MULTI-SCALE STRUCTURES FOR INFLUENCING THE TRIBOLOGICAL PROPERTIES OF METALLIC SURFACES

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INTRODUCTION

The surfaces of mechanical and precision components have a decisive influence on:

- tribological behavior
- dimensional precision of solid body contacts
- fatigue strength.

These important aspects are influenced, in turn, by the structure of the surfaces. The surface structures of solid bodies can be classified according to their characteristic feature size into meso, micro (e.g. roughness and waviness) and nanostructures.

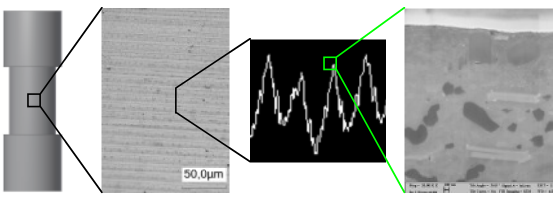


FIGURE 1. Overview of the various surface structure dimension scales.

To obtain desirable performance, whether it be higher wear resistance, lower friction, higher dimensional precision, or improved fatigue resistance, there's the opportunity to fabricate defined meso, micro or nanostructures on the surfaces. Meso and microstructures have been shown to improve the friction properties of lubricated gliding partners [1-3]. The structures act as pressure chambers and allow faster separation of the friction partners.
Also, nanostructures can have a positive influence on friction and wear. By suitable nanostructuring, the run-in condition can be generated prior to the service cycle. In this manner, the wear-intensive run-in period can be minimized or prevented.

REDUCTION OF TOOL WEAR BY SURFACE ENGINEERING

The influence of hardfacing on the wear resistance of hot forming tools has been investigated since several decades ago. Thick coatings of about 75 µm in thickness or greater have been shown to increase the wear resistance of hardened hot work steel in hot forging [4, 5]. However, hard coatings haven't found extensive usage in industrial hot forming because wear resistance improvements often do not make up for the high costs of coatings. Some studies have reported that surface treatments and small modifications of the alloying elements of hardened tool steel can actually provide higher wear resistance than hard coatings in critical areas of the tools [4, 6]. In the case of High-velocity Oxy Fuel (HVOF) thermal spray coatings, their poor adhesion to the substrate has limited their applicability in hot forging tools.

Surface preparation of the substrate prior to thermal spraying has an important influence on the development of coating-to-substrate adhesion stength. The state of the art consists of grit blasting to clean and roughen the substrate. Roughening creates the undercuts necessary for mechanical anchorage—generally regarded as the only relevant adhesion mechanism of thermal spray coatings. Sobolev et al. [7] proposed, however, that the constrain of thermal spray splat expansion upon impact imposed by surface asperities results in lower interfacial porosity and higher heat input into the substrate—two conditions that may increase adhesion strength. Yet, the variety of surface geometries and scales obtained from grit blasting is quite limited for any attempts to adjust the incoming spray-substrate interaction—by design.

Surface structuring by laser ablation is a promising technology to manufacture deterministic structures on metallic substrates. Tailoring of substrate geometries with consideration of the thermal spray particle size and service conditions presents an opportunity to improve wear resistance of coating-substrate composites. In the case of thermally sprayed coatings on hot work steel surfaces, the potential benefits of deterministic substrate structures include:

- Constrain thermal spray splat extension to promote diffusion bonding and reduce interfacial porosity
- Increase the coating-substrate interfacial area and thereby reduce interfacial residual stresses from coating deposition and from misfit thermal strains during hot forging temperature cycling
- Inhibit interfacial crack formation caused by cyclical loading of forging

To evaluate the feasibility of reaching the above goals, a pattern of conical cavities with a width of 110 µm and a depth-to-width ratio of approximately 3:1 was manufactured by laser ablation on hardened hot work steel 1.2367. The tool steel surface had been previously ground to 2 µm R_z. A HVOF-thermal-spray duplex coating was deposited onto the textured and untextured areas of the substrate by first spraying an iron-based, hard alloy FeCrV15 powder followed by an WC-12 % wt. Co top layer. The total thickness of the coating reached approx. 100 µm from the ground surface. The surface structures were filled exclusively with the iron-based powder, having an average powder size of approx. 50 µm.

