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# THE FRICTION MECHANISM BETWEEN SURFACES WITH REGULAR MICRO GROOVES UNDER BOUNDARY LUBRICATION

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**Abstract.** The results of research related to the influence of partially regular microrelief parameters on the adhesion component of the friction factor under boundary lubrication are presented. It has been shown that micro grooves are effective under boundary friction on precision surfaces with low roughness when lack of film and probability of seizure appear. The deformation component of the friction force of surfaces with micro grooves has been studied. The time of micro running-in was the key factor while assessing the dependence of the deformation component on friction when taking into account the depth of micro grooves and their relative area. The research was conducted using a tribometer according to the friction model entitled "shaft & flexible steel tape".

**Keywords:** boundary lubrication, friction force, lack of film, micro grooves, tribometer.

## 1. Introduction

There are many technological methods to improve the tribological characteristics of sliding friction pairs. One of these methods is the formation of regularly spaced sinusoidal micro grooves on friction surfaces that are called "surfaces with a partially regular microrelief" according to GOST 24773-81 (Schneider 1982; Shaikhutdinov 2010). The grooves are formed by means of surface plastic deformation performed by the spherical indenters (Fig. 1). The depth of these grooves can be taken from 5 to 50 μm.

The most common positive effect in the boundary friction between surfaces with a partially regular microrelief can be explained in relation to the lubrication conditions improved by increasing oil absorption (Schneider 1982, 1998, 2001). Apparently, this explanation cannot be considered the only correct one because during normal friction between real pairs too much lubricant is left in the pockets. These pockets form due to a shape error, a surface position error, and in spaces between the projections of the surface's roughness. The boundary friction between precision surfaces may cause the so-called "lack of film" when, due to a great number of point contacts on the tops of micro asperities, the boundary lubricant film does not have time to recover while being ruptured. The seizure leads to a further avalanche destruction of the boundary coating (Kragelskyi, Gitis 1983). Two researchers: I. Kragelskyi and N. Gitis, have proved that micro grooves on a friction surface reduce the effect of "lack of film". A number of researches have revealed the presence of hydrodynamic pressure on micro grooves. This pressure can appear even under boundary friction.

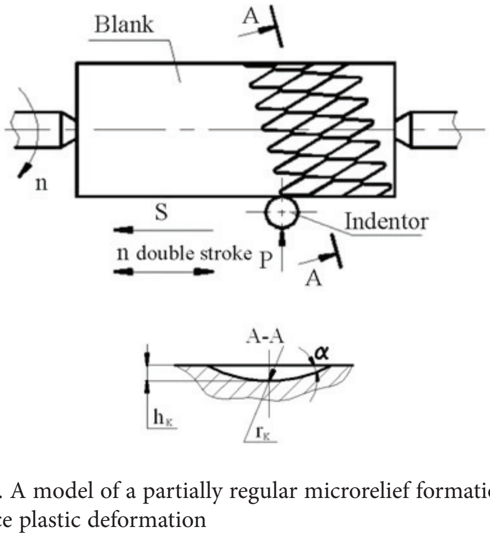


Fig. 1. A model of a partially regular microrelief formation by surface plastic deformation

## 2. Problem statement

Despite the large number of studies on friction surfaces with a partially regular microrelief, these surfaces are not widely used in practice, and some application attempts can lead to a negative effect. To investigate the influence of surfaces with a partially regular microrelief on the tribological characteristics of samples, it is necessary to eliminate the influence of shape errors as well as the influence of friction surface position errors. However, it is not possible to eliminate the influence of these errors when applying the tribometer used in mechanical engineering. In order to eliminate the errors mentioned, a macro running-in of the samples to equalize the nominal contact area and contour contact area is required. During this process the micro running-in takes place and uniform roughness is formed.

Research on surfaces with a partially regular microrelief and on surfaces with a regular microrelief is conducted. The study and implementation of the surfaces mentioned above are conducted in various industries pertaining to different friction pairs. However, the friction mechanism of these surfaces has been insufficiently investigated. There is no clear understanding of the scope of surfaces with a partially regular microrelief and surfaces with a regular microrelief in friction pairs (Chernyshev *et al.* 2010; Golubchikov, Kuzmin 2010; Morgounov *et al.* 2004; Popov, Avanish 2002).

