort laser pulses. On the one hand, the microstructures shall ensure the capture of abraded particles, which cause third-body wear and thereby increase aseptic loosening. On the other hand, the structures shall improve or maintain the tribologically important lubricating film. Thereby, the cavities serve as a reservoir for the body's own synovial fluid. The dry friction, which promotes abrasion and is a part of the mixed friction in the joint, shall therefore be reduced.

2. Methods

2.1. Micro-structuring of metallic and medical ceramic specimen using ultrashort laser pules

To produce fine cavities on metallic (CoCrMo) and medical ceramic (ELEC®plus, HiPer Medical AG, Oberkrämer, Germany) specimen for tribological functionalization, an ultrashort pulsed laser (TruMicro 5X50, Trumpf GmbH & Co. KG, Ditzingen, Germany), which is integrated in a high-precision micro-machining system (GL.evo, GFH GmbH, Deggendorf, Germany) was used. The laser-system features the following specifications:

- Average laser power: 50 W (1,030 nm) , 25 W (515 nm), 15 W (343)
- Pulse duration: 6 ps
- Repetition rate: 400 kHz
- Precision of axes and scanner: < 1 μm
- Number of axes: 5 (simultaneous)
- Axes speed: up to 2 m/s
- Scanning speed: up to 4 m/s

Fig. 1 shows the USP-micromachining system in in the SLV M-V GmbH.

Fig. 1: USP-micromachining system at the SLV M-V GmbH

Based on literature research and an analysis of the demands on the microstructures to be produced, the necessary dimensions of the structure geometries were determined. The aim was on the one hand a low notch effect and on the other hand to ensure a sufficiently large size of the structures, so that the abraded particles can be deposited over 20 years in the structures without filling them completely. Fig. 2 exemplary shows three different micro-structured patterns, which were applied on the CoCrMo and medical ceramic specimen.

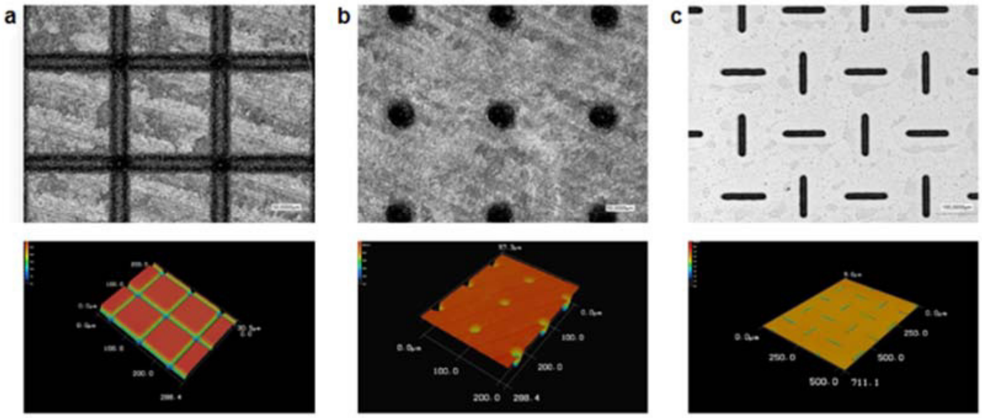

Fig. 2: Different micro-structured patterns on medical ceramic (a, b) and CoCrMo (c) specimen

Table 1 shows exemplary the process parameters for structuring grid patterns with a depth and width of about 20 μm on CoCrMo disc-shaped specimen with high quality.

Table 1: Process parameters for structuring grid patterns on CoCrMo discs

Process parameter	Value
Pulse duration [ps]	6
Wavelength [nm]	343
Spot size [μm]	~10
Focal length [mm]	100
Lens type	f-Theta
Pulse energy [μJ]	2,0
Number of parallel laser paths	2
Line distance of the parallel laser paths [μm]	4
Scanning speed [mm/s]	2,000
Repetition rate [kHz]	400
Repetitions	200

In addition, Table 2 shows the process parameters for structuring grid patterns with a depth and width of about 20 μm on ELEC®plus disc-shaped specimen with high quality.

