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# A new approach to link the friction coefficient with topography measurements during plowing

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## ABSTRACT

Running-in of sliding surfaces is a highly complex process that often defines the tribological properties of a contact. With a view to optimizing a tribosystem, more and more industrial research focuses on the mechanisms that occur during running-in. Such studies can nowadays benefit from the progress shown in the field of *in situ* tribometry. In this work, we present a novel approach to measure and separate the plowing and shear terms of the friction force [1], in the ideal case of a hard sphere sliding on a plane surface. The experiments were performed with ruby spheres and flat steel pins sliding against a flat copper surface immersed in poly alpha olefin (PAO8). A custom built tribometer was employed to measure the widening of plowing tracks within the wear scar. In these measurements, the relative motion of the surfaces in contact was performed in a linear reciprocating manner. Different methods to distinguish between plowing friction and sliding friction are compared. Our results with spherical sliders show that the widening rate of the wear track is linearly proportional to the plowing term, provided that the spheres do not sink in the Cu sample rapidly. Further experiments with flat on flat demonstrate the potential of expanding this method to multi-asperity systems in order to better understand the dynamics of sliding surfaces during running-in.

## 1. Introduction

In many tribological systems that involve sliding metallic surfaces plowing is observed in different stages during and sometimes even after running-in. The friction coefficient is typically monitored during such experiments to observe changes that occur at the real contact area. According to the theory of Bowden et al. [1], the friction force consists of two terms: the plowing term ($A'p'$) and the shear term ($A_r s$) as

$$F_F = A'p' + A_r s \tag{1}$$

with $A'$ being the plowing cross section area, $A_r$ the real contact area and $s$ the shear strength of the softer metal. In their experiments, the aforementioned authors investigated plowing for single pass tests of hard hemispherical spades rubbing on metallic surfaces. It was shown that the flow pressure for plowing $p'$ was not identical with the flow pressure for indentation $p$. This either indicates different mechanisms that govern the behavior of the contact, or non-identical material properties between the surface and the bulk. According to Eq. (1), plowing friction mainly depends on the geometry of the harder slider and is a constant. Subsequently several authors have calculated the plowing component for specific slider geomentries [2,3] including also elastic recovery of the wear track [4]. In many experiments, the first pass includes material changes near the surfaces, that only occur in this phase. For this reason, the data gathered during the first cycle of an experiment are often neglected. Considering the above, it is questionable whether the initial experimental approach of Bowden and Tabor considers the correct plowing flow pressure for advanced cycles. Therefore it is interesting to investigate the plowing contribution to friction for subsequent sliding cycles. An approach suggested to measure plowing *in situ* friction, is to use an indenter to scratch a surface and at the same time monitor the indentation of the probe [5]. The problem that arises in such measurements, is that the elastic recovery cannot be considered [6].

At the nanoscale, atomic force microscopy can be used for *in situ* studies of plowing [7]. Because of the limited normal load they cannot be used to examine complex lubricated multiple-asperity systems.

Plowing in lubricated metallic surfaces is mainly caused by harder asperities of the counter-face and particles entrapped

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between the two surfaces. The diversity of the geometries observed in these media has triggered research on the topography of wear scars. Based on their research, Komvopoulos et al. built a theoretical model which links geometrical parameters of asperities, particles and plowed zones to the friction coefficient [8]. It was shown, that the sharpness of asperities and particles play a dominant role in plowing and lead to abrasive wear [9].

Unfortunately, to date, there are no methods that allow for an efficient separation of the plowing and shear term of Eq. (1) when nano- or microplowing occurs in lubricated multi-asperity systems because most instruments only measure the friction forces, while wear or surface deformation is only determined with topographical methods after the application of mechanical load. Moreover, on-line wear measurement with radio-nuclide technique (RNT) has been proven to be very powerful [10], but only the amount of detached material can be determined. Plowing involves moving material aside without necessarily leading to wear particle generation.

A considerable effort to model plowing and shear friction coefficients during high-temperature ball on disk tests was presented by Wang et al. [11]. In this work, based on existing scratch models and a detailed calculation of the contact interface, a model was proposed to determine plowing and shear friction. The surface changes monitored in experiments that were carried out to confirm the presented model were in the order of hundreds of μm.

The new approach presented in this work takes advantage of a novel tribometer used for high resolution monitoring of plowing while sliding. Furthermore, the possibilities of a simplified approximation for the calculation of plowing and shear terms are put to the test.

