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The Effect of Sample Finishing on the Tribology of Metal/Metal Lubricated Contacts

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Abstract

Friction and wear can be influenced not only by materials, lubricants and the running-in, but also by the final manufacturing step employed to prepare the samples. A suitable surface finish for a metallic tribological system can be achieved by cutting procedures such as lapping, honing or grinding. In addition to topography changes, the finishing process also modifies the chemical composition as well as the crystalline structure of the near-surface material. In this contribution the impact of finishing on friction and wear during the running-in and the subsequent operation is evaluated for the grinding process. Different grinding parameters and coolant compositions were applied to generate samples for continuous and high-resolution pin-on-disk friction and wear tests. The experiments showed a significant correlation between grinding force, friction coefficient and wear rate.

1. Introduction

Sample preparation procedures for tribological model tests are usually selected with focus on roughness. A similar topography of real and model system ensures a comparable hydrodynamic behavior for lubricated contacts, at least at the beginning of the running-in. Besides hydrodynamics, the initial topography determines the real contact area of the system which in turn determines the power density that acts on the surfaces, the near-surface volumes and the confined lubricant. Whereas excessively high power densities – either caused by high loads, large sliding velocities or a small contact area – overstress the tribological system, power densities that are too low understress the system and may prevent a proper running-in [1]. Both over- and understressing are characterized by high wear rates, system instabilities and increased sensitivity to external fluctuations. A proper running-in of the tribological system, however, leads to coefficients of friction less than 0.05 and wear rates of smaller than 10 nanometers per hour. Theses values are found in engines, e.g., for piston ring and liner or cam and shaft [2]. Under proper running-in conditions the materials of the involved near-surface volumes undergo drastic changes with respect to topography, crystalline structure and chemical composition. This initial process is called third body formation [3] after which the tribological interface has a new quality. Whereas the macroscopic behavior of the system – reflected by the coefficient of friction and the wear rate – indicates equilibrium conditions, the processes at the interface and inside the third body are far from equilibrium. On average, the thickness of the third body remains constant, meaning that the incorporation of new materials from the bulk into the third body runs at the same speed as wear proceeds into the bulk [1]. In addition, the complex interplay of material removal and material incorporation seems to have a memory effect, since the wear rate long after passing the running-in depends strongly on how the samples were finished. In this contribution we therefore try to answer the question how the final manufacturing step conditions the materials and influences the running-in and the tribological long-term performance.

2. Experimental

To answer the question raised above, it is necessary to characterize the grinding process. During finishing both normal and tangential (grinding) force were measured to determine the grinding force relation ($F_{t,grinding}$ / $F_{n,grinding}$) and to correlate this value to the coefficient of friction measured in the subsequent pin-on-disk experiments. To transfer the results from the tribometer to friction pairings of real systems, we strove for energetic similarity between model and real system as described in [1]. In order to achieve this state, the tribometer was run under similar lubrication conditions and – more importantly – in the same wear rate regime as the real system, e.g. an engine. The tribological experiments were carried out in the regime in which the third body is allowed to build up, i.e., in the corridor between over- and understressing [4-8].

2.1. Preparation of disks

The disks (16MnCr5, not hardened) were first pre-turned and then finished using a peripheral face grinding machine (grinding wheel: cubic boron nitride, 3CB3 150-1 V2 B13) in contact with the rotating disk, see Fig. 1. For the determination of the grinding force relation a piezoelectric three-component measuring system (Kistler) was applied. The grinding procedure was controlled by force feedback. The cutting speed of 8 m/s is rather low compared to conventional grinding processes, however, in the same range as the sliding velocities of many mechanical applications [9]. In addition, this value was chosen because own pre-studies [10] and works of other groups [11] demonstrated that a finishing processes at low speeds result in lower friction and wear. As coolant liquid an additive-free base oil was used. The additivation was accomplished either with sulphur or phosphorous.

