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Friction reduction of stainless steel surfaces by laser microstructuring

Niklas Berger[a,*], Benjamin Keim[b], Munehiro Chijiiwa[a], Hicham Derouach[a], Senta Schauer[b], Mareike Schäfer[a], Johannes A.L'huillier[a]

[a]*Photonik-Zentrum Kaiserslautern e. V. (PZKL), Kohlenhofstr. 10, 67663 Kaiserslautern, Germany*
[b]*EPflex Feinwerktechnik GmbH, Im Schwöllbogen 24, 72581 Dettingen an der Erms, Germany*

Abstract

Recently, friction reduction has become important in a wide range of technical applications. One limiting factor is the abrasion of two surfaces when they are moved against each other, causing friction losses. To overcome this, a functional optimization is necessary and thus the effectiveness of components will be increased by structuring the surfaces. Our approach is to introduce a dimple structure by laser microstructuring into the surface and thus significantly reduce the friction. In order to avoid burr around these dimples, it is necessary to operate good heat management. For this reason, we carried out experiments using a USP laser with a pulse duration of 10 ps. Dimples with a diameter of 10 – 30 micrometers were made and systematic investigations were carried out by changing the depth and the arrangement of the dimples. By optimizing these parameters, friction could be reduced by 30 % compared to an unstructured surface.

Keywords: friction; dimples; picosecond-laser; microstructure

1. Introduction

In the modern engineered world, it is important for many applications to control the friction between two surfaces. In some cases, it is necessary to increase the friction to a maximum to prevent unwanted movement. In other cases, it is helpful to reduce the friction forces as much as possible. By reducing the frictional forces, for example, energy losses in motors can be reduced and their service life increased at the same time. Around the year 2000, Etsion et al. reported that textured surfaces covered with micro dimples are suitable for this type of application (Etsion et al., 1996; Etsion et al., 1999; Etsion et al., 2004).

Over the years, various texturing techniques have been developed and investigated (Müller et al., 2020; Conradi et al., 2018; Bonse et al., 2018). Techniques worth mentioning here include ion beam etching/milling (Marchetto et al., 2008), lithography (Pettersson et al., 2004), electrochemical machining (Walker et al., 2017),

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* Corresponding author.
E-mail address: niklas.berger@pzkl.de .

mechanical texturing (Greco et al., 2009), and laser surface texturing (LST) (Ryk and Etsion, 2006). Performed with an ultrashort pulse laser, LST stands out among these methods because it is possible to texture almost any material comparatively fast, variably, and with high precision without significant mechanical or thermal stress.

Our approach was to use these advantages to structure guide wires used by surgeons for positioning catheters. The aim was to reduce friction between the guidewire and the inner wall of the vascular system and thus prevent injuries. For these investigations, the tissue of the vascular system was represented by silicone pads. The aqueous environment present during surgery was represented by water for the tests. Unlike most other tests, in this application, one of the two surfaces is very easily and reversibly deformable. In addition, only one of the two surfaces, the metal wire, is available for functionalization. Due to these restrictions, the results of other investigations could not be transferred one to one. Thus, the exact properties for effective friction reduction had to be investigated.

2. Experimental Setup

2.1. Material

To investigate the technical feasibility of the friction reduction the investigation starts with flat wires. The experiments were conducted on stainless steel (type: 1.4301). The width of the wires was 800 µm and their thickness was 200 µm.

Before and after surface texturing the wires were cleaned by wiping five times with cleanroom wipes soaked in isopropanol. Before surface texturing this cleaning was necessary to prevent an interfering of contaminants to the laser process. The surface texturing process itself causes some debris to partially cover the surface close to the individual dimples. Therefore, another cleaning procedure was necessary.

2.2. Laser texturing with ps pulses

Dimples were textured on both sides of the wires by using a five-axis laser material processing system (GL.5, GFH GmbH). This system is equipped with an ultrashort pulsed laser system (Hyper Rapid 25, Coherent Kaiserslautern GmbH) and a 2-D scanner (hurry Scan II/14, Scanlab GmbH) for fast deflection of the beam on the sample surface. The laser can provide pulses with a pulse duration of 10 ps, a selectable wavelength of 1064 nm, 532 nm(SHG), or 355 nm (THG) and a variable pulse repetition frequency up to 1 MHz. To focus the laser beam on the surface of the material f-theta optics with a focal length of approximately 100 mm, made for the respective wavelength, were used.

