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SHANNON ENTROPY AS A CHARACTERISTIC OF A ROUGH SURFACE: WHY THE RUNNING-IN TRANSIENT PROCESS LEADS TO FRICTION REDUCTION [1]

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Abstract
When friction is initiated, there is a certain transient period, referred to as the "running-in", during which friction and wear decrease to their stationary value. During the running-in period, the surfaces roughness of contacting solid surfaces changes, until it reaches a certain equilibrium value and thus the adjustment of surfaces to each other occurs. This process can be viewed as self-organization that leads to minimized energy dissipation and thus minimum friction and wear]. In this research, theoretically and experimentally, the minimization of friction and wear by adjustment of surface roughness to an equilibrium value during the running-in transient process was investigated. A control model, using feedback loop due to the coupling of two mechanisms, was developed with Matlab / Simulink software. The time-dependence of the coefficient of friction and roughness parameter during the simulated running-in process were analyzed. In order to check whether the self-organization occurs, the Shannon entropy of a rough profile was calculated. The Shannon entropy is a generalization of the thermodynamic entropy for the information theory. A surface profile with lower Shannon entropy is "more ordered" (or "less random") than a profile with a higher Shannon entropy, and, therefore, decreasing Shannon entropy during the transient process is an indication of self-organization.
Key words: Friction; Entropy.

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INTRODUCTION

Surface adjustment during the running-in is a simple case of friction-induced self-organization, which can be viewed as a model example. It is well known that the static coefficient of friction is usually greater than the kinetic coefficient of friction. This phenomenon often leads to the so-called non-linear stick-slip motion (Figure 1). During the stick-slip motion, the frictional force does not remain continuous, but rather oscillates significantly as a function of sliding distance or time. During the stick phase, the friction force builds to a critical value. Once the critical force has been attained (to overcome the static friction), slip occurs at the interface, and energy is released so that the frictional force decreases.

When friction is initiated, there is a certain transient period, referred to as the "running-in", during which friction and wear decrease to their stationary value (Figure 1). Furthermore, when the load or sliding velocity change, the friction force usually increases at first, and then decreases to the steady state value. This is an experimental observation, and it is not obvious at all *a priori*, why the opposite tendency (increasing friction during the transient period) is almost never observed.

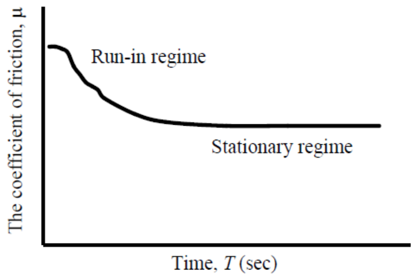

Figure 1. Typical decrease of friction during the running-in

During the running-in period, the surfaces roughness of contacting solid surfaces changes, until it reaches a certain equilibrium value and thus the adjustment of surfaces to each other occurs. This process can be viewed as self-organization that leads to minimized energy dissipation and thus minimum friction and wear. However, a particular mechanism of this process remains to be explained.

2 MODEL

Running-in is a simple example of friction-induced self-organization. During the running-in stage, the surfaces adjust to each other and their microtopographies evolve to a certain equilibrium value. Friction and wear rate during the running-in usually decrease to the minimum value. We investigate a simplified model, which, however, captures the main qualitative features of the running-in (Figure 2). We assume that both friction and wear are determined by two different mechanisms, namely, the deformation and the adhesion. The surface roughness of the softer surface at any moment of time is characterized by certain distribution of micro-topography. For simplicity, we assume that surface roughness is sufficiently characterized by only one parameter, *R*.