2.2. Tribological Tests

For the measurements of friction and wear a pin-on-disk (POD) tribometer with radionuclide technology was applied. In contrast to regular POD tribometers, the oil circuit is opened to guide the oil through a detector chamber in which the concentration of wear particles is measured in real-time. After proper calibration the concentration can be converted into the wear rate. For lubrication commercial engine oil was used. The pin was made of chromium-plated steel with a diameter of 3 mm. For the wear measurement the pin was radioactively labelled by conversion of a fraction of the Cr atoms (less than 10^{15} cm^{-3}) into an unstable state by means of thermal neutrons. The procedures for the activation of machine parts have already been described in detail in the past [12]. The continuous measurement of friction and wear permitted the characterization of the running-in as well as the acquisition of force-speed diagrams. The running-in of all tribosystems described here was accomplished at a sliding speed of 2.5 m/s and a load of 90 MPa. The normal forces chosen for the subsequent measurements resulted in contact pressures between 5 to 90 MPa. The sliding velocities ranged between 1 and 5 m/s, and covered boundary lubrication and hydrodynamics. In addition to the tribological measurements pre and post characterization using profilometry, Atomic Force

Microscopy (AFM) as well as chemical depth profiling by means of X-ray Photoelectron Spectroscopy (XPS) were carried out.

3. Results

3.1. Variation of the coolant composition

The base oil used as coolant was first blended with a sulphur-containing additive (20%). With increased sulphur content not only the forces between tool and disk increased, but also the friction and wear performance worsened. Already during the running-in as well as in the subsequent acquisition of the force-speed diagram (see Fig. 2, middle section), the coefficient of friction of the disk finished with the coolant containing 20% sulphur additive was clearly higher than the coefficient of friction obtained from the disk finished with the additive-free coolant. Wear only showed a slight increase.

When the base oil was additivated with phosphorous we observed the inverse trend, see Fig. 2, right. Here, in contrast to the sulphur-containing coolant, the grinding forces and the coefficient of friction decreased. In contrast to friction, the wear rates – smaller than 5 nm/h – did not change. Since the resolution of the RNT techniques is about 1 nm/h, differences of the wear rate at individual operational points are not significant and are no subject of discussion.

For both coolant blends the roughness determined by means of classical profilometry and by high-resolution atomic force microscopy showed no significant influence of the additive concentration.

3.2. Variation of contact force and contact time

The variation of the contact force induced significant changes of the tangential force during grinding. As a consequence, both friction and wear of the samples finished with a contact force of 600 N and with a contact force of 1,400 N differed substantially, see Fig. 3. The disk finished with a contact force of 1,400 N showed significantly increased coefficients of friction and high wear rates both for the pin and for the disk. The roughness values determined with profilometry did not show a uniform trend.

The contact time variation (15 s and 30 s) induced the most significant changes of friction and wear, see Fig. 4. All friction coefficients increased by a factor of two. The wear rate showed the largest values at low sliding velocities and high contact pressures.

3.3. Temporal behavior and force relations

By acquisition of tangential and normal forces during grinding and tribological operation two dimensionless numbers – the grinding force relation and the coefficient of friction – were available to correlate the finishing process with the subsequent tribological performance. Both numbers are plotted in Fig. 5, showing the case of 30 s contact time and 20% sulphur or phosphorous additive content. The left section of the diagram depicts the grinding force relation whereas the middle and the right section show the coefficients of friction with a significant correlation between manufacturing and operation. A low force relation during grinding directly leads to a low coefficient of friction. The values in the right section are the mean values of all friction coefficients determined in the force-speed parameter field.

By plotting the friction coefficients of all experiments against the grinding force relation, a correlation becomes evident which indicates a slightly nonlinear relationship between these two dimensionless numbers, see Fig. 6.

3.4. Microtopography and chemical composition

The microtopography after grinding was determined by AFM and was very similar for all disks. Both R_a and *RMS* as well as the distribution of valleys and peaks were comparable.

All chemical depth profiles showed an interaction depth of about 10 nm, see for example Fig. 7 and Fig. 8. We defined the interaction depth as the depth where the concentration of the major element (iron) levelled to its bulk concentration. The depth profile shows a maximum of oxygen, sulphur or phosphorous. The distribution of carbon resembles a diffusion profile with its maximum at the surface. However, this profile is also the result of mechanical intermixing with carbon contributions coming from the cooling liquid and the alloy.

