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Laser structuring of PVD multi-layer systems for wear reduction

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Abstract

Surface texturing is an effective way of improving tribological properties. Its main effect mechanisms are to trap wear particles and store lubricants. One of these technologies is texturing the surface with micro dimples by laser ablation. In this paper, the selective texturing of multi-layer systems, i.e., removing only the top layer by ultra-short pulse laser processing is presented. The removal of the top layer of the multi-layer systems is proven by laser confocal microscopy and EDX analysis. The selective laser structuring of the multi-layer systems generated by PVD synthesis developed for tribological applications, among others for the aerospace industry, results in precise structures with depth deviations of less than 0.2 µm without burrs or melt residues. These textures will further on result in reduced wear of thereby treated components depending on the structured layer systems and the geometry of the textures regarding dimple diameter and density.

Keywords: Ultra-short pulsed laser machining; multi-layer deposition; laser convocal microscopy; EDX analysis

1. Introduction

In the aviation industry, there is an effort to reduce emissions significantly to achieve extensive climate neutrality. There are various approaches to this, ranging from a weight reduction through lightweight construction to a reduction in air resistance through the 'hybrid laminar flow control' technology and to an increase in the efficiency of the engine technology. The latter requires a reduction gear between the fan and the turbine to be able to reduce the fan speed, since the speed of sound must not be exceeded, and thus to enable the implementation of a larger fan diameter. These reduction gears are exposed to high loads due to strong friction and wear caused by high local contact pressures.

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Surface texturing is an effective way of improving tribological properties under both dry and lubricated conditions (Wu et al., 2012). Its main effect mechanisms are to trap wear particles, store lubricants, and increase load carrying capacity (Xing et al., 2013). One of these technologies is texturing the surface with micro dimples (Gropper et al., 2016). Such a surface texturing can be performed by indentation (Pettersson et al., 2006), chemical etching (Costa et al., 2009) or laser ablation (Vilhena et al., 2009). Due to its flexibility and economic as well as ecological aspects, laser surface texturing is widely used for that purpose.

While dimples are more commonly used to decrease friction (Kligerman et al., 2005), channels can be applied to increase friction (Zum Gahr et al., 2009). Nevertheless, the influence of texturing parameters, like dimple diameter and density, spatial arrangement and aspect ratio on friction forces is not explicitly known at all, as it depends on many different conditions of the tribological system. Variations of the dimple diameter showed that there is an optimum in the dimple diameter and that this optimum depends on the oil viscosity and the velocity gradient along the contact area (Greiner et al., 2015). The aspect ratio (Shinkarento et al., 2009) and the textured area (Wang et al., 2001) widely influence the tribological properties of the texturing.

In terms of texturing parameters and their influence on tribological properties, there is consensus in the literature that an optimum in aspect ratio can be found around 0.1 (Shinkarento et al., 2009). Additionally, numerical simulations in elastic-hydrodynamic lubrication indicated that the aspect ratio is the most important parameter with respect to building up additional hydrodynamic pressure (Shinkarento et al., 2009). Besides structuring, hard coatings are used to increase the wear resistance, e.g., multi-layer PVD (physical vapor deposition) coatings. Therefore, in defined multi-layer systems with respect to depth the diameter of the structured dimples and the dimple density also should be of most importance to improve the tribological properties according to decreasing friction and wear.

2. Method

Structured multi-layer systems, as low-friction and low-wear surfaces, provide a way of increasing the load-bearing capacity of the transmission parts. A suitable laser system and the process control suitable for the layer system must be developed for laser structuring. The individual layers must be able to be removed selectively. PVD-synthesized multi-layers with the necessary tribological properties were used for structuring, see Fig. 1. The surface by means of laser processing then serves to form lubrication pockets, which lead to a further reduction in friction and wear on the highly stressed component.

