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The running-in corridor of lubricated metal–metal contacts

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ABSTRACT

In this paper the question is raised whether the coefficient of friction and the wear rate of a lubricated metal–metal system after passing the running-in can be deduced from the initial friction power density this tribological system was subjected to. This contribution defines a running-in corridor as specific energetic range in which the tribological system is able to develop ultra-low wear rates and small coefficients of friction. It will be shown that this corridor is associated with the formation of the third-body. The running-in corridor has a certain width which depends on external tribological stressing conditions, on materials, lubricants and mainly on the initial coefficient of friction. Using two different material pairings it will be demonstrated how tribological systems can be taught to find the route into the running-in corridor. Furthermore, levers of optimization employing friction-modifying additives or appropriate final machining routines will be discussed. The results of this contribution help to improve the understanding of ultra-low-wear systems. In addition comprehensive support for tribological optimization is given.

1. Introduction

The majority of tribological applications in mechanical engineering is based on lubricated metal–metal contacts. Required lifetimes of several thousand hours demand for ultra-low wear rates. Expressed in wear depth per hour, the systems have to show rates smaller than 20 nm/h, often less. The achievement of such small wear rates depends on the ability of the system to form the third body, a state when both frictional members have developed adjusted topographies, chemical compositions and grain structures [1,2].

The running-in is the most critical stage in the life of a tribological system. A successful running-in is the prerequisite for low friction and small wear rate. In addition, system stability and sensitivity to changing boundary conditions crucially depend on the way the running-in progresses. During running-in the tribological contact experiences conditions far from thermodynamic equilibrium. Thus, subtle changes of the acting boundary conditions may cause catastrophic failure. In contrast, when the running-in quickly leads to low friction and small wear rate, the system enters a state of improved stress resistance and failure tolerance [3].

Detailed physical and chemical analysis revealed that during running-in the interfacial topography as well as the near-surface chemical composition and grain structure are subject of significant changes [4–6]. In many cases topography responds to external stresses (load, sliding velocity, temperature, a.s.o.) by developing dissipative structures. For the case of gray cast iron sliding against chromium wave-like structures was observed [6]. At and underneath the surface plastic flow and mechanical intermixing lead to grain refinement and the incorporation of foreign elements of counterbody and lubricant into the matrix of the base material. Third body formation is necessary to develop and to maintain a low coefficient of friction and a small wear rate. In this state first and second bodies contribute equally to the tribological system performance. Moreover, due to tribo-chemical reactions in the interface as well as the mechanical response in deeper regions of the material, the third body conserves itself with respect to thickness, nanostructure and composition [7].

During the first minutes or hours of operation the friction coefficient and the wear behavior can pursue different routes. According to the external stressing level the system can either quickly develop low friction and wear rate (case I), maintain constant friction and wear rate (case II) or may run into catastrophic failure characterized by the exponential increase of friction and wear (case III). Obviously, for a tribological system like a journal bearing or a piston ring/liner assembly, case I is the most desired regime [8]. Case I may also be called a proper running-in.

Since the tribo-chemical processes enabling third body formation require activation energy, the running-in strongly depends on the friction power density acting at the initiation of sliding. It is easy to see that over-stressing will drive the system into a state of high wear and high friction (case III). However, under-stressing is harmful as well. In this case the system does not receive a sufficient amount of energy

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necessary to develop the third body and friction and wear remain high (case II). It has to be mentioned that high friction usually means coefficients of friction larger than 0.2 and high wear rates involve values larger than 100 nm/h. As a consequence, for every tribological system there must be an energetic corridor in which the third body can evolve. The corridor might be very wide for systems that are known to behave tribologically reliable such as chromium against cast iron. However, the corridor can also be narrow. This is the case, when similar materials are combined.

In this contribution, results of own pin-on-tribometer measurements were analyzed with respect to the expected running-in corridor. Data originated from tests sliding a chromium-plated steel pin against a gray cast iron disk [9]. In addition, results were obtained from tribological tests with a steel pin against a disk made of an AlSi alloy. To pay attention to the initial state of the materials the AlSi disks were finished with two different turning procedures, one with a diamond tool and additional with a Wiper cutting tool applying a flat chamfer in cutting direction (Sandvik Coromant, Düsseldorf, Germany).

2. Experiments

The experiments were carried out with a pin-on-disk (POD) tribometer, as shown in Fig. 1.