4. Discussion

The finishing procedure discussed in this contribution was a grinding process, which deposits a certain amount of frictional power into the near-surface material and causes material changes. Earlier works showed that finishing processes texture the worked material and lead to grain size reduction [1], accompanied by chemical intermixing which was proven with the depth profiles. When the finishing process leads to a mere material removal, then the depth profile shows a constant element distribution from the bulk towards the surface. Only processes that work the near-surface alter the depth profile in the shown way. Thus, the grinding process evaluated here, modified the near-surface material and resulted in better tribological properties.

After finishing the worked surfaces meet their counter body and come in contact with the oil. If the running-in was energetically optimized, a mutual quasi-viscous zone in the near-surface areas of both friction bodies can be built, which the literature refers to as the third body. During tribological operation the micro-contacts experience further elastic and plastic deformations. The formation of the third body, thus, is a combination of mixing processes of the base material with components of the environment, the lubricant and reaction layers. When formed, the third body can be described by energetic entities such as friction power density and frictional shear strength [13]. Tribochemical reactions as well as the emergence of a nano-crystalline structure are accompanying processes.

A major result of this work is the finding, that the grinding force relationship can be used as indicator for the subsequent tribological behavior. Low “friction” during finishing leads to low friction in operation. As an open point the question remains, how this information is stored inside the worked material. The material, i.e. the disk, had its first tribological contact with the grinding wheel. Then the tribo-system was changed from the grinding wheel to the pin. In addition, the chemical environment changed from the coolant liquid to the engine oil. Since there is always a certain time span between finishing and running-in, the information cannot be stored in form of heat. Roughness effects certainly play a role. Finishing processes usually decrease the roughness. As a consequence, the frictional power density decreases and the system is driven out of the running-in corridor. Thus, additional mechanisms must exist.

A probable way of information storage can be dislocation pile up in combination with pinning due to mechanical intermixing of the metal with foreign elements of counterpart and coolant liquid [14]. Upon the sudden contact of the worked material with the coolant liquid, it seems that the properties of the finished material freeze and become reactivated during the running-in. It is highly possible that due to mechanical activation during finishing chemical reactions take place that lead to intermediate reaction products that react further during the running-in. Further studies should therefore mainly focus on the tribochemical aspects of finishing and the running-in.

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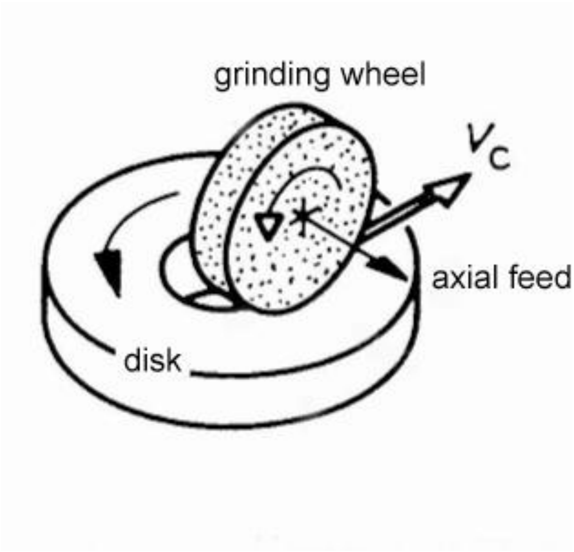