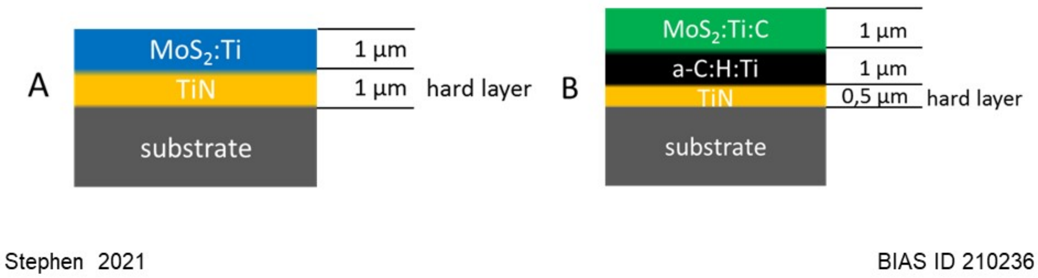

Fig. 1. Used multi-layer systems for testing the influence of laser structuring on tribological properties with respect to reduction of wear

The coating systems are deposited using a CemeCon CC800/9 HiPIMS PVD coating device. The target configuration consists of two titanium, two molybdenum-disulphide and two carbon targets, arranged as shown in Fig. 2.

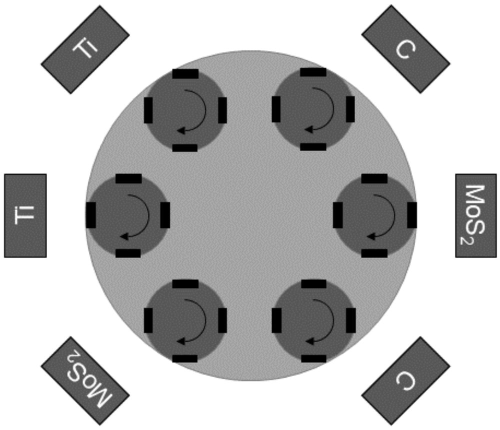

Fig. 2. Target configuration of the CemeConCC800/9 coating device

One Titan and MoS2 target each are operated in HiPIMS mode, in order to increase the substrate-coating adhesion and decrease the columnar growth of the TiN and MoS2 layers. In this work, two different coating layouts are being investigated. A two-layer design, consisting of a hard TiN ground layer and a MoS2:Ti solid lubricant layer is compared to a three-layer design. This extends the mentioned two-layer design by another a-C:H:Ti middle layer. In addition, the solid lubricant top layer is doped with carbon, forming an a-C:H:Ti:C composition.

3. Experimental

An ultrashort pulse laser with a wavelength of 1030 nm was used as the laser beam source for structuring the multi-layer system. The laser used (Trumpf TruMicro 5050) has a pulse length of less than 10 ps with a maximum output power of 50 W and a pulse repetition rate of 200 kHz. The laser beam was guided over the workpiece by a Galvano scanner with a focus diameter of 40 µm. The laser processing was performed without a protective gas supply. Applied to the multi-layer systems were four different textures varying the dimple diameter and the dimple density, see Fig. 3. The dimple diameter is indicated as *d* with a pitch *a* hexagonally orientated leading to a dimple density of *A*, i.e., the percentage of surface area covered by dimples.

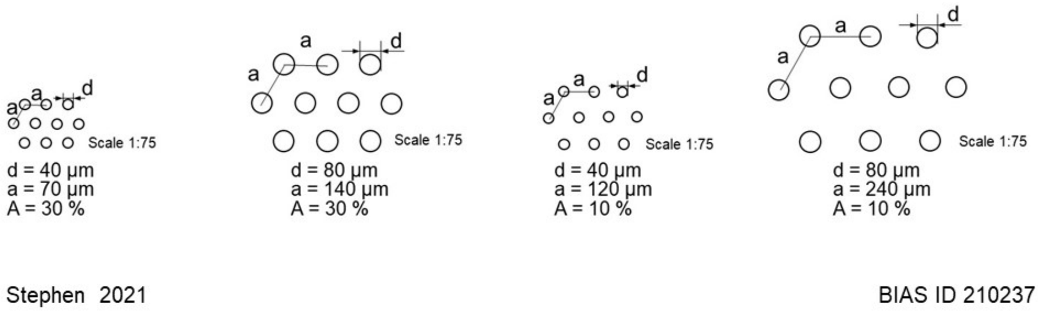

Fig. 3. Different textures defined for laser structuring to test the influence on tribological properties with respect to reduction of wear

4. Results

A defined diameter of the dimples could be set using a circular irradiation strategy, whereby the diameter of the laser beam path applied is according to the beam diameter 20 µm smaller than the dimple. That means, the diameter of the laser beam path is 20 µm for the dimples of 40 µm in diameter and 60 µm for those of 80 µm. For the later one an additional laser beam path of 5 µm in diameter is applied in the middle of the dimple for a complete lateral removal of the upper layer. The laser machined textures with different dimple diameters and densities are shown in Fig. 4 generated by changing diameter and pitch of the laser beam path.