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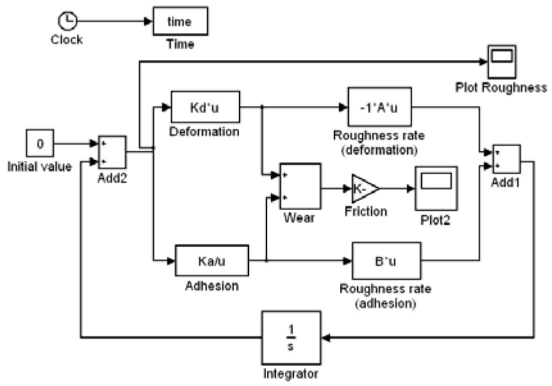

Figure 2. A feedback loop model in Simulink Two simultaneous processes (adhesion and deformation) affect surface roughness in different manners. Consequently, an equilibrium value of roughness exists, which corresponds to minimum friction.

For the deformational mechanism, higher asperities results in higher wear rates *k* and higher friction coefficients. We assume a simple linear dependence

$$\mu_{def} = C_{def} R \qquad k_{def} = K_{def} R \tag{1}$$

where *C* and *K* are proportionality constants. There is a feedback between wear and surface roughness since high asperities tend to fracture due to wear and make the surfaces smoother, so that

$$\dot{R} = -Ak_{def} = -AK_{def} R$$

For the adhesional mechanism, smother surface results in higher adhesion force, and, therefore, higher friction and wear. We assume a simple 1/*R* dependency

$$\mu_{adh} = C_{adh} / R \qquad k_{adh} = K_{adh} / R \tag{2}$$

The adhesive wear tends to make surface rougher, so

$$\dot{R} = Bk_{adh} = BK_{adh} / R \tag{3}$$

Consider now a combination of the two mechanisms acting simultaneously. The total friction, wear, and rate of roughness are given by the sum of the components

$$\mu = C_{def} R + C_{adh} / R \tag{4}$$
$$k = K_{def} R + K_{adh} / R$$
$$\dot{R} = -AK_{def} R + BK_{adh} / R$$

The solution has a stationary point that corresponds to $\dot{R} = 0$ or $R = \sqrt{BK_{adh} / AK_{def}}$ The stationary point is stable, since the slope of the curve $\dot{R}$ vs. *R* is negative. The coefficient of friction and wear that correspond to the stationary state are given by

$$\mu = C_{def} \sqrt{BK_{adh} / AK_{def}} + C_{adh} / \sqrt{BK_{adh} / AK_{def}} \tag{5}$$
$$k = K_{def} \sqrt{BK_{adh} / AK_{def}} + K_{adh} / \sqrt{BK_{adh} / AK_{def}}$$

Note that the minimum wear occurs at the minimum point of *k* in Eq. 4, that is, $R = \sqrt{K_{adh} / K_{def}}$, whereas minimum friction occurs at $R = \sqrt{C_{adh} / C_{def}}$. The stationary point