According to molecular mechanics theory of friction, the total friction force under boundary lubrication can be resolved into an adhesion component and a deformation component. The measurement of these components can be done with some difficulties. This paper has investigated the adhesion and deformation components of friction under boundary lubrication of surfaces with regular micro grooves.

To conduct tribological research without using the macro running-in process, a new tribometer has been developed on the basis of friction between a shaft and metal tape (Radionenko 1987). The metal tape can be used as a mating sample due to its small thickness – 0.06 mm. It is flexible, which allows locating it on the sample without committing shape errors and surface position errors. Thus the nominal contact area and the contour contact area are equalized. The tribometer is equipped with an air damper to reduce self-oscillations and with an inductive friction torque transmitter (Fig. 2). The drive of a tribometer has the ability to provide stepless speed control of the sample. Different loading can be obtained by means of two tension springs and the application of mating samples of different lengths. This tribometer allows to perform testing at a pressure up to 2 MPa on a sample and at a loading up to 470 N. Due to the small thickness of the tape it is possible to control the temperature in the friction area with high precision. This is achieved by soldering the chromel-copel thermocouple of Ø 0.2 mm directly to the tape of a mating sample over the friction area. The tribometer and its instrumentation allow one to control lubrication modes (boundary lubrication, mixed lubrication, liquid lubrication) according to the electrical resistance of lubricant film. While studying surfaces with a partially regular microrelief, the friction torque is monitored and the friction factor is calculated by a formula obtained on the basis of the Euler equation derived for the case of wrapping the shaft with a flexible cable.

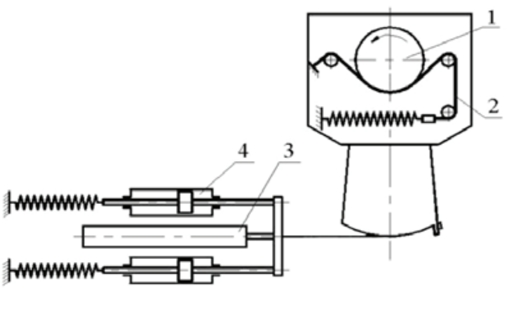


Fig. 2. Diagram of a tribometer (1 – sample; 2 – steel tape as a mating sample; 3 – friction torque transmitter; 4 – air dampers)

## 2. The purpose of the research

The purpose of the research on surfaces with a partially regular microrelief is to study the influence of micro grooves on the adhesion and deformation components of the friction factor and to identify the lubricant removal mechanism from the micro grooves.

All the studies were conducted with the oil "Industrial 20" and steel C80W2 of 30-32 HRC. Micro grooves of different depth $h_K$, with the radius of the bottom $r_K$ and the relative area $F_K$ are formed parallel to a cylinder element on the samples with a diameter of 30 mm by means of plastic deformation. After micro grooves formed the cold laps and swellings of metal on the edges of the micro grooves were carefully removed by grinding and polishing with an abrasive paper on a hard stuffer, which excluded an intensive lowering of the edges of micro grooves.

The adhesion component was studied using the method of exclusion of the deformation component of friction, for which the roughness of samples and the roughness of mating samples were taken as $R_Z$ = 0.08 – 0.1 mm. The surface of the sample was fed with a strictly dosed small drop of oil, carefully distributed over the entire surface. The measurement of the friction torque is performed between the 3$^{rd}$ and 5$^{th}$ friction cycles when the friction force is maximal. When friction started a small number of cycles did not change the initial roughness, and provided self-location of a mating sample (tape) on the sample and a reliable contact between the friction surfaces. After 3–5 cycles the friction force decreased due to the start of formation of the uniform roughness and the improvement of lubrication conditions. All experiments related to the adhesion component were performed under boundary lubrication at a sliding velocity of $3.14 \times 10^{-2}$ m/s. The temperature was kept constant at (33 ± 2) °C.