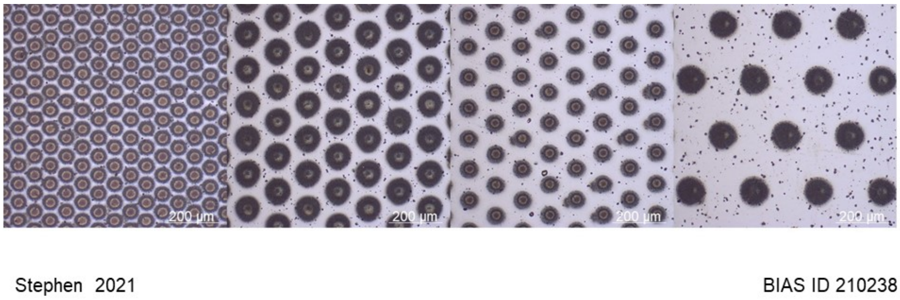

Fig. 4. Micrographs of different textures shown in Fig. 2 machined by laser structuring (from left to right: diameter/density of 40 µm/30%, 80 µm/30%, 40 µm/10%, 80 µm/10%)

Corresponding laser confocal microscope images of layer A and B applying a dimple diameter of 40 µm and a density of 10% are shown in Fig. 5. The 3-dimensional measurements show a constant depth of approximately 1 µm for all measured micro dimples. Around the dimple edges the laser confocal microscopy indicates a narrow heat influenced zone of the upper layer.

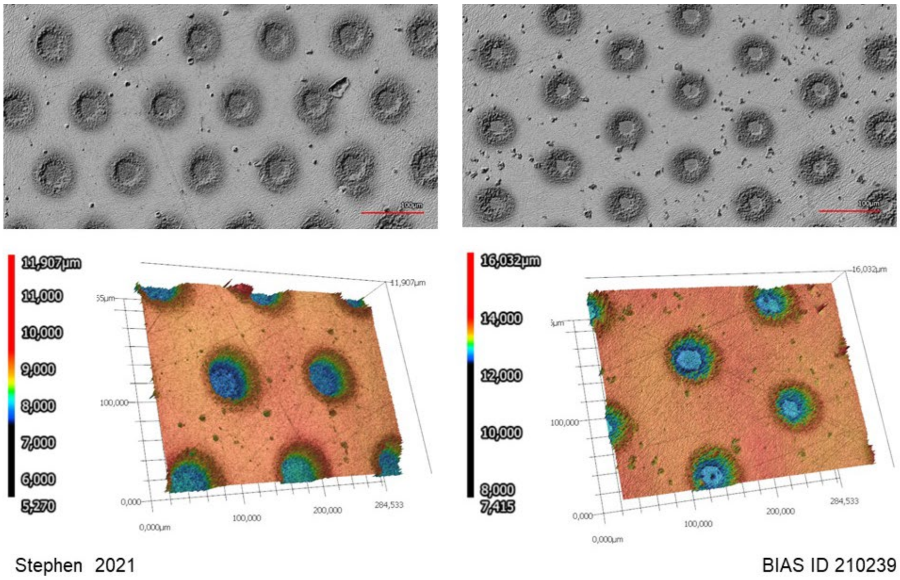

Fig. 5. Laser confocal microscopy of the laser structured multi-layer systems (left: layer system A, right: layer system B)

By choosing a suitable laser pulse energy (5 µJ) and pulse repetition rate (50 kHz), the ablation could be set in such a way that the MoS_2:Ti layer respectively MoS_2:Ti:C layer for the layer systems A resp. B are removed (1 µm depth) and the underlying layers retained on the substrate as proved by EDX analysis shown in Fig. 6 for system A respectively Fig. 7 for system B. Difference between the processing of layer A and B is the number of applied scans (5 resp. 7) at a constant speed of 250 mm/s.