Table 2: Process parameters for structuring grid patterns on medical ceramic (ELEC®plus)

Process parameter	Value
Pulse duration [ps]	6
Wavelength [nm]	1,030
Spot size [μm]	~10
Focal length [mm]	100
Lens type	f-Theta
Pulse energy [μJ]	6,1
Number of parallel laser paths	3
Line distance of the parallel laser paths [μm]	3
Scanning speed [mm/s]	2,000
Repetition rate [kHz]	400
Repetitions	17

2.2. Numerical Analysis of the fluid dynamic processes in the lubricating gap

Based on the obtained knowledge, a numerical simulation of the fluid dynamic processes in the lubricating gap of the micro-structured surfaces was performed by using ANSYS (ANSYS Inc., Canonsburg, USA). In this case, the gap describes the space between the articulating surfaces, as it is shown schematically in Fig. 3.

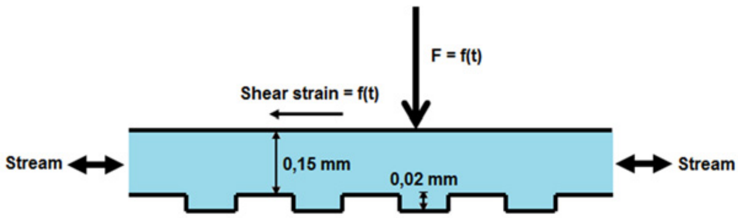

Fig. 3: Lubricating gap between the articulating surfaces

Gap thicknesses as well as flow conditions in the gap of an artificial hip joint were investigated under dynamic load for the micro-structured surfaces respective to the load analyses of Bergmann (2001). In the study of Bergmann, the dynamic stress cycle was determined by analysing the human gait experimentally. Fig. 4 shows the stress cycle for dynamic load used in the simulation.

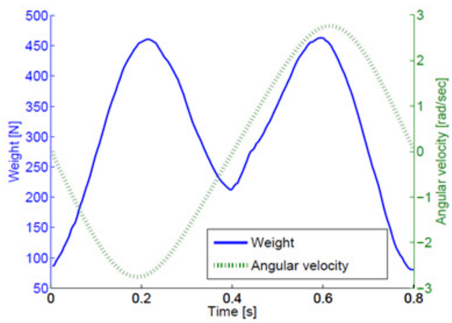

Fig. 4: Stress cycle for dynamic load respective to Bergmann (2001)

Fig. 5 shows the numerical models used for the three different micro-grooves.

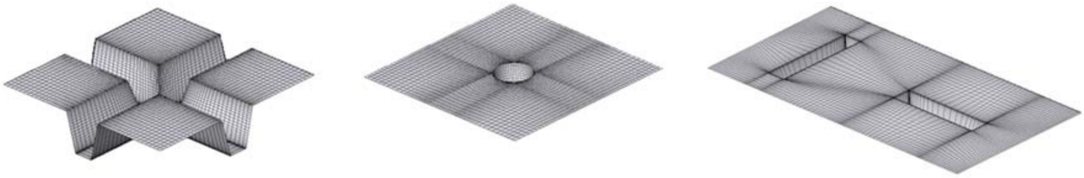

Fig. 5: Simulation models with numeric meshes of the three different micro-pattern grooves

2.3. Abrasion tests according to the Ring-on-Disc- method

In an experimental setup according to the Ring-on-Disc-method (DIN ISO 6474), different micro-structured ring- and disc-shaped specimen were tested tribologically. Fig. 6 shows the metallic and ceramic Ring-on-Disc specimen, which were used for the tests.