It was necessary to investigate surfaces with micro grooves of different areas $F_K$ and, consequently, surfaces with different contour areas of contact. The preliminary experiment was carried out to identify the influence of contour pressure $p_C$ on the friction factor for samples without micro pits. The experiment confirmed the total independence of the friction factor f after the micro running-in and the adhesion component of the friction factor $f_a$ from contour pressure $p_C$ in the range up to 2 MPa for both surfaces without micro grooves (Fig. 3) and surfaces with micro grooves (diagrams 1 and 2 in Figs 4, 5).

The diagrams in figure 4 were obtained at a constant contour pressure $p_C$. The constancy of $p_C$ was provided by reducing the loading force N on the sample. This reduction is proportional to the decreasing contour area due to increasing $F_K$. Figure 5 illustrates dependences obtained under continuous pressure of loading N for different $F_{K,}$ and, consequently, for different contour areas. In other words, increasing $F_K$ and decreasing the contour area caused a proportionate increase of the contour pressure. As illustrated, the diagrams in figure 4 and the diagrams in figure 5 are identical. In the diagrams (Fig. 5), the contour pressure is calculated for the surfaces excluding the area of micro grooves and is designated as $p_0$.

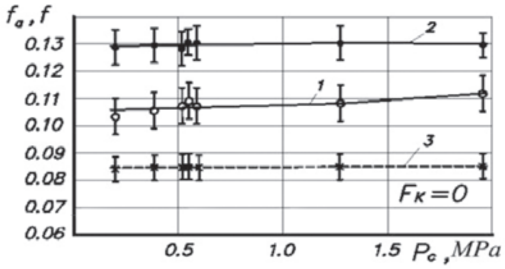


Fig. 3. Dependence of the adhesion component of the friction factor $f_a$ (curves 1, 2) and the friction factor f after the micro running-in (curve 3) on contour pressure $p_C$ for surfaces without micro grooves

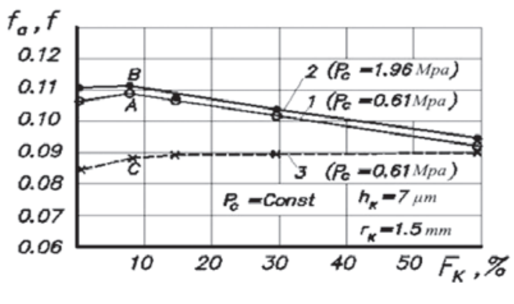


Fig. 4. Dependence of the adhesion component of the friction factor $f_a$ (curves 1, 2) and the friction factor f after the micro running-in (curve 3) on the relative area of micro grooves $F_K$ under constant contour pressure $p_c$

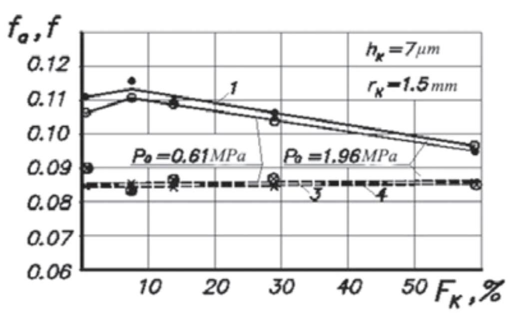


Fig. 5. Dependence of the adhesion component of the friction factor $f_a$ (curves 1, 2) and the friction factor f after the micro running-in (curves 3, 4) on the relative area of micro grooves $F_K$

Dependences 1 and 2 in figure 3 are obtained for different conditions of lubrication. In case 2, the lubricant film is much smaller than in case 1. The thickness of the lubricant film is determined by a few monolayers, and the friction mode is intermediate between boundary friction and friction without the lubricant. Dependence 1 is obtained when the lubricant film has partly volumetric properties. In this case, the effect of compressed film is observed as well as the effect of squeezing the remaining oil out of the contact area or into the micro pits on the friction surface. The breaks of curves in points A, B and C on the diagrams provided in figure 4 can be explained by the above-mentioned effects.

### 3. Research results

During the studies, the possible location of a mating sample along the chord (the effect of a chord) above a micro groove has been verified. In this case the thin steel tape is used as a mating sample. Besides, the influence of the above mentioned effect on the readings of the tribometer has been determined. The test results showed that "the effect of a chord" does not appear.