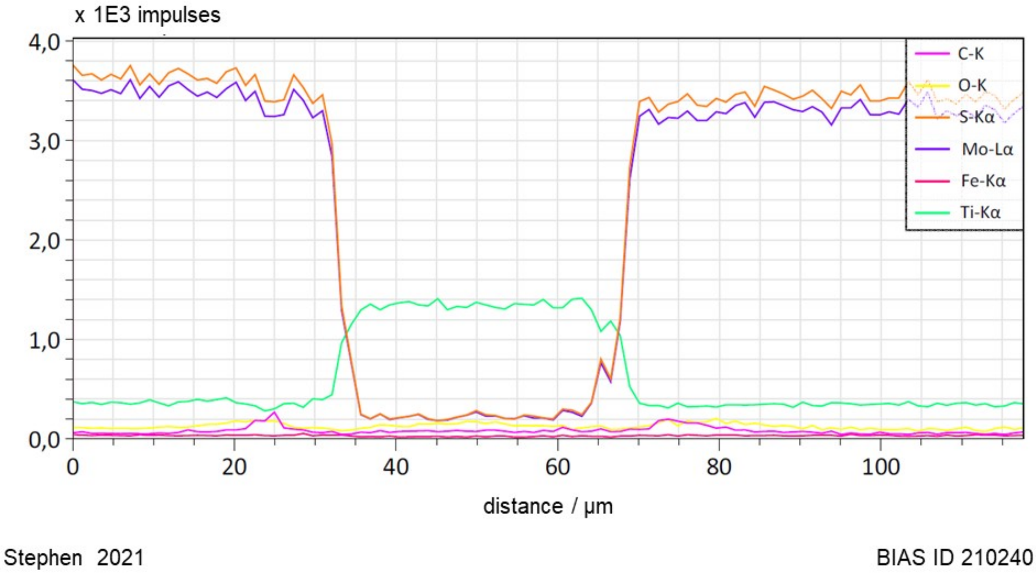

Fig. 6. EDX analysis for system A; Mo and S signals decreases whereas that of Ti increases

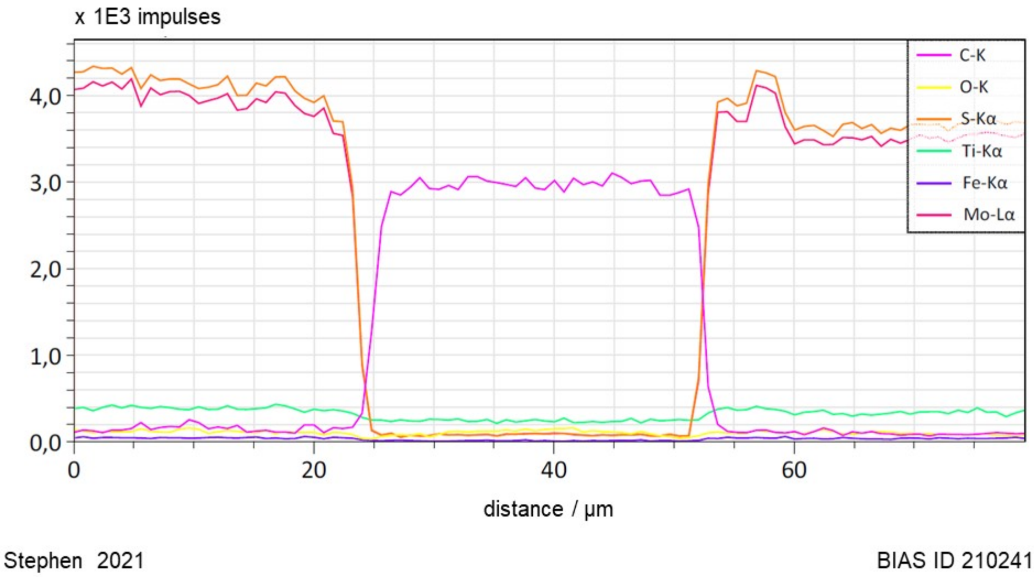

Fig. 7. EDX analysis for system B; Mo and S signals decreases whereas that of C increases

The remaining TiN layer or with additional a-C:H:Ti layer serves to protect the hardened steel substrate underneath from corrosion. The depth can be reproducibly set with an absolute deviation of less than 0.2 µm. The evenness of the dimple is in the range of ± 0.1 µm. Almost no burr formation or melt residues can be observed.

5. Summary

The selective laser structuring of the multi-layer systems by PVD synthesis developed for tribological applications, among others for the aerospace industry, results in precise structures with depth deviations of less than 0.2 µm without burrs or melt residues. These textures can be applied only in the top layer of the multi-layer system retaining the underlying layer or layers unaffected. The strategy is that the top layer acts as a reservoir for wear particles and the underlying layers as hard layers for better mechanical properties as well as protecting the textured component. These textures will further on result in reduced wear of thereby treated components depending on the structured layer systems and the geometry of the textures regarding dimple diameter and density.

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