The experiments were performed using pins either made of chromium-plated steel or 100Cr6. Both types were band-finished and paired with disks of different materials, i.e. gray cast iron and an AlSi alloy as used for engine blocks. Table 1 shows the pairings and specifies the lubricant. The pin assembly consisted of a shaft holding a tiltable hemisphere to realize a self-adjusting flat contact with the disk; see inset of Fig. 1. The sample, a circular tablet, was attached to the flat side of the hemisphere. With the tribometer normal forces up to 1000 N can be applied, corresponding to contact pressures up to 140 MPa in relation to the pin area. The sliding velocities range between 0.1 m/s and 5 m/s.

The tribometer was equipped with an oil circuit containing a heater. The oil temperature of the fully formulated engine oil ranged between 70 °C and 90 °C.

To determine the wear behavior of the system the pins were marked radioactively to allow the use with a radionuclide wear measuring unit (RNT). RNT is based on counting gamma pulses emitted by wear debris leaving the tribological interface. After proper calibration wear rates as low as 1 nm/h can be resolved. Further details of RNT can be found in [3]. The shown RNT measurements were performed with a device of Zyklotron AG, Karlsruhe, Germany (AlSi) and IAVF, Karlsruhe, Germany (Gray Cast Iron).

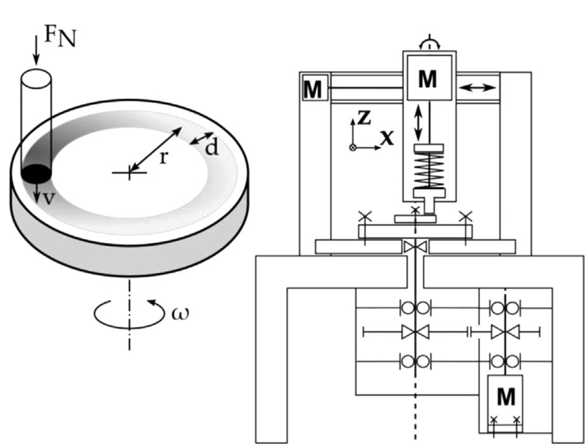

Fig. 1. Schematic of pin on disk tribometer.

Table 1
Pin and disk materials and lubricants.

Pin material and diameter	Disk material	Lubricant
Cr, 3 mm	Gray cast iron (GG25) –band-finished	Fuchs Titan 5W30, Fuchs, Mannheim, Germany
100Cr6, 5 mm	AlSi (AlSi9Cu3) –precision finished –cutting (Wiper)	Castrol Edge FST 5W30; Castrol, Hamburg, Germany

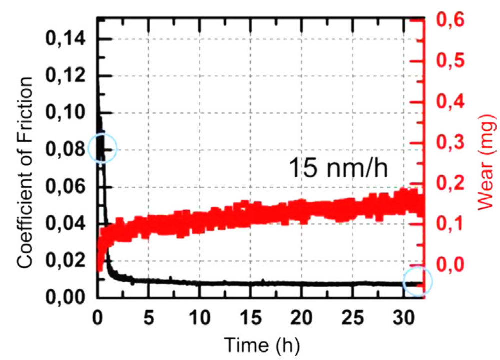

Fig. 2. Running-in of a tribological system. The circles specify initial and final coefficient of friction.

In order to analyze the running-in behavior each friction test was performed with fixed values of sliding velocity, normal force and oil temperature. Friction and wear were recorded continuously; see Fig. 2.

For each test the coefficients of friction of the first 100 revolutions were averaged to receive the initial coefficient of friction μ_i. For the example above, μ_i has a value of 0.08. In addition, the friction coefficients of the last 100 revolutions were averaged to obtain the final coefficient of friction, i.e., μ_f=0.01. Using μ_i the initial power density was calculated by:

$$P_i = \frac{\mu_i v F_n}{A} \tag{1}$$

v is the sliding velocity, F_n is the normal force and A is the nominal area over which the power is dissipated. A was calculated by multiplying the diameter of the pin by the track length on the disk:

$$A = 2\pi r d, \tag{2}$$

r is the track radius on the disk and d is the diameter of the pin; see Fig. 1.

3. Results

3.1. Gray cast iron disk versus chromium pin

Using the values of the experimental parameters and the results presented in [9], the final coefficients of friction were retrieved and the power densities were calculated. Fig. 3 shows two representative experiments out of a series of 6 tests at a constant sliding velocity of 2.5 m/s. The first experiment was performed with a contact pressure of 15 MPa. In each following test, using new pin, new disk and fresh oil, the contact pressure was increased by 15 MPa. With increasing pressure the coefficients of friction exhibited a more pronounced running-in behavior, expressed by decreasing noise, faster transition to low values and lower final friction. The wear rates measured in [9] were very low. In the first