Fig. 1: Schematic of the grinding process,

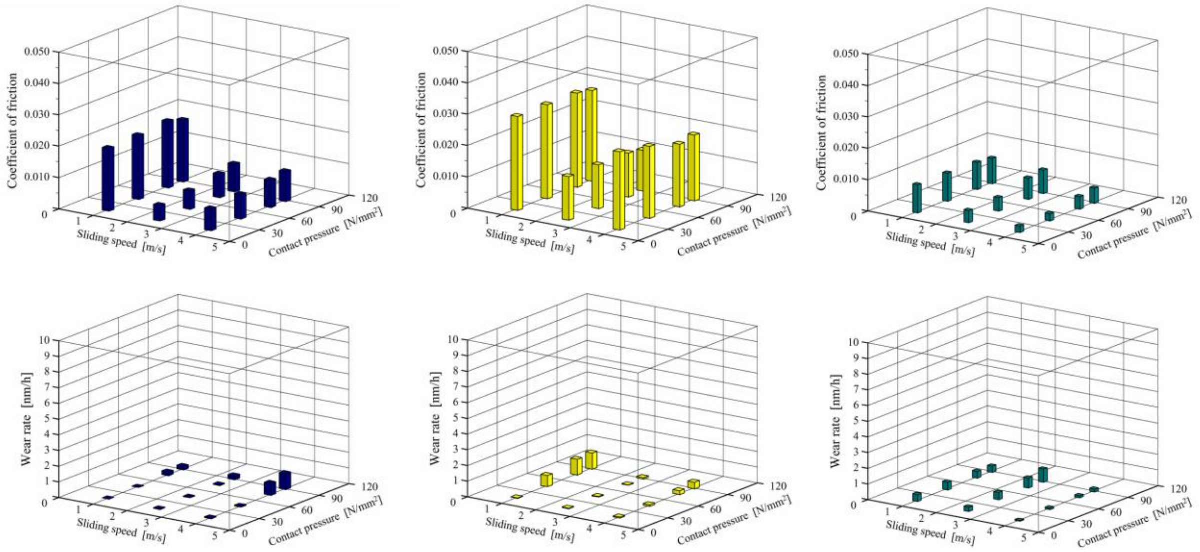

Fig. 2: Coefficient of friction and wear rate after finishing with different sulphur and phosphorous additive concentrations in the coolant. Contact time 15 s, contact force 1,000 N. Left hand side: no additives; Middle: 20% sulphur additive; Right hand side: 20% phosphorous additive.

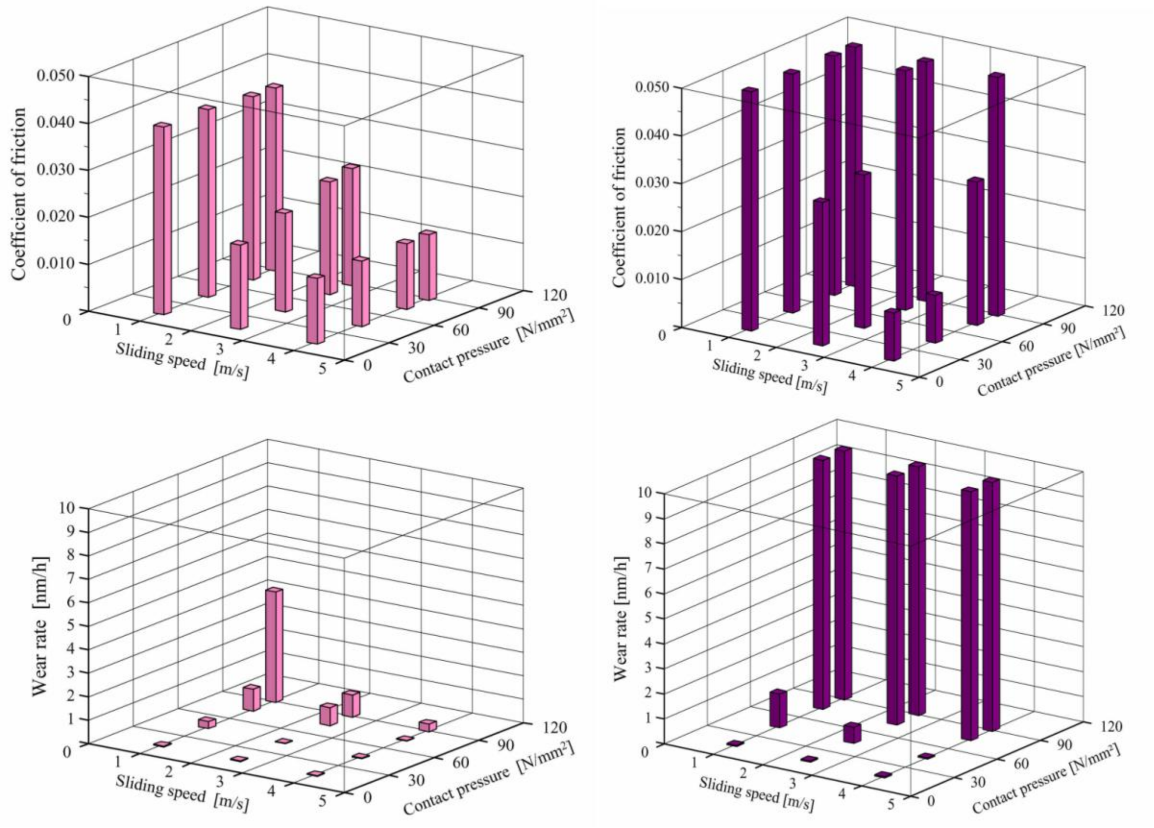

Fig 3: Coefficient of friction and wear rate after finishing with different contact forces. Time of contact 15 s. Left hand side: 600 N. Right hand side: 1,400 N. Coolant with 5% sulphur additive.