Figure 2 shows a cross-sectional view of the structured substrate after being thermally sprayed. The cavities were filled almost completely by the thermal spray coating (iron-based layer) with the exception of the sharp corners of the conical cavities in some instances. In this case, interfacial coating-substrate surface area well exceeds what would be achieved by grit blasting the hardened tool steel. In fact, peak-to-valley distances on a grit-blasted hardened steel surface would hardly exceed 10 µm. Figure 3 contrasts the coating adhesion developed on the structured surface vs. the adhesion on the ground surfaces. The coating delaminated completely off the ground surface immediately after the deposition process whilst it remained well-adhered to the laser-structured surface.

This initial evaluation confirmed that laser-machined structures of about twice the width of the average particle size of the deposited thermally-sprayed powder and a relatively high depth to width ratio (3:1) hold promise in increasing the adhesion strength of hardfacing coatings. Future work will focus on evaluating deterministic laser-machined structures with an array of geometry topologies and dimensions using metallographic characterization of the coating-substrate interfaces and tensile adhesion tests.

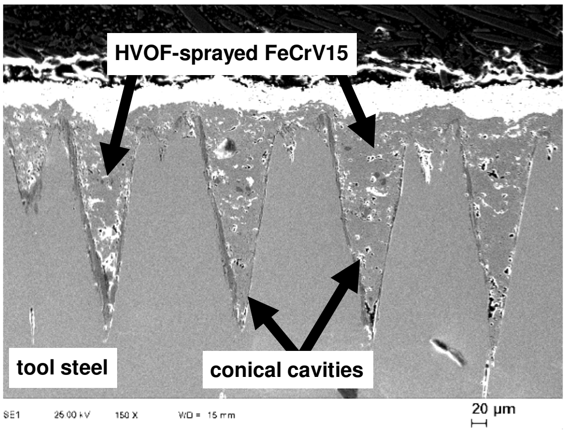


FIGURE 2. Scanning electron microscopy cross-sectional view of coating and laser-structured tool steel.

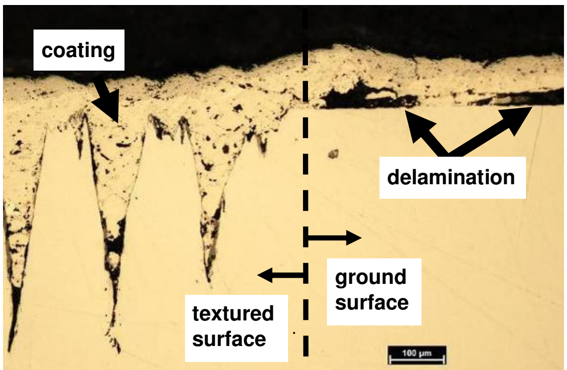


FIGURE 3. Cross-sectional optical micrograph of coating-laser structured tool steel composite.

REDUCTION OF FRICTION BETWEEN LUBRICATED SURFACES

An optimization of tribological systems can improve the performance and lifetime of mechanical components. Surface structures have a substantial influence on the tribological behavior. Friction and wear coefficient can be reduced considerably by a specific change of the surface in the form of meso or microstructures.

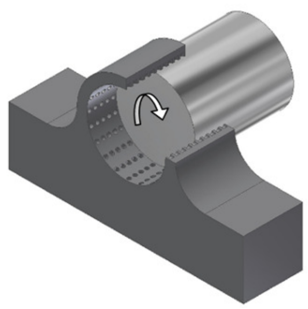


FIGURE 4. Shaft and microstructured bearing.

The goal of microstructuring of gliding partners can be represented by a shift of the Stribeck curve as shown in Figure 5. The Stribeck curve can be divided into the three regimes: boundary, mixed and hydrodynamic lubrication. First, a targeted surface structuring is intended to reduce the friction coefficient across the three regimes. Second, it would shift the curve toward the left, enabling to reach the hydrodynamic lubrication regime at lower operating velocities.