2.3. Characterization of the samples

The morphology and topography of the textured surfaces were studied by using optical microscopy (Axio Imager, Carl Zeiss AG) and confocal microscopy (Zeiss smart proof 5, Carl Zeiss AG). Figure 1 shows a confocal image as an example with a dimple textured surface. For the characterization of the wettability of selected textured samples, we used a drop shape analyzer system (DSA30, Krüss GmbH).

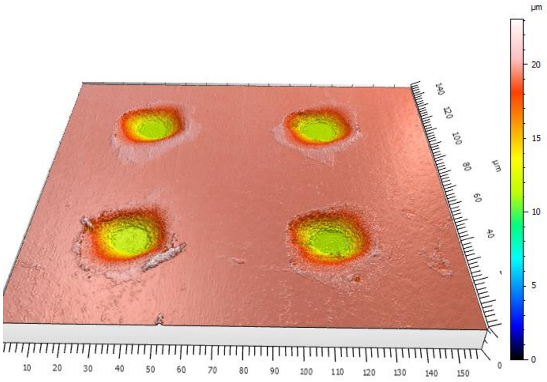


Fig. 1. Confocal microscope image of four dimples on a stainless steel surface

2.4. Friction measurement system and test conditions

The tribological characterization has been carried out by a specifically developed measuring system, as can be seen in figure 2. For the friction measurement, the stainless steel samples were pulled through two silicone pads that were pressed together with a force of 3 N by a 3-D printed clamp. Adjusting the closing force to this value was done by attaching a weight of 122 g to one arm of the clamp (see figure 3). The contact area between a silicone pad and the stainless steel was 16 mm² (width of the silicone = 20 mm times the width of the stainless steel flat wires = 800 µm), resulting in an average pressure between the silicone pads and the stainless steel wire of approx. 1,9 bar.

To determine the maximum occurring frictional forces the following measuring procedure was used: One end of the stainless steel samples was fixed to the digital force gauge (Digital Force Gauge Series 3, Mark-10). From there the wire hung downwards between the silicone pads. For simulating the aqueous environment in the application, the silicone pads were submerged under water. By moving the digital force gauge with the motorized linear stage the stainless steel sample was pulled with a speed of 2 mm/s through the silicone pads. While this was happening, the digital force gauge measured the force that was necessary to overcome the friction between the steel sample and the silicone. This process was repeated 25 times per sample. Afterward, the maximum force for each round was measured and an average value for F_{max} for the sample was calculated.

A reference value was determined by applying this procedure to various unstructured samples. The mean value for F_{max} for these samples was at 2.5 N with a standard deviation of 0.25 N. This gives a reference range from 2.25 N to 2.75 N which will be marked green in the following diagrams when presenting the experimental results in section 3.

