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The influence of topography on the specific dissipated friction power in ultra-mild sliding wear: Experiment and simulation

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ABSTRACT

Current political, economic and ecological guidelines demand the increase of power densities of nearly all machinery parts. In order to further lower the wear rate towards the ultra-mild sliding wear regime, an integral approach is needed, which has to regard contact conditions, surface topography, surface chemistry, as well as sub-surface properties. Still, there are no simple parameters to classify the performance of a tribosystem. In this study the area affected by tribocontacts is calculated by means of a three dimensional elastic–ideal plastic contact model. The surfaces are prepared by means of conventional machining procedures and characterized by scanning white light interferometry. The further input data as to normal and friction forces are derived by reciprocating sliding wear tests under boundary lubrication conditions of carburized steel against carburized steel and 52100 steel against case-hardened spheroidal cast iron. This contribution will depict the distinct influence of the topography on friction and ultra-mild sliding wear of common Fe-base materials and point out the marked importance of highly localized effects, which govern the acting mechanisms.

1. Introduction

Wear of machinery parts is inevitable during the transmission of power by means of contacting surfaces. Even in properly lubricated systems wear occurs during periods of boundary lubrication during start-up and shut-down sequences. Nowadays, modern economic and ecological guidelines demand an increase of the power densities of nearly all machinery parts which can also cause a shift from EHL towards mixed and/or boundary lubricated regimes for the entire operation time. Thus, whenever it comes to the design of such machinery parts, the designer needs to bear in mind the amount of wear in the system during service time e.g. for dimensioning the parts and scheduling the maintenance intervals. The wear rate is often assumed as a simple linear relationship between an empirical measured wear depth or wear volume and the sliding distance of a specific system, e.g. [1]. Looking at the wear rates of tribosystems over time, a running-in and a steady-state wear rate can be distinguished which might decrease by some orders of magnitude [2]. This effect can be roughly explained by the adaption of the surface topographies of the contacting bodies. Here surface irregularities or roughness summits will be plastically deformed and/or worn off in the running-in phase [3].

Wear rates are generally desired to be within the ultra-mild wear regime. This means that the actual wear depth does not exceed the maximum surface roughness for a long period of time. Highly localized effects of the dissipation of friction will have a major influence on the performance of such tribosystems, which up to today cannot be described by classical wear or statistical surface roughness parameters. To further decrease those wear rates, an integral approach is needed, which covers the surface topographies, near surface materials' properties and microstructural alterations during tribological loads.

One idea is to generate optimized contact conditions in order to avoid a distinct running-in phase already in the machining step. Thus in this study two different martensitic materials with similar topographies are analyzed in a boundary lubricated reciprocating ball-on-plane wear test. One system is a carburized steel running self-mated in gear oil while the other consists of a 52100 steel ball sliding against case-hardened spheroidal cast iron in motor oil. Two different types of surface topographies were generated by means of standard milling and by a polishing process. In addition numerical contact simulation is conducted (3D linear elastic–ideally plastic half-space [4,5]) in order to analyze the real area of contact (affected area) during run-in and steady state. These values were then combined with the measured forces, displacements, and velocities to gain the locally dissipated friction power over one half-cycle of the reciprocating movement. The results are presented and discussed as to the tribological behavior. The aim of

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this study is to develop a new methodology to characterize wear tests by quantifying the frictional power input characteristics on top of the contacting surfaces over testing time. Closely related to the well-known methodology of S. Fouvry [6] this methodology uses friction power instead of frictional energy. The specific dissipated friction power is presented over one half-cycle of the reciprocating movement after different predefined wear test intervals and summarized in a histogram type manner. This allows quantifying different dissipative regimes during running-in.

2. Materials and methods

The first part of this study covers the conducted wear tests on a custom built tribometer. Here two different material combinations consisting of a self-mating carburized steel and a 52100 steel against a case-hardened spheroidal cast iron are subjected to the same nominal tribological load expect that the lubrication was provided by a gear oil (Mobile SHC Gear Oil; $\eta(40\ ^\circ\text{C})=320\ \text{mm}^2/\text{s}$) for the steel couple and by an engine oil (Mobile 1™ ESP Formula 5W-30; $\eta(40\ ^\circ\text{C})=72.8\ \text{mm}^2/\text{s}$) for the cast iron at 80 °C. Two topographies were chosen for each couple; milled and polished, respectively.

2.1. Carburized martensitic steel – 18CrNiMo7-6 (1.6587)

The carburized martensitic steel 18CrNiMo7-6 (Table 1) is used, amongst others, in highly stressed gears for wind power plants.

