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.

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 were observed [6]. At and underneath the surface plastic flow and mechanical intermixing lead to grain refinement and the incorporation of foreign elements of counter body 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 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).

Experiments

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

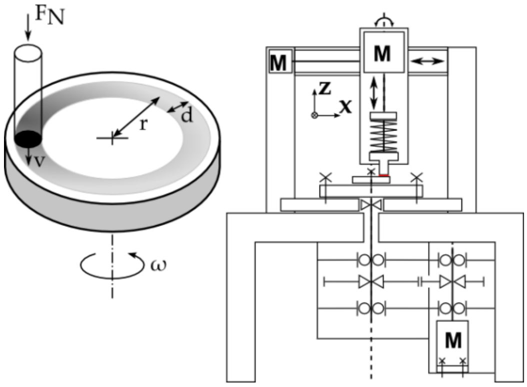

Fig. 1: Schematic of pin on disk tribometer.

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 1,000 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.

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

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

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.

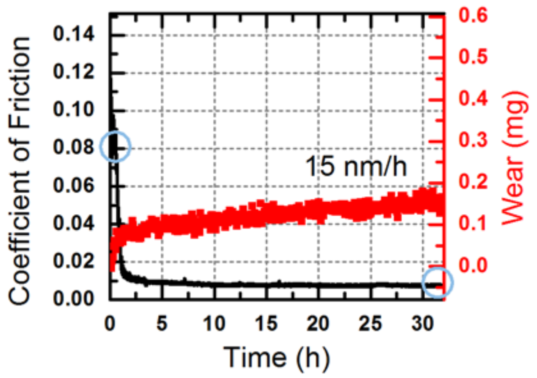

Fig 2: Running-in of a tribological system. The circles specify initial and final coefficient of friction.

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., $\mu_f = 0.01$. Using μ_i the initial power density was calculated by:

$$P_i = \frac{\mu_i v F_n}{A}, \qquad \text{Eq. 1}$$

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:

$$A = 2\pi r d, \qquad \text{Eq. 2}$$

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

Results

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. Figure 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 experiment, wear increased linearly and reached about 120 nm after 68 hours, which corresponds to a wear rate of 1.8 nm/h. This value is already close to the limit of resolution. Therefore, for evaluating the running-in corridor only friction data are used. The additional increase of pressure beyond 90 MPa resulted in a system fail by galling characterized by high coefficient of friction and wear rate.

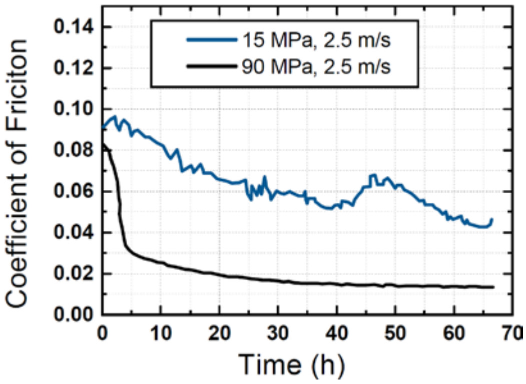

Fig. 3: Friction and wear data of chromium versus gray cast iron. Redrawn from [9].

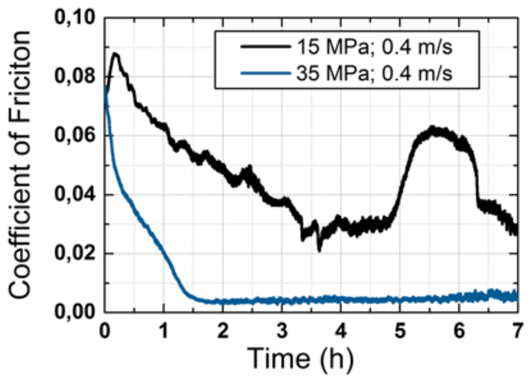

Fig. 4: Friction and wear data of steel versus AlSi (precision finished) [10].

AlSi disk (precision finished) versus steel pin

A second set of friction data (8 experiments) were received from tests with the AlSi alloy disk that was precision finished. The finishing generated a 500 to 700 nm thick submicrocrystalline near-surface microstructure. Two of the friction tests are shown in Fig. 4. Similar to the data obtained for cast iron the friction signal showed less scatter and a faster approach to lowest values for higher contact pressures. At 35 MPa minimum friction was detected. Higher contact pressures resulted in increased friction, pointing towards the existence of a running-in corridor. The data of both experiments are summarized in Tab. 2. Several repetitions proved the validity of data.

Table 2: Results of friction tests.

Chromium/gray cast iron		100Cr6/AlSi	
P´ [W/mm^2]	$\mu_{final} \pm 0.005$	*P´* [W/mm^2]	$\mu_{final} \pm 0.005$
0.03	0.05	0.014	0.095
0.06	0.025	0.017	0.064
0.088	0.2	0.03	0.028
0.12	0.02	0.033	0.029
0.15	0.025	0.034	0.033
0.18	0.2	0.048	0.057
		0.05	0.045
		0.076	0.074

When all values of Tab. 2 were summarized in one diagram, the behavior shown in Fig. 5 was received.