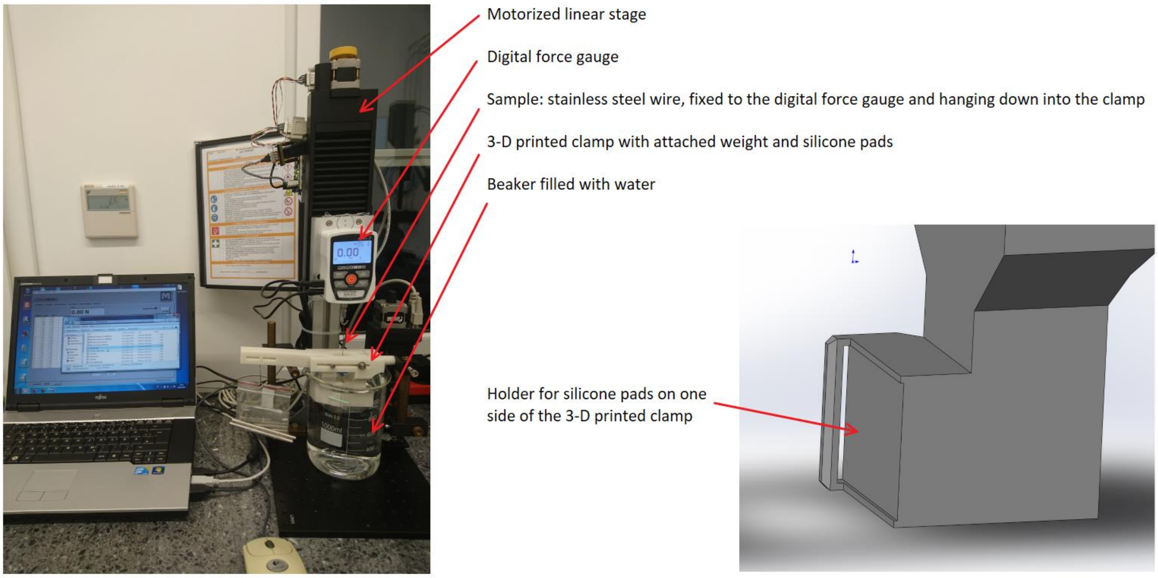
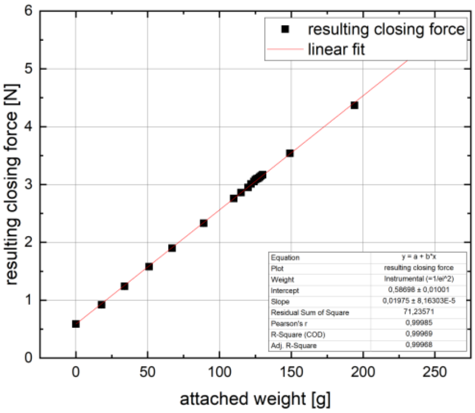


Fig. 2. (a) friction measurement system; (b) Holder for silicone pads at the bottom of the 3-D printed clamp



Equation	y = a + b*x
Plot	resulting closing force
Weight	Instrumental (=1/ei^2)
Intercept	0,58698 ± 0,01001
Slope	0,01975 ± 8,16303E-5
Residual Sum of Square	71,23571
Pearson's r	0,99985
R-Square (COD)	0,99969
Adj. R-Square	0,99968

Fig. 3. Closing force of the clamp with different weights attached

3. Results and Discussion

In order to study systematically the influence of the laser textured surfaces on the friction behavior, we separate our investigation into two parts. It is known, that surface functionalization is an interaction between surface chemistry and realized micro/nanostructures on the surface by laser texturing (Samanta et al., 2020). Therefore, in the first step, we study the influence of topographic modifications by changing the texture dimensions and texture density. In a second step a controlled chemically modification of the surface will be conducted to investigate the friction behavior.

3.1. Topographic modifications

Since dimple structures have already proven to be suitable for achieving friction reduction under lubricant influence, we focused on this kind of structures. For the topographic modifications to the surface, we focused on two major aspects: The proportion of the dimple surface area to the total surface area and the aspect ratio (depth / diameter) of the individual dimples.

Density and diameter of the dimples (/ proportion of the dimple surface area to the total surface area)

According to Lie et al. (Lie et al., 2017) the friction reduction for a dimple structured surface is based on hydrodynamic flows, occurring in every single dimple. Although if the dimples are too close to each other, they can affect each other's fluid dynamics. Due to the elastic material we were using, we expected the optimal dimples to be slightly different than researched for undeformable surfaces (e.g. Lie et al., 2017). Therefore, we analyzed the optimal distance between two dimples for a dimple diameter of 30 µm, 17 µm and 10 µm. The three different dimple diameters were made by using the 3 available wavelengths of the laser and focusing the laser beam with a f = 100 mm f-theta optic. For a better comparison of those structures, the x-axes in figure 4 show the percentage of the surface covered by the dimples. The most friction reduction for dimples with a diameter of 30 µm could be observed with a proportion of surface coverage by the dimples of 4 %. But at this point, even small changes in the dimples shape or the distance between two dimples had a dramatic effect on the friction reduction. As it can be seen in figure 4, the smaller the individual dimples are, the more stable this minimum of friction appears to be. Nevertheless, for smaller dimple sizes the production time for one sample increases significantly and is therefore not economical. So we decided to go on with the medium-sized dimples, with a diameter of 17 µm and a surface coverage by the dimples of 4 %, which is equivalent to a distance between two dimples of 75 µm.