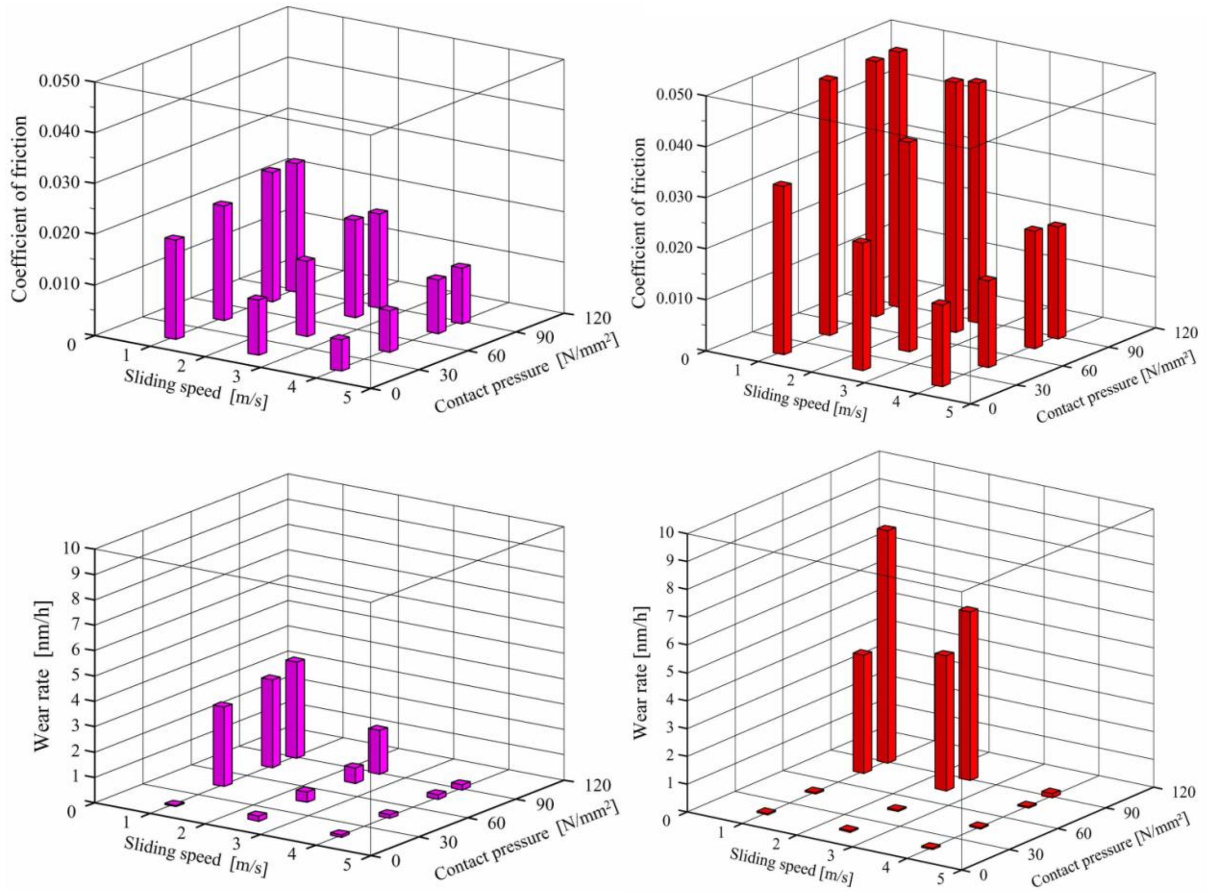

Fig 4: Coefficient of friction and wear rate after finishing at different contact times, 15 s and 30 s. Contact force 1,000 N. Coolant with 5% sulphur.