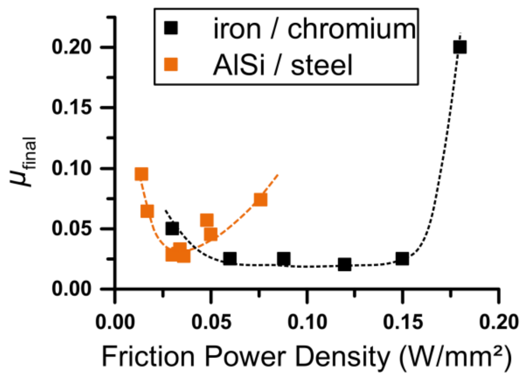

Fig. 5: Final coefficient of friction as function of the initial friction power density. The dotted line is to guide the eye. Error bars are smaller than the symbols.

As evident from Fig. 5, both systems show a pronounced running corridor. The corridor of chromium versus cast iron is much wider than the one of steel versus AlSi. In addition, the AlSi corridor is shifted to lower power densities. The data show larger scatter at the left border of both corridors.

AlSi disk (Wiper cut) versus steel pin

Finally, a second set of AlSi disks was prepared to consider different morphological conditions of the near-surface material. Whereas the precision finished disks showed a very shallow submicrocrystalline area, the disks prepared by cutting possessed a significantly thicker zone of about 9 µm. For details see [11]. The contact pressure was varied from 25 MPa to 45 MPa and the sliding velocity was either 0.8 m/s or 2 m/s. In total 5 different stressing levels were applied, see Fig. 6.

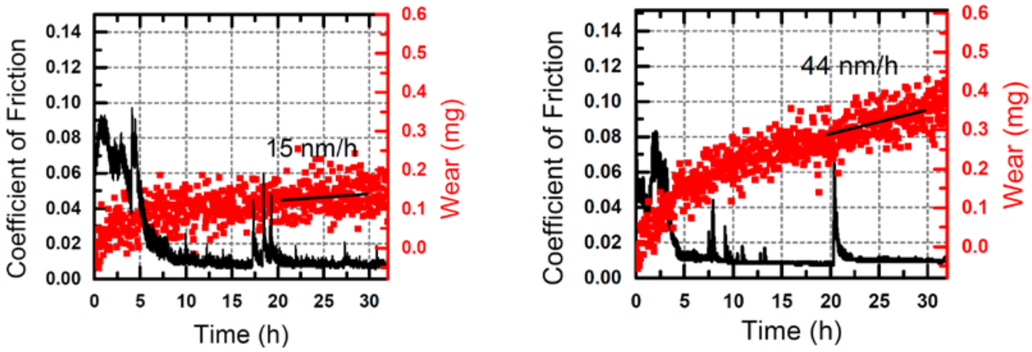

Fig. 6: Representative friction and wear data of steel versus AlSi. Left: 25 MPa at 0.8 m/s. Right: 45 MPa at 2 m/s [11].

The development of noise was similar to the other experiments. Higher contact pressures resulted in reduced data scatter.

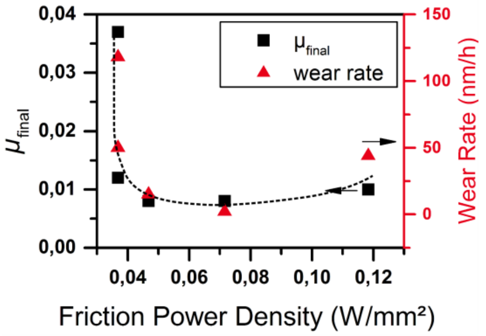

Fig. 7: Coefficient of friction and wear rate as function of the initial friction power density.

Both friction and wear data can be approximated by a master curve, see Fig. 7. In terms of corridor location, a shift to higher power densities can be observed compared to the system with the precision finished disks. In terms of width the corridor is slightly wider.

Discussion

The running-in corridor

Before entering the discussion of the running-in corridor, the question of repeatability of the friction and wear results has to be addressed. As for entities like hardness, yield stress or Youngs modulus friction and wear data a subject to fluctuations. The fluctuations are more intense the farther away the system is operated from optimum running-in conditions leading to lowest friction and ultra-low wear rates. It was shown by numerous experiments [12-14] that friction and wear curves behave extremely repeatable when the adequate energetic range for the running-in was found, provided that sample finishing and materials homogeneity did not introduce further deviations.

The results obtained for friction coefficient and wear rate indicate that a running-in corridor exists. It is obvious that the corridor has a width in accordance to the tribological experience with these materials. Systems with gray cast iron as one of the friction bodies are known to respond with great stability. These systems adjust to a wide range of boundary conditions. Other systems like AlSi vs steel are more difficult to handle. The running-in corridor is much narrower and shifted to lower initial friction power densities.