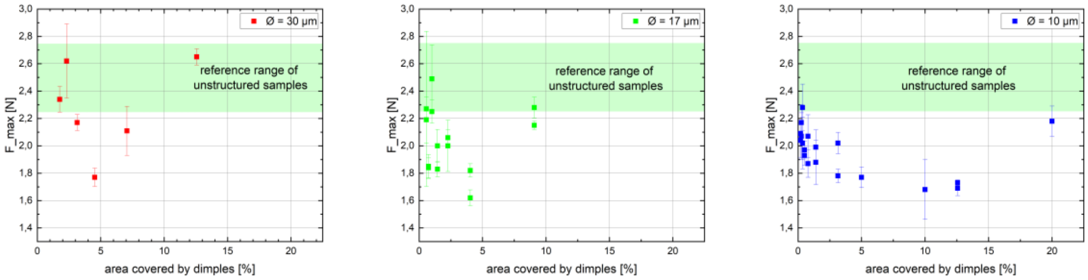


Fig. 4. F_{max} measured for structured steel surfaces with (a) dimples with a diameter of 30 µm; (b) dimples with a diameter of 17 µm; (c) dimples with a diameter of 10 µm

Aspect ratio

For the determination of the ideal aspect ratio, 7 structures with different depths were made. The aspect ratio is given by the dimple depth divided by the dimple diameter. Achieving the ideal and consistent friction reduction, an aspect ratio of at least 0.32 must be achieved as shown in figure 5. Increasing the aspect ratio above this value did not lead to any further improvements. According to Li et al. (Lie et al., 2017), the ideal aspect ratio should only be 0.08. However, two rigid, non-deformable bodies were considered by Li et al. (Lie et al., 2017). In contrast, we are dealing here with a body that is easily and reversibly deformable. This may cause some changes in the hydrodynamic flow between both surfaces and therefore cause a much higher aspect ratio to represent the optimum.

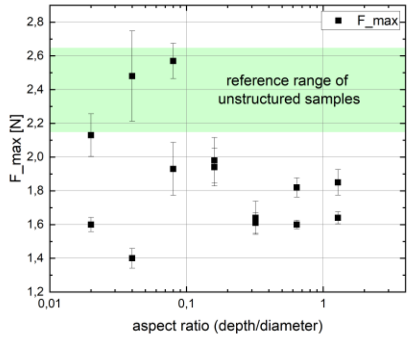


Fig. 5. F_{max} measured for structured steel surfaces with dimples with a diameter of 17 µm and a distance between two dimples of 75 µm. The aspect ratio (= depth / diameter) was changed by changing the depth of the dimples.

3.2. Chemical modifications

Since the friction reduction is based on hydrodynamic flows within the dimples, we expected the wettability of the surface to have a great influence on the frictional forces. In (Chijiiwa et al., 2021) methods were investigated to convert the surface of steel samples to a hydrophilic or hydrophobic state. To establish a hydrophilic state the samples were put into boiling water after the structuring and cleaning process. For establishing a hydrophobic state the samples were put into a vacuum chamber.

For this test, we studied a total of six samples, three of whose surfaces were transferred to a hydrophilic state and three of whose surfaces were transferred to a hydrophobic state. Before the wettability adapting treatment all 6 samples were structured with the same, “optimal” dimple structure, found in previous experiments. The results of the friction measurements are shown in figure 6. Here it can easily be seen, that the friction reduction effect of the dimples only took place for the hydrophilic surfaces, when the dimples are filled with lubricant.

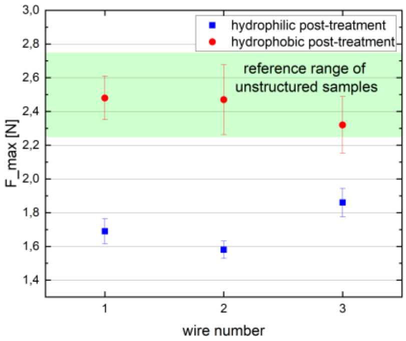


Fig. 6. F_{max} measured for structured steel surfaces with dimples with a diameter of 17 µm, a depth of 10 µm and a distance between two dimples of 75 µm. 3 samples were treated for a hydrophilic surface, and 3 samples were treated for a hydrophobic surface.

