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The influence of the initial near-surface microstructure and imposed stress level on the running-in characteristics of lubricated steel contacts

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ABSTRACT

The tribological behavior of polished and lapped 56NiMoCrV7 and Ck45 disks with lubrication was studied to link the impact of initial near-surface microstructure to the running-in behavior of the systems. The tests were performed using a pin-on-disk tribometer with radionuclide technique to resolve ultra-low wear rates. For the running-in different stressing regimes were applied. Whereas the lapped disks developed low friction and wear as response to a high-power running-in, the polished disks had to be stressed by a step-wise increase in load to achieve a similar result. In addition, the duration of some load steps and the sliding velocity had to be adjusted in order to obtain a proper running-in. With the help of focused ion beam and transmission electron microscopy the response of the microstructure to the stressing conditions was investigated. It turned out that the quality of the running-in crucially depends on a subtle equilibrium between material strengthening and softening. Strengthening by finishing and running-in was a prerequisite for the formation of the third body, whereas softening resulted in scuffing. When it was possible to charge the near-surface material in relation to its strengthening capabilities, low wear rates in the nanometer per hour regime were obtained.

1. Introduction

Besides the action of oil and additives, the way a tribological system performs crucially depends on the type of surface finish [1] and the first minutes of operation, that means the running-in [2]. During the running-in, first the topographies adjust (topographical running-in), then the deposited energy results in heat, plastic deformation and intermixing as well as material deposition. The involved friction bodies respond by changes in topography (dissipative structures [3], material transfer or film formation), changed near-surface microstructure and modified chemical composition. Godet called this the third body formation [4]. The introduction of heat was discussed by Kuhlmann-Wilsdorf and others [5,6]. Targeting the materials response, Rigney et al. investigated the involved mechanism leading to changes in near-surface structure and to the introduction of foreign elements as result of intermixing processes [7,8,3,9]. Martin et al. elucidated on film formation effects due to tribo-chemical reactions with oils containing ZDDP [10]. The general consensus is that friction and wear are significantly influenced by interfacial processes as well as mechanical and chemical properties of the near-surface material. Plastic deformation, flow of asperities and micro-crackings are the most prominent mechanisms [4]. Despite all research, the tribological impact of the evolving third body on low friction coefficients and small wear rates is still a matter of discussion. Moreover, it is not clear why only under specific conditions the system can develop low friction coefficient and small wear rate and what the predominant influencing parameters are.

In the past, influencing parameters like the total dissipated power during running-in or the sequence of operation points (contact pressures and sliding velocities) were discussed. Systems that were subjected to a high-power running-in developed significantly lower friction than systems operated under low initial loadings [11]. In addition to lower friction, the high-power running-in yielded lower wear rates after a shorter running-in time. The results suggest that the initial power of friction $\mu F_n v$ influences the long-term behavior of the entire system as described in [12]. Volz discovered that differently designed running-in routines, with a certain sequence of pressures and velocities, result in different friction and wear patterns [13]. His findings were based on engine bench tests using high-resolution and continuous wear measurements with radionuclide technique (RNT) [14]. At this time the first attempts were undertaken to design running-in

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routines. The success, however, was limited since the formation of the third body was not considered. Meanwhile, this issue was pursued over the last 15 years and a tremendous progress can be witnessed in research on tribological systems showing ultra-low wear rates.

The aim of this study is to show how initial conditions set by the microstructure and the way how contact pressure and sliding velocity are controlled lead to the development of lowest coefficients of friction and ultra-low wear rates as desired for lubricated tribological contacts. The role of surface finishing – polishing and lapping – was evaluated with focus on initial microstructural properties. To reduce complexity, radionuclide-assisted pin-on-disk tribometry was carried out. Since steel is widely used in mechanical engineering, lubricated steel-steel contacts were evaluated. Whereas the pin material was kept constant, the material of the disks differed in hardness. By means of focused ion beam analysis (FIB) and transmission electron microscopy (TEM) the near-surface volume was characterized prior and after the tribological tests to monitor the evolution of the microstructure. Photoelectron spectroscopy (XPS) was applied to follow the chemical changes due to shear. Nanoindentation was used to characterize the mechanical properties of the near-surface material. As a first order approximation, nanoindentation hardness was considered a measure of conditioning, since by changing grain-size and dislocation density, the micro-hardness is affected.