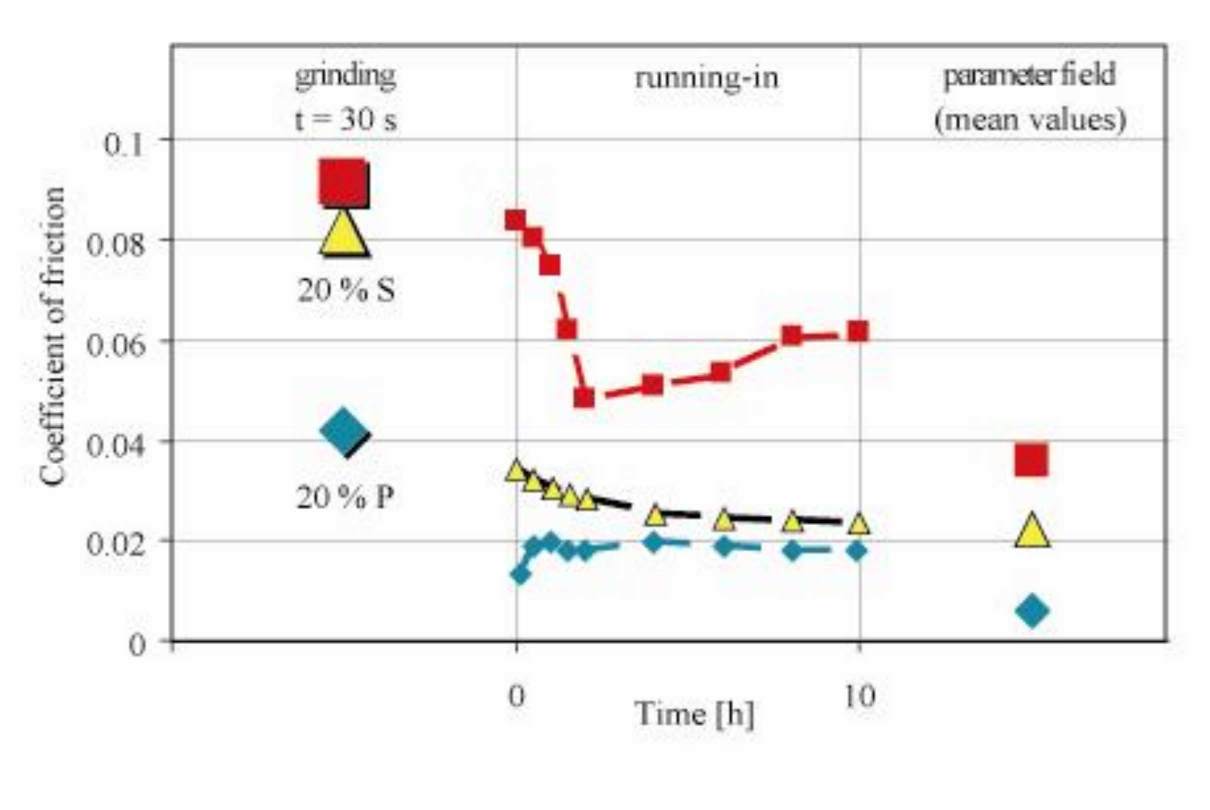

Fig. 5: Grinding force relation and/or friction value in the pin-on-disk tribometer. Left section: grinding force relation; Middle section: coefficient of friction during the running-in; Right section: average of the coefficient of friction coming from the parameter field.