From the diagrams in Figures 4 and 5, it is concluded that the contour pressure in the range of 0.25–2.0 MPa does not affect the adhesion component of friction and the total friction factor of grinding surfaces under boundary lubrication. This conclusion puts into doubt the statement that the increase of the friction factor on surfaces with a partially regular microrelief under the increase of the relative area of micro grooves $F_K$ higher than the optimum value (ranged from 25 to 45%) is connected with the reduction of the rated contact area and the increase of pressure. The optimal area of micro grooves in this range is the result of a simultaneous increase of oil absorption and contour pressure (Schneider 1982).

In this experiment the friction factor $f_a$ depends on the relative area of micro grooves $F_K$ only due to the lubrication mechanisms:, due to the ability of friction surfaces to absorb the lubricant from the micro grooves and to form reliable boundary lubrication (Radionenko 2005; Radionenko, Kindrachuk 2005).

The depth of micro grooves $h_K$ and their radius $r_K$ affect the $f_a$ value and, consequently, the ability to absorb lubricant from micro grooves. The diagrams in figures 6 and 7 prove that when the depth of micro grooves decreases and their radius increases the absorption of lubricant from micro grooves improves and the adhesion component of the friction factor decreases.

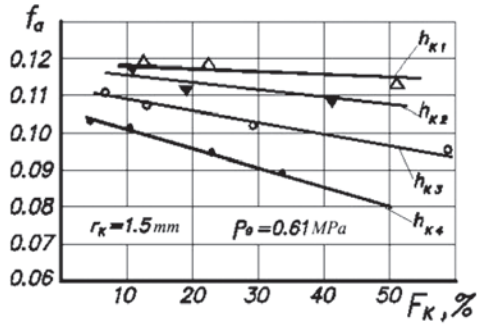


Fig. 6. Dependence of the adhesion component of the friction factor $f_a$ on the relative area of micro grooves $F_K$ at a depth of micro grooves $h_K$: $h_{K1}$ = 20 μm; $h_{K2}$ = 11 μm; $h_{K3}$ = 7 μm; $h_{K4}$ = 3 μm

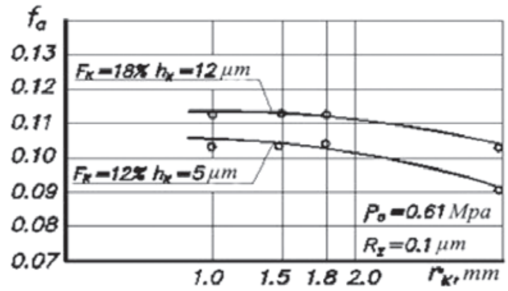


Fig. 7. Dependence of the adhesion component of the friction factor $f_a$ on the bottom radius of a micro groove $r_K$

The mechanism of boundary lubrication of surfaces with a partially regular micro-relief can be represented as follows. If the micro pits formed by asperities of uniform roughness are located between rubbing surfaces, they can be filled with lubricant either completely or in part. The contact and friction between surfaces take place along the projections of micro asperities. The lubricant is supplied to the projections in the actual contact area from nearby micro pits. Micro grooves with a partially regular micro-relief appear to be ineffective if the distance between them is greater than the uniform roughness asperity spacing. The lubricating effect of micro grooves under boundary lubrication appears in cases when the actual contact areas are extended to cause lack of film. In such a case, the pitch of micro grooves can be commensurate with the distance between the contact areas (National… 1971).

The effect of micro pits is experimentally confirmed when the roughness of samples and tape roughness are equal to or less than Rz = 1.0 μm. In other words, when the greatest lack of film and probability of seizure take place (Figs 8, 9).

In practice, the effect of micro pits is observed when the extension of the actual contact areas increases. Examples of such cases are: the plastic deformation of micro asperity projection; the inability of a friction pair to reproduce uniform roughness during friction, when the projections are smoothed out and spaces are reduced; the running-in of precision friction pairs with low roughness.