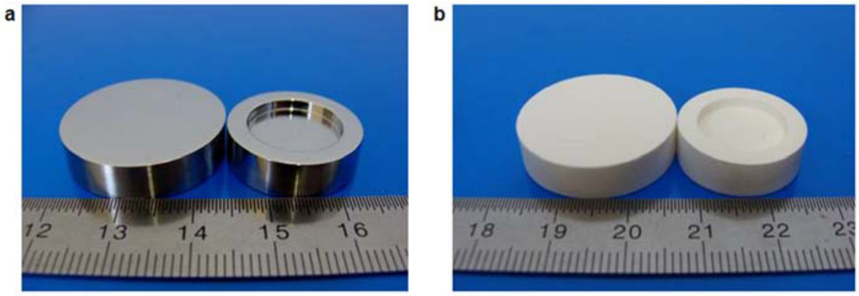

Fig. 6: (a) CoCrMo and (b) ELEC®plus Ring-on-Disc specimen

By micro-structuring the disc surfaces with 20 μm deep and 20 μm wide patterns with a lateral distance of 100 μm, as it is shown in Fig. 2, five specimen of each pattern were structured (n = 5). In the tests, the rings were oscillated at 25° rotational movement on the corresponding discs. Bovine serum was used as the test fluid to simulate the human synovia at the best. With an oscillating frequency of 1 Hz, each pair of specimen was tested for 100 h under an axial load of 100 N. In addition to the structured specimens, unstructured specimens were tested as references under the same test conditions. After testing, the amount of wear was determined by profile measurement of the wear track using laser scanning microscopy (VK-X200, Keyence Corporation, Osaka, Japan). Fig. 7 shows a Ring-on-Disc test plant.

Fig. 7: Ring-on-Disc test plant with mounted pair of specimen [EndoLab (2015)]

3. Results

3.1. Numerical Results

Due to turbulences in the cavities longitudinal and transversal to the flow direction, different dynamic viscosity layers appeared along the cavity depth, as it is shown in Fig. 8.

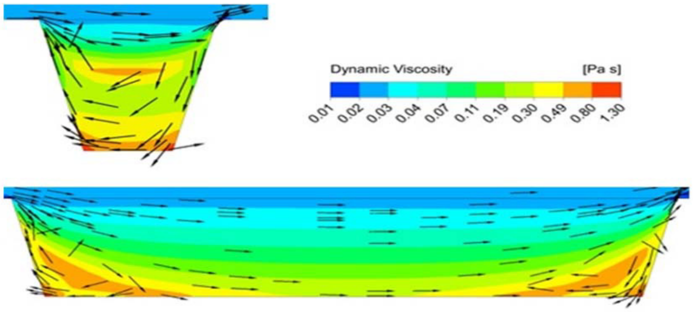

Fig. 8: Viscosity and velocity vectors in the cavities

The graphics also show, that the dynamic viscosity increases in the cavities. Generally, an exchange of the highly viscous synovia from the cavities to the lubricating gap is advantageous for the gap flow. Fig. 9 shows the micro-pattern based changes of the dynamic viscosity and the remaining gap, which lead to an improvement of the fluid dynamic processes in the lubricating gap.

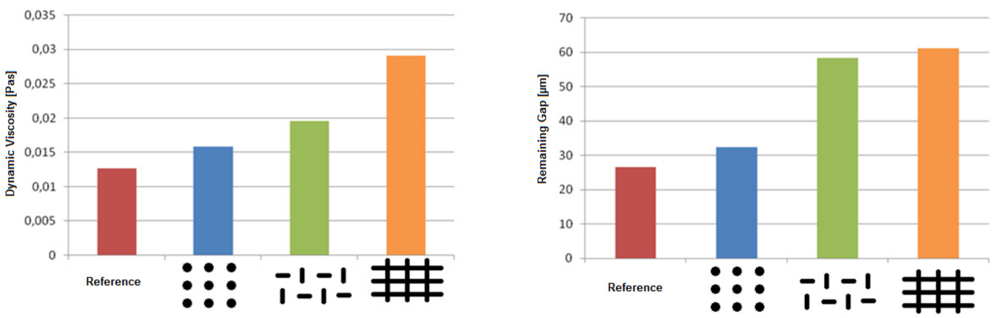

Fig. 9: Numerical results of the dynamic viscosity and the remaining gap respecting the different micro-patterns

By means of a structural analysis, the mechanical stress of the treated surfaces was investigated in the joint gap with regard to their notch effect. The equivalent stress maximums appear in the lower edges of the cavities. However, these stresses are much lower than the flexural strength of both materials, CoCrMo and ceramic.

3.2. Reduction of abrasive wear

In the first step, only grid patterns and unstructured specimen were tested. Currently, the other patterns are in the tests. After testing according to the Ring-on-Disc method, the grid-structured specimens were analysed using the laser scanning microscope. Thus, the abrasive wear was measured on each disc specimen. Fig. 10 exemplary shows the reduction of the wear volume measured on CoCrMo disc specimen, comparing reference and grid-structured surfaces.