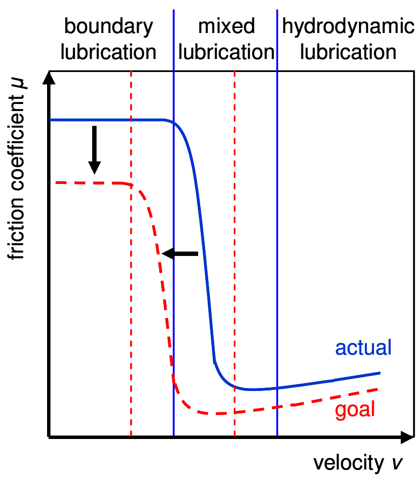


FIGURE 5. Desired effect on lubricated friction by means of structured surfaces.

A CFD simulation was performed to analyze the effect of surface microstructures on hydrodynamic lubrication. The simulation model consists of a lubrication gap between a static, structured base body and a smooth counter body which moves parallel to the former with a velocity of 1 m/s. For the purposes of this investigation, a spherical segment cavity was chosen. The simulation results showed that the cavity acts as a pressure chamber. The lubricant circulates in the structures (Figure 6) and consequently creates a pressure peak over the microstructure. This pressure would lead to faster separation of the lubricated solid bodies.

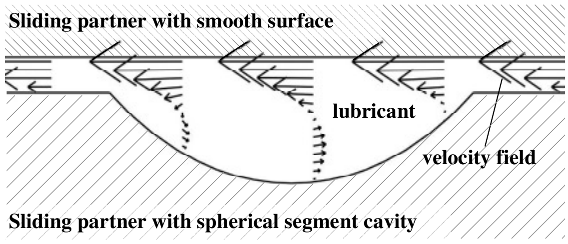


FIGURE 6. CFD simulation of lubricant circulation on a surface microstructure.

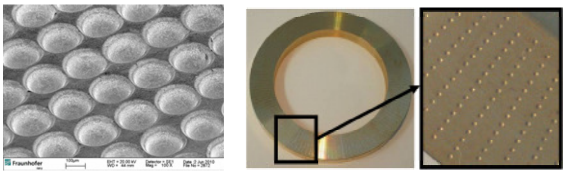
The following conclusions were drawn from the CFD simulations under hydrodynamic lubrication regime:

- with rising diameter, the pressure value increases almost linearly
- For maximum pressure, the depth of the structures should be between 5 µm and 20 µm
- The distance between adjacent surface structures should be kept as small as possible to create maximum pressure.

The simulation results were verified experimentally by measuring the friction coefficient between lubricated, textured surfaces. To this end, a tribological ring-on-disc test rig was built. The ring partner was structured and the disc was flat-ground. The disc consisted of heat-treatable 42CrMo4 steel with an outer diameter of d_a = 100 mm, a thickness of h_d = 8 mm and a hardness of 650 HV. The ring-shaped counterbody was produced from bronze CuSn8 (hardness 125 HV) with outer diameter d_a = 100 mm, inner diameter d_i = 70 mm and thickness of h_r = 10 mm.

Electrochemical Machining by closed-electrolytic-free Jet (Jet-ECM [8]) was used to produce patterned spherical segments. In Jet-ECM, a high-velocity electrolytic jet is generated from a cathodically polarized nozzle and led toward the anodically polarized workpiece. As positively charged ions are attracted to the nozzle, the negatively charged ions are attracted to the workpiece and material is removed as metal ions are drawn into the electrolytic solution. In contrast to conventional electrochemical machining, Jet-ECM enables localized material removal by control of jet position without relying on a solid electrode with the negative form of the feature to be machined.

Initially, the electrochemical machining process parameters for the production of spherical-segment cavities were determined (Figure 7a). Afterwards, the cavities were machined on the ring samples (Figure 7b).



(a) (b)

FIGURE 7a. SEM image of the microstructured surface; 7b. spherical-segment cavities in a bronze ring (d = 500 µm, h =10 µm).