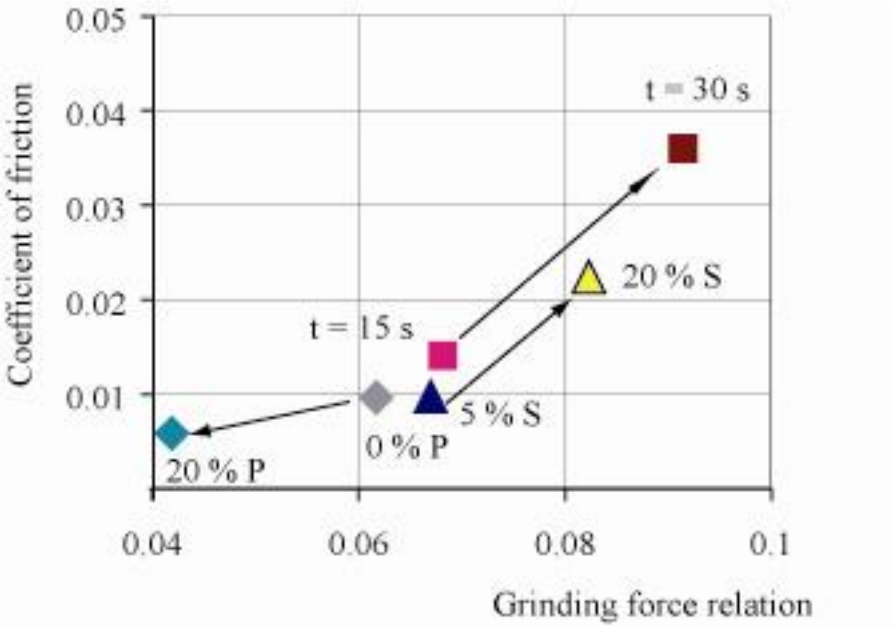

Fig. 6*:* Coefficient of friction as a function of the grinding force relation. The arrows indicate the transition between different additive concentrations or grinding times.