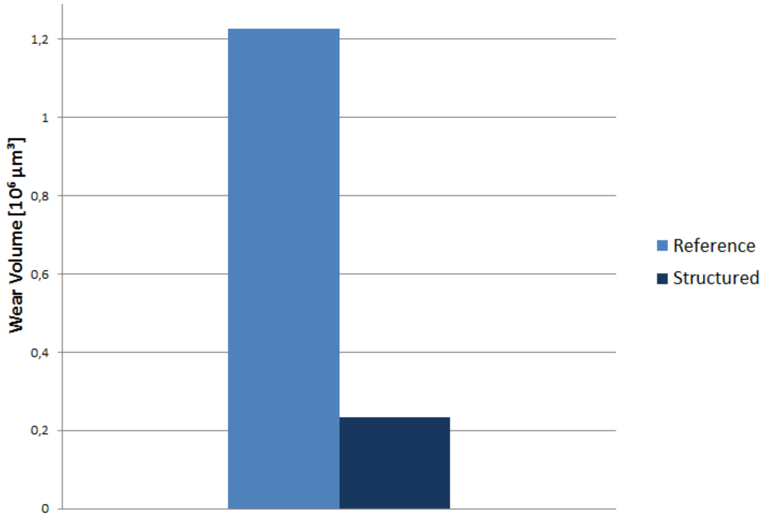

Fig. 10: Measured wear volume on reference and grid-structured CoCrMo disc specimen

Due to the micro-structuring, a reduction of the abrasive wear volume of about 80% was achieved on CoCrMo specimen. Due to the high hardness of the medical ceramic, the abrasive wear of the reference and structured specimen approached zero, so that no significant reduction of the abrasive wear volume was measured on the ceramic specimen using laser scanning microscopy. However, the reduction of wear particle induced scratches can be seen on SEM images, as shown in Fig. 11.

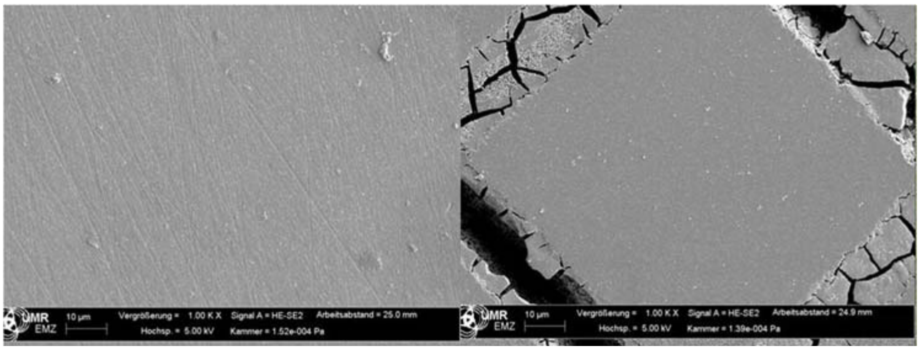

Fig. 11: Reduction of surface scratches due to micro-structuring of medical ceramic specimen after Ring-on-Disc tests (left: reference, right: micro-structured)

The SEM image clearly shows fewer scratches on the micro-structured surface. It can also be seen, that the patterns are filled with material residues. In this case, these residues are probably based on dried proteins from the bovine serum for the most part, as well as on a few wear particles.

4. Perspectives

The numerical simulations as well as the experimental tests have shown a significant improvement of the tribological properties of articulating metallic and ceramic implant materials. In preliminary tests an abrasive wear reduction of about 80% was achieved. The next milestone of the project will be the transfer of optimized micro-structures on artificial femoral heads. Subsequently, the notch factor of the micro-structures will be tested according to Berst-tests. In the last step, micro-structured artificial femoral heads will be tested in a hip simulator according to DIN ISO 14242 to simulate the human gait for five million cycles, which corresponds to walking about 5 years, to measure the abrasive wear reduction afterwards. Regarding to the *in vivo* state of hip endoprostheses, this should reduce the abraded particle induced aseptic implant loosening and, due to improved tribological properties, increase the durability of hip implants significantly.

Acknowledgements

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