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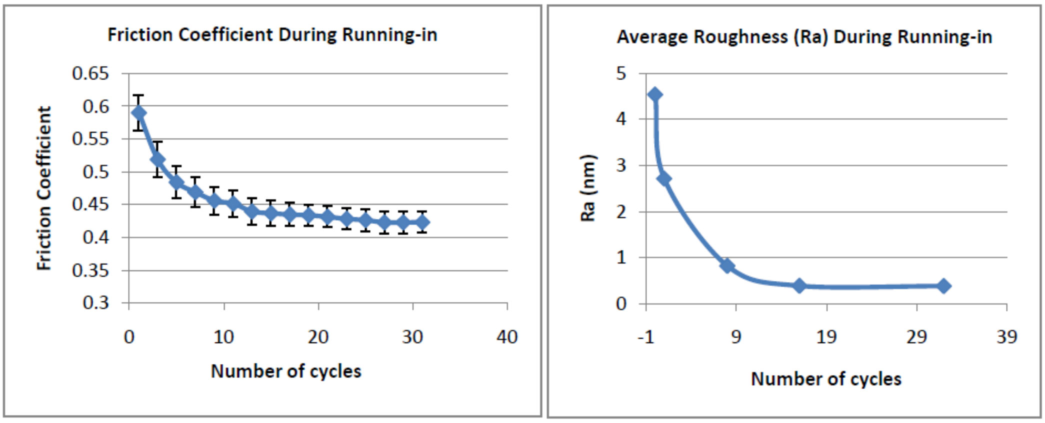
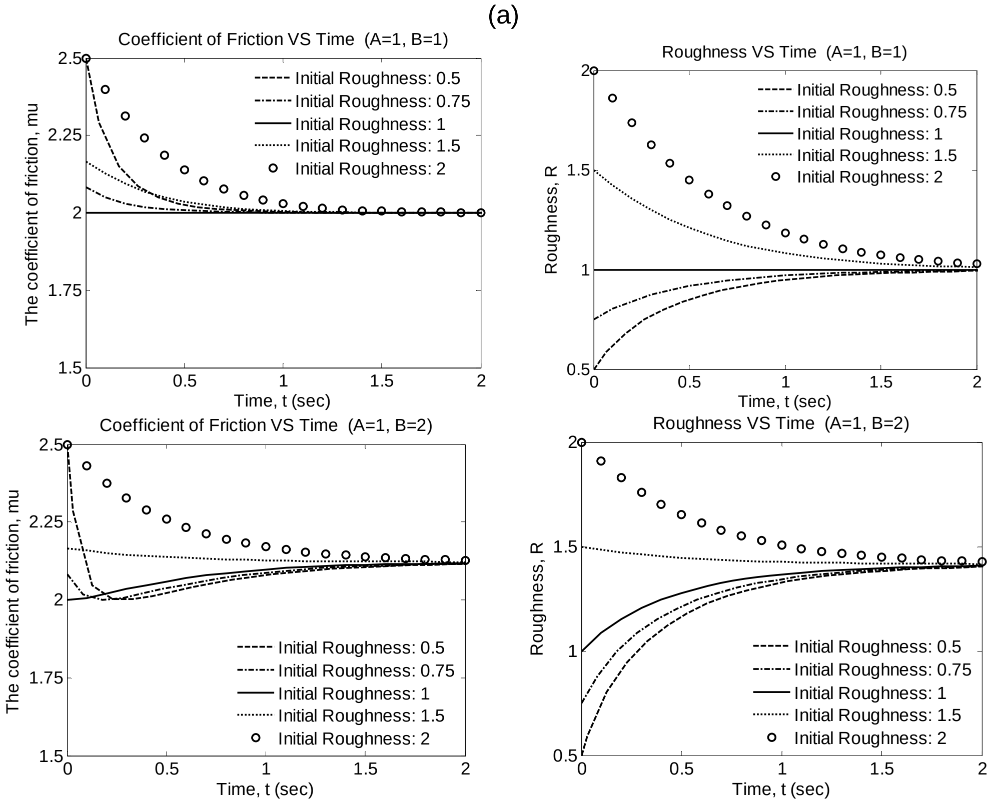
($R=\sqrt{BK_{adh}/AK_{def}}$) corresponds to minimum wear only if *A*=*B*, and it further corresponds to minimum friction if $K_{adh}/K_{def}=C_{adh}/C_{def}$. This assumption of *A*=*B* is justified if the rate of change of roughness is proportional to the wear rate. The assumption $K_{adh}/K_{def}=C_{adh}/C_{def}$ is justified if wear is proportional to friction. The model shows that friction decreases always, whereas roughness can increase or decrease (Figure 3).



(a)



(b)

Figure 3. (a) Experimental results and (b) theoretical modeling (bottom). The time-dependence of the coefficient of friction and roughness parameter during the running-in simulated with Simulink. For A=B, the coefficient of friction always decreases, while roughness reaches its equilibrium value,. Therefore, self-organization of the rough interface results in the decrease of friction and wear. For A≠B, the coefficient of friction can slightly increase.