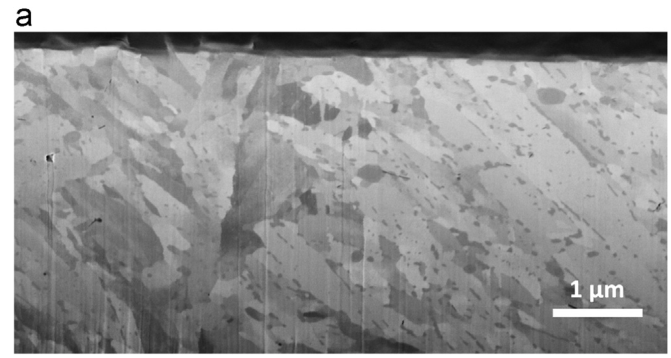
2. Experiments

Pin-on-disk tribometer tests were performed on steel disks made of 56NiCrMoV7 (disk D1) and Ck45 (disk D2), using a pin made of C86 carbon steel. 56NiCrMoV7 is an alloyed steel with following chemical constituents (at%): C: 0.5–0.6; Si: 0.1–0.4; Mn: 0.65–0.95; P: <0.03, S: <0.03; Cr: 0.1–1.2; Ni: 1.5–1.8; Mo: 0.45–0.55; V: 0.07–0.12. Ck45 (=AISI/SAE 1045) is a plain carbon steel with following chemical constituents (at%): C: 0.43–0.5; Si: <0.4; Mn: <0.5; S: <0.035; Cr+Ni+Mo: <0.65. 56NiCrMoV7 exhibits a homogeneous microstructure with less than 2% of residual austenite and minor carbidic precipitates at the grain boundaries. 56NiCrMoV7 has a martensitic microstructure, whereas Ck45 and C86 have a ferritic/pearlitic microstructure. The pin C86 (=AIS/SAE 1086) contains the following chemical constituents (at%): C: 0.35–1; Si: 0.1–0.3; Mn: 0.5–1.2; P: <0.035; S: <0.035; Cu: <0.2. The steel disks were cut, ground and annealed. After annealing, half of the disks was lapped with a 9 µm suspension at a working pressure of some MPa. The other half was handpolished with cloth and suspension (grain size ≈ 1 µm) at a working pressure of less than 1 MPa. The polishing procedure was applied to the pins as well, see Table 1. The materials selection was a compromise between simplicity, applicability in mechanical engineering and further use of the results to feed atomistic simulations (to be published).

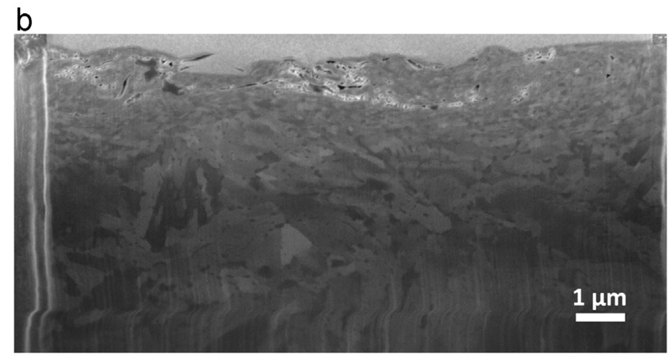
Table 1
Samples, compositions, Vickers hardness, heat treatment temperature and roughness.

	D1	D2	Pin
Material	56NiCrMoV7	Ck45	C86
HV01 lapped and polished[a]	400 ± 20	270 ± 20	450 ± 20
Austenitizing temperature	850 °C	880 °C	N/A
annealing temperature	630 °C	530 °C	N/A
R_a[b] polished	12 nm	10 nm	10 nm
R_a[b] lapped	150 nm	200 nm	N/A

[a] Microhardness Vickerstest with Wolpert VDT 12 using DIN EN ISO 6507 - 1:2006, test method HV, load duration 10 s.
[b] Sensofar-Tech S.L.



Initial microstructure polished.



Initial microstructure lapped.

Fig. 1. SEM characterization of FIB cross sections of the initial state of D1 in polished and lapped condition.

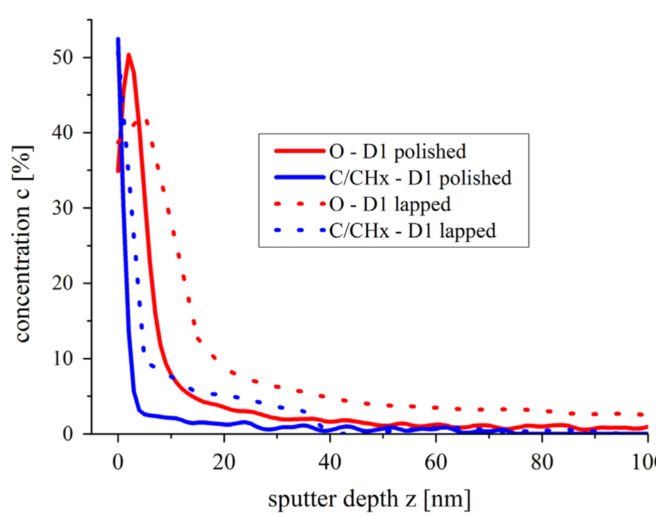


Fig. 2. Chemical depth profile (XPS) of initial the near-surface layer due to lapping and polishing of D1.

Cross sectional secondary electron microscopy (SEM) imaging of the new samples was carried out and is presented for D1 after polishing and lapping, see Fig. 1. The polishing procedure did not have a significant influence on the near-surface structure, while lapping introduced clear changes in the near-surface microstructure up to a depth of 2.5 µm. Chemical analysis by XPS revealed that there is no distinct difference between the polishing and lapping process, see Fig. 2. The penetration depths of O and C/CH_x for both procedures ranged between 10 nm and 20 nm. The shift to larger penetration depths after lapping can be related to increased roughness. The depth profiles for D2 and pin were