After carburizing the near-surface hardness is 650 ± 30 HV10. Both base and counter bodies were taken from identical blanks. The geometry of the base body is $10\times10\times15\ \text{mm}^3$ (height × width × depth) while the counterbody is a polished hemisphere with a 5 mm radius. Material properties of the bulk material are given in Table 2.

2.2. 52100 steel balls according to DIN 5401/ISO 3290

Standardized 52100 (100Cr6) roller bearing steel balls (Table 3) with a radius of 5 mm according to DIN 5401/ISO 3290 were used as counterbodies against spheriodal cast iron blocks.

2.3. Speroidal cast-iron EN-GJS-HB 265 (case-hardened)

Spheroidal cast iron (Tables 4 and 5) is a possible alternative to steel and, therefore, used e.g. as crankshafts in combustion engines of cars and trucks [7]. The chemical composition an material properties are given in Tables 4 and 5.

After flame hardening the near-surface hardness is 550 ± 30 HV10.

2.4. Surface topographies of base bodies

Before wear testing the base bodies were processed by milling and polishing. The milling process was carried out with the same process parameters for both base body materials on a five-axis machining center [8]. The process parameters are given in Table 6.

Polished surfaces were prepared by standard metallographic methods using diamond suspension with a particle size up to 1 µm. Figs. 1 and 2 show the unworn surfaces profiles after milling and polishing.

2.5. Wear tests

All wear test were carried out as reciprocating sliding wear tests (Fig. 3; sphere-on-plane) at $f_{Test}=5$ Hz, a total stroke length of $s=6$ mm and under a normal force of $F_N=30$ N. The tangential (friction) force in sliding direction F_{R_y} and that orthogonal to it F_{R_x} were measured by a 3-axis dynamometer (Type 9257A, Kistler Instrumente AG, Winterthur, Switzerland) every 200 cycles (sampling rate = 2048 Hz) over three cycles. Here only F_{R_x} is considered and further mentioned as F_R. In addition the actual displacement was recorded. After predefined test-cycles (75,000, 150,000, 300,000, 600,000, 1.2 m and 2.0 m) the samples were dismounted and cleaned for 1 min in an ultrasonic bath using ethanol. Then the worn surfaces were examined as to the wear appearances by means of confocal white light microscopy (CWLM) (µSurf, Nanofocus, Oberhausen, Germany) as well as light microscopy (LM). The confocal scanning process was carried out with a lateral resolution of $\Delta x=\Delta y=1.56\ \mu\text{m}$ and a vertical resolution of <10 nm. Afterwards surface height data were filtered with a software high pass and low pass Gaussian filter with a cutoff-wavelength *of* $\lambda_{CH}=15\ \mu\text{m}$ to avoid high surface slopes and $\lambda_{CL}=800\ \mu\text{m}$ to filter out the waviness, respectively. Special attention was paid to the re-positioning of both samples after each test period in order to avoid or at least minimize the recurrence of any new running-in. Therefore two hardness indents placed beside the wear scar allow superimposing the topographies measured at different stages of the test duration and calculating the wear volume.

Table 1
Chemical composition of 18CrNiMo7-6.

C	Fe	Si max.	Mn	P max.	S	Mo	Ni
0.15–0.21	Bal.	0.4	0.5–0.90	0.025	0.035	0.25–0.35	1.4–1.7

Table 2
Physical properties of 18CrNiMo7-6.

Young's modulus	Possion's ratio	Thermal conductivity	Spec. heat capacity	Density
210 GPa	0.3	49.0 W/m K	431 J/kg K	7770 kg/m^3

Table 3
Physical properties of 52100.

Young's modulus	Possion's ratio	Thermal conductivity	Spec. heat capacity	Density
210 GPa	0.3	42.6 W/m K	470 J/kg K	7610 kg/m^3

Table 4
Chemical composition of EN-GJS-HB 265.

C	Fe	Mg	Mn	Ni	Si
3.3–3.8	Bal.	0.02–0.07	0.2–0.5	0–1	2–3

Table 5
Physical properties of EN-GJS-HB 265.

Young's modulus	Possion's ratio	Thermal conductivity	Spec. heat capacity	Density
174 GPa	0.275	32.5 W/m K	515 J/kg K	7200 kg/m^3

Table 6
Milling process parameter.

Indexable insert	Cutting speed	Feed per tooth	Cutting depth
TiAlN	640 $m/$ min	0.05 mm/z	0.2 mm