4. Conclusion

We have shown that dimple structures can not only be used to reduce the friction between two non-deformable surfaces, but also to reduce the friction between one solid, and non-deformable surface and one elastically deformable surface. Compared to a system of two non-deformable surfaces the density of the dimples and their aspect ratio had to be adjusted for an optimal friction reduction. Especially the aspect ratio has to be increased drastically. Although it is important that the surface can easily be wetted by the lubricant because the effect of friction reduction can only occur when the dimples are filled with the lubricant. For our system of a stainless steel surface and a silicone surface, the optimal friction reduction took place for a dimple diameter of 17 µm and a surface coverage of 4 %. Due to the elasticity of the silicone surface, the optimum aspect ratio of the dimples was found to be 0.32. While a higher aspect ratio didn’t lead to any further improvement, a lower one definitely had to be avoided. If the steel surface had hydrophilic properties due to post-treatment, a friction reduction of 30 % could be achieved.

Acknowledgements

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References

BONSE, Jörn, et al. Femtosecond laser texturing of surfaces for tribological applications. Materials, 2018, 11. Jg., Nr. 5, S. 801.

Chijiiwa, M., et al. The effect of chemical components on wettability at ps laser micromachined surface on stainless steel 304. Accepted for Laser in Manufacturing, 21.-24.06.2021.

CONRADI, Marjetka; DRNOVŠEK, Aljaž; GREGORČIČ, Peter. Wettability and friction control of a stainless steel surface by combining nanosecond laser texturing and adsorption of superhydrophobic nanosilica particles. Scientific reports, 2018, 8. Jg., Nr. 1, S. 1-9.

ETSION, Izhak. Improving tribological performance of mechanical components by laser surface texturing. Tribology letters, 2004, 17. Jg., Nr. 4, S. 733-737.

ETSION, Izhak; BURSTEIN, L. A model for mechanical seals with regular microsurface structure. Tribology Transactions, 1996, 39. Jg., Nr. 3, S. 677-683.

ETSION, Izhak; KLIGERMAN, Yuri; HALPERIN, G. Analytical and experimental investigation of laser-textured mechanical seal faces. Tribology Transactions, 1999, 42. Jg., Nr. 3, S. 511-516.

GRECO, Aaron, et al. Surface texturing of tribological interfaces using the vibromechanical texturing method. Journal of manufacturing science and engineering, 2009, 131. Jg., Nr. 6.

Li, Kangmei, et al. Numerical investigation of the tribological performance of micro-dimple textured surfaces under hydrodynamic lubrication. Beilstein journal of nanotechnology, 2017, 8. Jg., Nr. 1, S. 2324-2338.

MARCHETTO, Drn, et al. AFM investigation of tribological properties of nano-patterned silicon surface. Wear, 2008, 265. Jg., Nr. 5-6, S. 577-582.

MÜLLER, Daniel Wyn, et al. Applying Ultrashort pulsed Direct Laser interference patterning for functional Surfaces. Scientific reports, 2020, 10. Jg., Nr. 1, S. 1-14.

PETTERSSON, Ulrika; JACOBSON, Staffan. Friction and wear properties of micro textured DLC coated surfaces in boundary lubricated sliding. Tribology letters, 2004, 17. Jg., Nr. 3, S. 553-559.

RYK, G.; ETSION, It. Testing piston rings with partial laser surface texturing for friction reduction. Wear, 2006, 261. Jg., Nr. 7-8, S. 792-796.

SAMANTA, Avik, et al. Roles of chemistry modification for laser textured metal alloys to achieve extreme surface wetting behaviors. Materials & Design, 2020, S. 108744.

WALKER, J. C., et al. Tribological behaviour of an electrochemical jet machined textured Al-Si automotive cylinder liner material. Wear, 2017, 376. Jg., S. 1611-1621.