## 2. Material and methods

### 2.1. Methods

A home-built *on-line* tribometer was used to study friction and the evolution of the sliding track. Details on the experimental layout can be found in [12]. In short, the tribometer consists of a planar nanopositioning system (Tetra GmbH), a 3D force sensor, a holographic microscope (Lyncée Tec SA), and an atomic force microscope (Bruker AXS Microanalysis GmbH, Germany). The holographic microscope has a field of view (FOV) of about 80 μm × 80 μm, which on the one hand provides the necessary lateral resolution for the measurement, but, on the other hand, it does not allow for monitoring of the whole wear track.

### 2.2. Materials and experiment conditions

All friction/wear experiments were conducted in ambient conditions at a temperature $T=25\ ^\circ\mathrm{C}$ and a humidity of approx. 45%. *In situ* topography images were acquired after every loading cycle with the digital holographic microscope. As the objective lens remained in immersion during acquisition, a transparent PAO-8 oil with a viscosity of $45.8\ \mathrm{mm}^2\ \mathrm{s}^{-1}$ at 40 °C, provided by Fuchs Petrolub AG, was selected as lubricant. The oil circulation was performed by a pump integrated in a radio nuclide technique apparatus (Zyklotron RTM 2000 of Zyklotron AG, Germany). During the experiment, the lubricant's temperature was stabilized at approx. 33 °C. The plate samples were made of oxygen free highly conducting copper (OFHC Cu, purity: 99.98 wt%) and polished with a 1 μm diamond particle suspension without further treatment. The measured hardness of the Cu plate was 77.5 HV 0.1 and the average grain size measured on the surface was $1452\ \mu\mathrm{m}^2 \pm 71\ \mu\mathrm{m}^2$. The flat pins were made of bearing steel (100Cr6/0.9–1.05% C and 1.35–1.65% Cr) with a hardness of 830 ± 10 HV 0.1. The contact area was circular in shape with a diameter ranging from 1.6–2 mm depending on the edge taper. These samples were polished before testing in the same way as the Cu plates. The pin samples had a slight curvature due to the polishing procedure. The root mean square roughness (rms) was measured for both counter surfaces and was 26 nm for the pin. The ruby spheres used had a diameter of 1 mm and a rms roughness of 13 nm.

The sliding experiments were performed in a linear reciprocating motion at various normal loads and speeds, in the range of 2–12 N and 10–25 $\mathrm{mm\ s}^{-1}$. The normal loads and friction forces shown in the results are recorded at the same area where the sample is examined with the DHM. To determine normal and lateral forces at this position, the values are interpolated from the closest measured points in the two sliding directions during one cycle. The initial normal load was adjusted to 2 N for the first 10 cycles of every experiment to avoid deeper damage of the sample due to the high nominal pressure developed before the initial plastic deformation.

Using this instrument we performed model experiments that allow to calculate $p'$ after monitoring the wear track widening that occurs during each cycle.

Considering the above, experiments were performed with a ruby sphere sliding in a reciprocating motion against a Cu plate in lubrication. The criteria that lead to the selection of these samples are the following:

1. The selected spheres have a very well-defined geometry that allows for easy calculation of the plowing cross section by looking at a small area of the overall wear track.
2. No plastic deformation is expected to occur on the ruby surface, as it is significantly harder than Cu.
3. Ruby is an inert material, so no chemical reactions should occur on the surface. This prevents changes in the nature of the intimate contact between the two bodies.
4. The lubricant prevents the accumulation of debris in front of the slider, which could affect the friction values.
5. Using a sphere leads to higher nominal pressure, which leads to a higher contribution of plowing induced changes in friction compared to changes caused by third body formation.

An additional axis with a screw-drive adjust was fixed to the digital holographic microscope (DHM). This allows it to move horizontally and perpendicular to the sliding direction. With this addition, the DHM can be brought to the edge of the wear track. As cycles progress, the track becomes wider, shifting the edge to a new position. Once the edge has reached the end of the FOV, the position of the DHM is readjusted. At certain time intervals we measured the total width of the wear test in order to confirm that the wear track geometry is symmetric. This is achieved with a scaled indication of the axis, with a precision of 2 μm. With the present setup, this is a manual measurement with limited precision.

For the majority of the results shown, the ruby sphere was used as slider. Additional experiments were conducted with flat steel pins. The purpose of using a multi-asperity system is to investigate if plowing in smaller sections of the apparent contact area can be correlated with $F_F$.

## 3. Results

### 3.1. Monitoring wear track edge

In the reciprocating sliding experiment plowing causes the formation of pile-up at the side of the wear track, leading to the formation of a ridge. After the first cycle, the microscope had to be brought to the side of the track in order to monitor the position of the ridge. The ridge evolves after multiple passes of the slider. An example after 50 cycles is presented in Fig. 1(a–c). The height of