The results for friction and wear were combined in one diagram, see Fig. 7, showing that the overall behavior can be approximated by a single master curve. It seems that for many tribological systems a master curve can be generated. The width of the corridor is a function of the tribological stressing conditions, i.e., load, sliding velocity, temperature, finishing, a.s.o. In addition, the type of the materials and the lubricant impose a great impact. All corridors showed a larger data scatter at the left border. Whereas at the right hand side of the corridor the system is driven into catastrophic failure, at the left hand side the systems partly jump between high and low friction. In this range the system a highly sensitive to external changes – load, temperature, viscosity – and internal deviations such as changes in topography or structural changes due to finishing. These changes act on the friction power density and determine whether the system follows case I, II or III.

To bring some order into the discussion of the influences, an evaluation of the parameters based on Eq. 1 was introduced. The equation of the initial friction power density contains the coefficient of friction, the normal force and the sliding velocity in the enumerator. The area over which the energy is dissipated is located in the denominator. Thus, the initial friction power density can be varied over a wide range.

The role of the initial coefficient of friction

The sequence of friction coefficients at the beginning of a mixed friction experiment is mainly influenced by the initial shear stress of both materials and the lubricant. These effects are reflected by the Stribeck curve expressing the coefficient of friction as function of viscosity η , sliding velocity and contact pressure p; $\mu = f(\eta v/p)$. By changing the viscosity of the oil the coefficient of friction can be considerably lowered or increased. When it is not possible to change viscosity, the introduction of friction modifiers can help to reduce initial friction. Other additives like ZDDP are known to cause an initial increase of friction [15,16].

The role of normal force and sliding velocity

Whereas normal force and sliding velocity can be treated as system input values, the coefficient of friction has to be considered the system output. Usually the input values

cannot be changed by the tribologist, since they are pre-defined by construction or the scheme of operation. If, however, a variation is possible, as in the case of an engine in a test cell, then normal force and sliding velocity can be used to vary the initial friction power density. Although the increase of normal force and sliding velocity nominally increase the initial friction power density, the impact of each entity is not equal. The increase of normal force increases the contact pressure and by this the stress state in the near-surface volume. The response of the material with respect to plastic flow might be different. Variations in sliding velocity, however, yield a different result e.g. due to possible strain rate sensitivities of the materials. Since the formation of the third body is not an instantaneous process, the temporal behavior of tribological stressing has great influence.
The increase or decrease of normal force and/or sliding velocity not only change the friction power, but lead to a different *v/p* value in the Stribeck curve as well. Increased sliding velocity and decreased contact pressure shift μ to lower values and vice versa. When the sliding velocity becomes too large, the system is likely to switch from mixed lubrication to hydrodynamic lubrication. This transition is accompanied by a significant drop in friction, thus the friction power density becomes smaller.

The role of contact area

In the experiments shown above the initial power of friction was divided by the area over which the power was dissipated. This was necessary to make different experiments comparable. However, this approach is premature since it ignores the fact that both friction bodies form a real area of contact which is a fraction of the geometric contact area. When the real area of contact is introduced to Eq. 1, running-in optimization is furnished with another large lever. By choosing different kinds of final machining the real contact area can be varied over a very wide range.
For the AlSi disks two different kinds of surface finishing routines were applied. In addition to topography, the routines resulted in a different range of mechanical interaction, quantified by a different depth of the submicrocrystalline near-surface zone. It has to be mentioned that the chemical composition of the near-surface material was changed as well. However, this kind of complex interplay is subject of further investigations. The finishing with the Wiper cutting insert resulted in a wider running-in corridor shifted to higher values of the initial friction power density. This means that such a conditioning generated a tribological system that can be stressed more severely and responds with decreased sensitivity, i.e., is less prone to catastrophic failure in the range of chosen boundary conditions. Furthermore, the findings show that friction power should be related to the interacting volume instead of contact area. However, this approach is far from being applicable, since the basics describing tribologically interacting volumes do not exist.

Arguments for a well-aimed optimization of the running-in

In this paragraph the question is answered how a tribological system can be brought into the running-in corridor to safely achieve low friction and small wear rate. Assuming that the system suffers from over-stressing, i.e. the initial friction power density is too high, then lowering normal force and/or sliding velocity would be the first choice. As a second approach, the addition of a friction modifier might provide another solution. The additive lowers the initial coefficient of friction and shifts the system into the corridor. The same result can be received by using a sliding lacquer. Finally, the contact area should be increased, which is possible for example by switching from a surface finish by e.g. turning to honing or lapping.

When these measures are applied at the opposite end of the running-in corridor, i.e., the area of under-stressing, detrimental results will be obtained. For instance, the introduction of a friction modifier will then lower the initial coefficient of friction. Since the initial friction power density is already too low, this action will result in high friction and wear. At the left hand side of the running-in corridors actions like increased normal force, sliding velocity and coefficient of friction will lead to the desired results. With respect to final machining a rougher surface can evoke the shift into the corridor.

Conclusions

The following conclusions can be drawn:

-the running-in process can be controlled by finding the appropriate energetic corridor that enables the system to enter the third-body regime

-the identification of the width of the running-in corridors provides the user with a valuable design tool

-the identification of the initial power density with respect to the energetic location of the running-in corridor allows to set the boundary conditions (oil viscosity, friction modifier, a.s.o.) correctly

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