Tribological measurements were carried out in a Wazau TRM 500 tribometer. The ring and disc were loaded with a normal force of 220 N and the disc was rotated with the following velocities: 0.05 m/s, 0.33 m/s, 0.66 m/s, 1 m/s and 3 m/s. The tests were conducted under immersion lubrication with engine oil Castrol EDGE 5W-30 at a temperature of 60 °C. The friction moment was measured to determine the friction coefficient. A ring-disc pair with smooth surfaces served as the reference condition.

An example result of the tribometric tests is shown in Figure 8. Here, the frictional behavior of the 42CrMo4 / CuSn8 pair with spherical-segment cavity depths of 10 µm and 80 µm, with a pattern density *pd* of 20 % (4080 cavities per ring), is plotted as a function of speed.

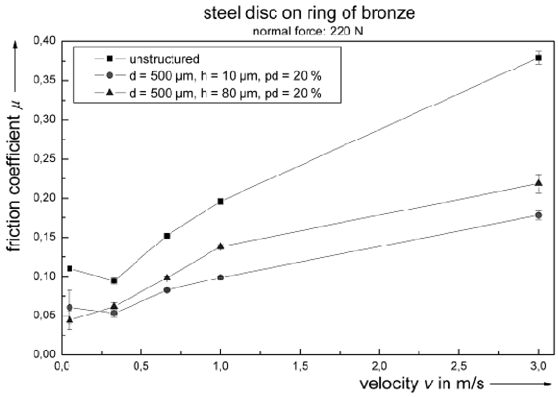


FIGURE 8. Comparison of the friction coefficient of an unstructured vs. a structured ring-on-disc for a pattern density pd = 20 %.

The unstructured pair showed a friction coefficient at the two smallest test velocities: 0.05 m/s and 0.33 m/s, of approx. 0.1. With a further increase of test velocity the friction coefficient rose nearly linearly and reached, at the maximum test velocity of 3 m/s, a maximum value of 0.37. The friction partners structured with spherical-segment cavities of 10 µm and 80 µm in depth maintained a lower friction coefficient than the unstructured partners over the complete speed range, with the exception of *v* = 0.05 m/s. A reduction of the friction coefficient of up to 55 % was possible.

NANOSTRUCTURED SURFACES BY FINISH MACHINING

Nanostructured surfaces can occur during the running-in phase of two friction partners. The running-in phase includes both mechanical and chemical effects. Peaks of roughness are leveled and a nanocrystalline structure is generated in the surface layer [9]. Furthermore, additives of lubricant and oil penetrate into the surface layer during the running-in phase and influence the frictional behavior. This nanostructured surface layer is known as the 'tribological mutation' or third body. The grain sizes of the primary alloy constituting a third body are smaller than 500 nm. The formation of these structures during the running-in phase depends of the material properties, the surface parameters and the load conditions of the friction partners. The third-body in the boundary layer leads to reduction of friction and reduce the wear rate. This effect should be utilizable for highly loaded systems. The objective is the reduction of the running-in time of highly loaded systems and generation of defined conditions for layer formation. Hence, the energy efficiency would be improved in the early stages of service life. This can potentially be realized by inducing a nanocrystalline structure and a tribologically mutated surface with penetrated additives.

An example of a highly loaded system is a combustion engine. An important frictional interaction occurs between the cylinder liner and piston ring. In the present investigation, the material for finishing was a hypoeutectic AlSi alloy (AA 380.0). Focus centered on the machining of surfaces with nanostructures and chemical manipulation by turning. A further step was the development of nanostructures on a cylinder liner.

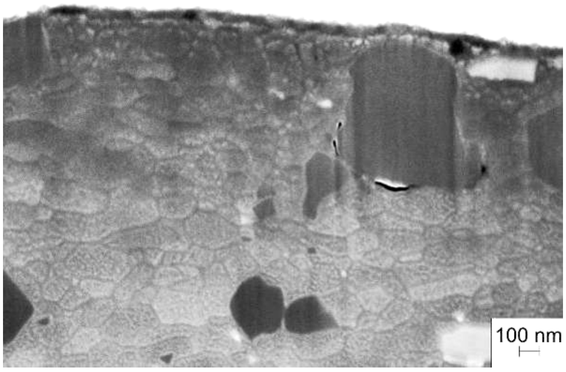


FIGURE 9. Nanostructured surface of a hypoeutectic AlSi alloy (AA 380.0) (FIB).