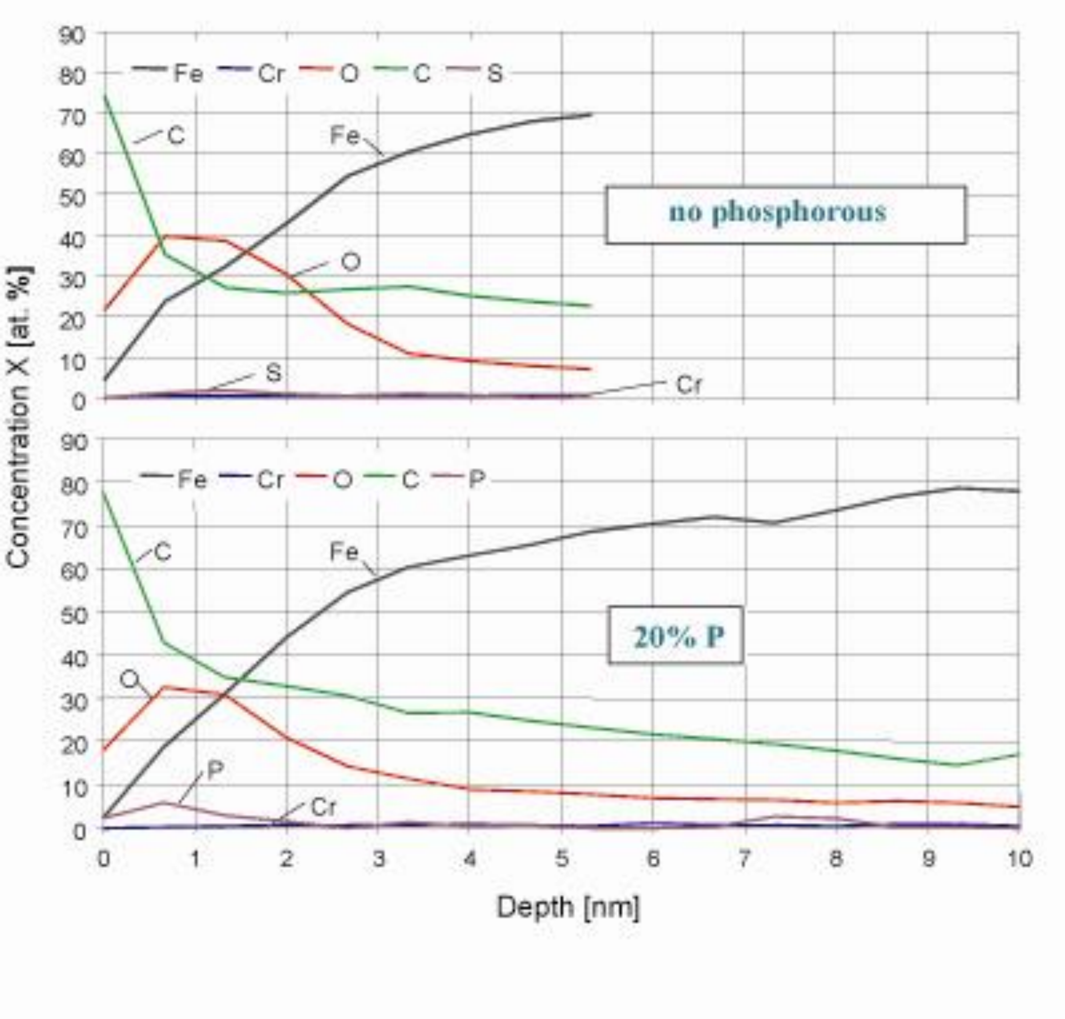

Fig. 7: Depth profiles of iron, carbon, oxygen, sulfur, phosphorous. The content of chromium is a carry over from the pin.

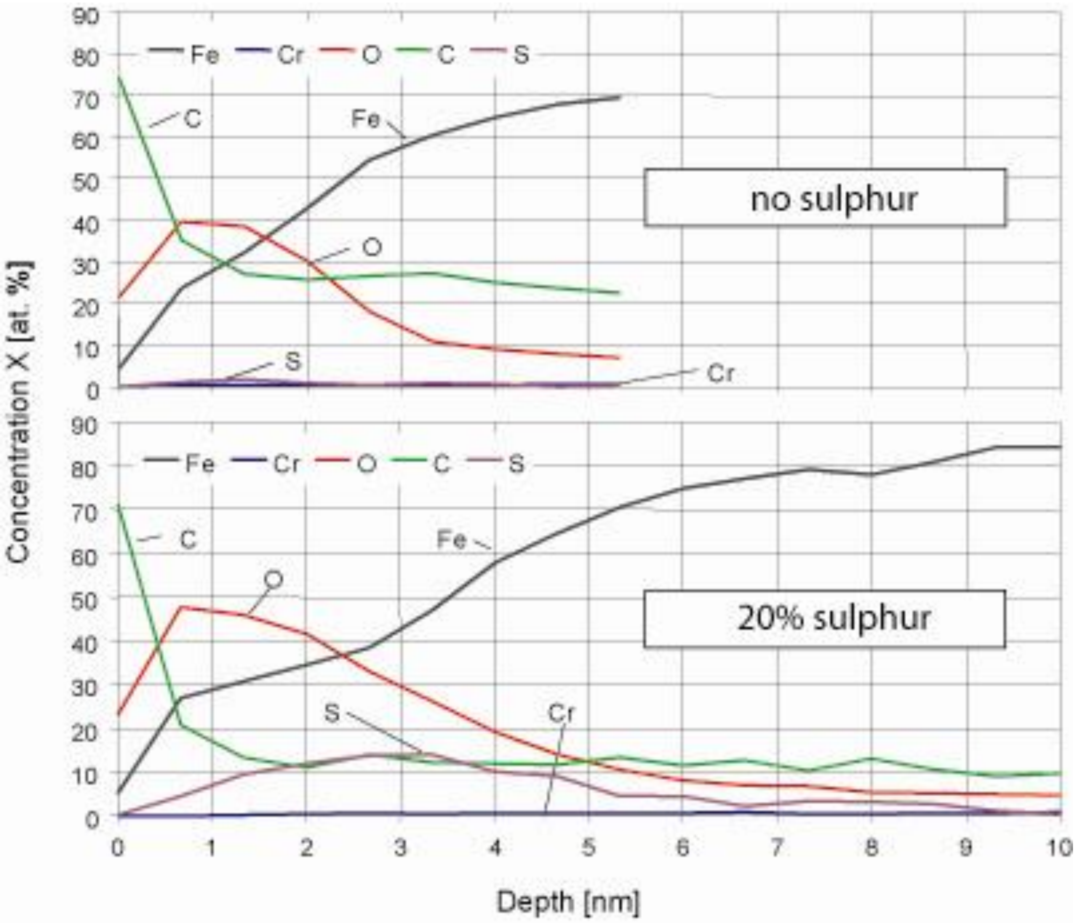

Fig. 8: Depth profiles of iron, carbon, oxygen, sulfur, phosphorous. The content of chromium is a carry over from the pin.

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