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To check experimentally whether the self-organization occurs, the Shannon entropy of a rough profile was calculated

$$S = -\sum_{j=1}^{B} p_j \ell og[p_j] \qquad (6)$$

where p_j is the probability of appearance of a height in the bin j, and B is the total number of bins. The Shannon entropy is a generalization of the thermodynamic entropy for the information theory. A surface profile with lower Shannon entropy is "more ordered" (or "less random") than a profile with a higher Shannon entropy, and, therefore, decreasing Shannon entropy during the transient process is an indication of self-organization.(3)

3 EXPERIMENTAL

To inspect the changes of roughness parameters in transient running-in process, an experiment was conducted. The experiment was carried out in an ultra-high vacuum (UHV) chamber tribometer. The aim was to produce some spots, each one representing different period of transient running-in process. The Cu sample (about 2 cm × 1 cm) was mounted to a sample manipulator, which was oriented horizontally and on the opposite side of the chamber to the tribometer. A tribopin, mounted to the end of an arm, then was brought into contact with the sample and rubbed its surface. The triboarm can be moved in the x, y and z-directions using servo motors which allowed to precisely determin the pin position, while the normal and lateral forces were determined by strain gauges mounted to thinned sections of the tribo-arm. The apparatus is under computer control, so the normal load, scan speed, scan area and scan pattern are selected.

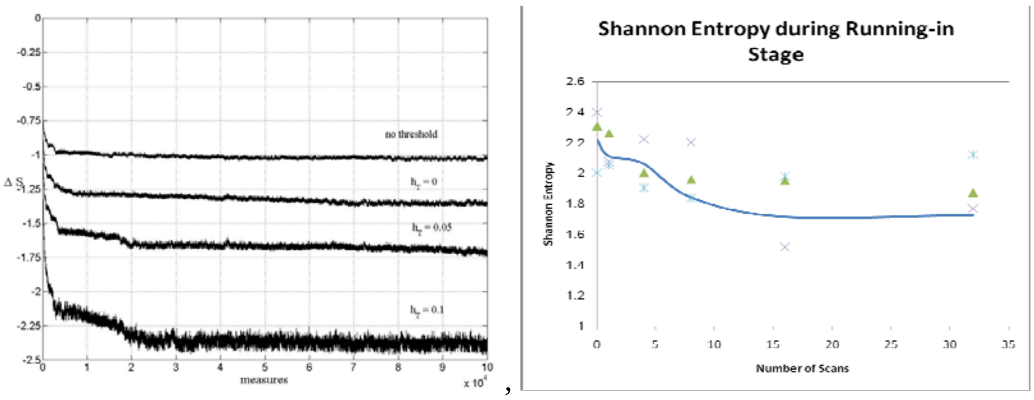

Figure 4. An example of decreasing Shannon entropy with time during the transient process [2] experimental results for WC pin vs. Cu disk UHV tests.

In this experiment, the testing sample was made of pure copper, while the material of pin was tungsten carbide (WC), selected due to its hardness and stiffness. The normal load was set at 0.9 N and the sliding speed was 4 mm/s. The experiment was conducted at the room temperature, and five different spots, with the length of 4 mm each with different rubbing time were produced on the surface of the sample. To do so, number of scans of tribopin on the surface of sample respectively increased from spot 1 to 5, namely, 1, 4, 8, 16 and 32 scans. Two series of these spots were produced.

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After preparing the sample, Atomic force microscopy (AFM) images of different spots were obtained using Pacific Nanotechnology Nano-R™ AFM instrument. It includes a motorized zoom/focus video microscope, an AFM scanner, three motors for moving the probe towards the sample, a sample holder and a motorized X-Y positioning stage. Images were produced in contact mode. Scans (512 x 215 pixels) were collected at a minimum of three different locations on each spot. Then, image processing was performed using the SPIP software package by image metrology rather than the instrument manufacturer's software to obtain figures of different roughness parameters.

4 CONCLUSIONS

In this research, we investigated the adjustment of surface roughness to an equilibrium value during the running-in transient process as an example of friction-induced self-organization. Such process leads to the minimization of friction and wear. Shannon entropy as a characteristic of a rough surface, which quantifies the degree of disorder of the self-organized system.

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