Different measurement methods were used for to evaluate the surface manipulation results. The Focused Ion Beam (FIB) method was used in order to analyze the structure of the surface layer. The key advantage of this procedure is the high disbanding and non-oxidization of the sample during analysis. Figure 9 shows a nanostructured surface of a hypoeutectic AlSi alloy finished by turning. The dark particles in this picture are silicon particles whereas the lighter grains are made of aluminum.

The present investigations on the turning process showed that the contribution of high shear stresses during cutting lead to the formation of a fine-grain surface layer. The high shear stresses were generated by comparatively high passive forces and modified cutting tool geometry. During generation of a fine-grained surface layer, passive forces of 6 N to 14 N were measured for this AlSi alloy.

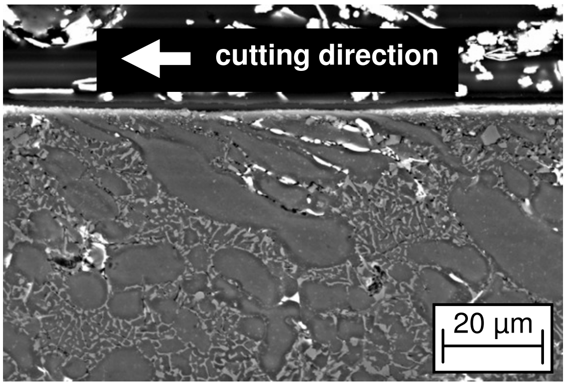


FIGURE 10. Cross-section of an affected matrix.

Figure 10 presents the cross-section of an affected matrix after conducting a finishing process with high shear stresses. A characteristic effect of the high shear stress is the cross-section deformation in the cutting direction. Also, the destruction of the dendritic structure in the surface zone is an indication of finishing with high shear stress.

For comparison purposes, Figure 11 depicts an unaffected matrix. In this instance, there were no signs of grain refinement nor dendritic phases in the surface layer. During the finishing process for this unaffected matrix, passive forces of 1 N to 2 N for this AlSi alloy were measured [10].

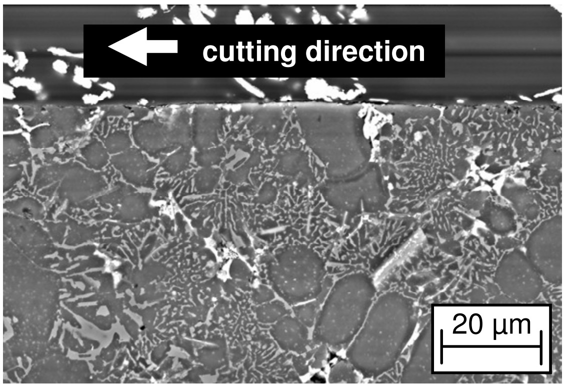


FIGURE 11. Cross-section of an unaffected matrix.

CONCLUSION

The performance and energy efficiency of engineering components is greatly influenced by their surface properties. This investigation showed that improvements in friction and wear behavior are possible by the manufacturing of appropriate surface structures in the nano, micro and mesoscales.

It was determined that surface structures have the potential to improve the adhesion strength of thermal spray coatings on tool steel surfaces. These structures would enable thermal spray hard coatings to increase the wear resistance of hot forging tools.

The influence of surface structures on friction between lubricated sliding partners was investigated. CFD simulations of lubricated sliding partners indicated that surface microstructures act as micro-pressure chambers that lead to hydrodynamic lubrication regime at lower operating speeds. It was determined from lubricated ring-on-disc tests that surface microstructures may reduce friction by up to 55 %.

Nanostructures are formed during the highly energetic break-in period of sliding components and constitute the so-called "third body" This paper presented preliminary results on the generation of nanostructured surfaces for powertrain components with the purpose of reducing or eliminating the break-in period of sliding components such as cylinder liners.

It is possible to obtain further improvements in the tribological behavior of functional surfaces by simultaneously combining surface structures in the meso, micro and nanoscales. Such integration of multi-scale surface features should be the focus of future research.

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