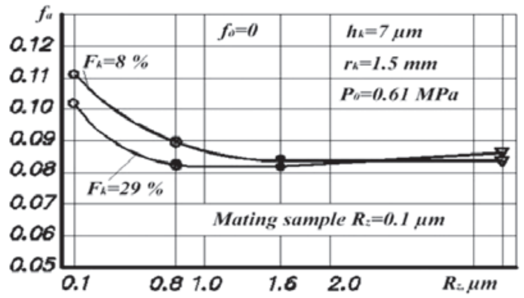


Fig. 8. Dependence of the adhesion component of the friction factor $f_a$ on the relative area of micro grooves $F_K$ at different sample roughness $R_Z$

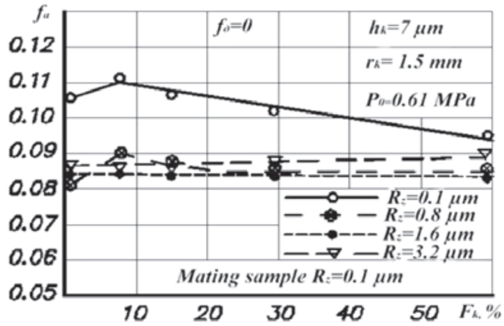


Fig. 9. Dependence of the adhesion component of the friction factor $f_a$ on the roughness $R_Z$ of the sample carrying surface

According to molecular mechanics theory of friction, the mechanical component of the friction force can be considered the force which is required to penetrate the surface layer of a solid body with infiltrated micro asperities (Dmitriyev *et al.* 2005).

During friction between surfaces with micro grooves the deformation component can be added to the mechanical component of the friction force due to the engagement of micro asperity tips with the edges of micro grooves, which can cause an additional increase of the resulting friction force and the friction factor under certain conditions (Fig. 10).

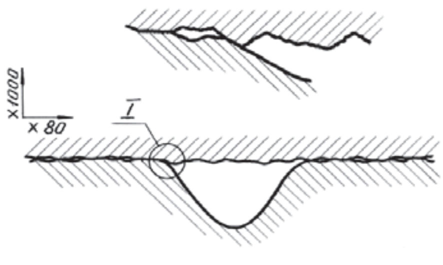


Fig. 10. The engagement of micro asperity projections with the edge of a micro groove in sliding friction

The micro asperities located over micro grooves do not experience compression under load during the process of friction; hence, their height is greater than the height of micro asperities in the contact area between micro grooves.

Taking into account that the edges of micro grooves are not sharp and slightly expanded, it is presumed that the deformation component of friction caused by the engagement with the edges of micro grooves is insignificant. However, there is evidence that, after long term operation of a sliding friction pair with micro grooves on one of the operational surfaces, one of the edges of micro grooves gets more worn than the opposite one (Fig. 11).

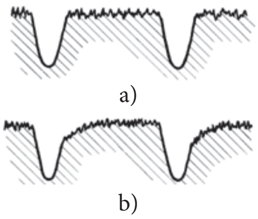


Fig. 11. Wear of the edge of a micro groove: a) before operation; b) after 1500 hours of operation

To determine the role of the deformation component, the running-in of surfaces with micro grooves has been studied. If there is an engagement of micro asperity projections with the edges of micro grooves, the duration of the micro running-in should depend on the number of micro grooves per an area unit, to rephrase, on the relative area $F_k$ of micro grooves with a constant width $b_k$. In this case, an equivalent factor is the number of projections n per an area unit.

The duration of the micro running-in of the samples with micro grooves and mating samples has been studied in order to determine the influence of the deformation component. During analysis, a flexible steel tape with the surface roughness in the range from 5 to 7 μm (Ra ≈ 0.8 μm) was used as a mating sample. The roughness of the tape was provided by means of grit paper, and the direction of the roughness traces was shifted perpendicularly to the tape axis.

Research was conducted with the help of a tribometer (Fig. 2) using the steel C80W2 of 30–32 HRC.

Micro grooves on samples were formed by means of pressing with a spherical indenter with a radius r = 1.5 mm. The micro grooves were located parallel to a cylinder element. Cold laps and metal swellings on the edges of micro pits were carefully removed in order to cause minimum obstruction to the edges of micro grooves. The carrying surface roughness was in the range from Rz = 0.8 to 1.0 μm (Ra ≈ 0.15 μm). The analysis was conducted in the boundary lubrication mode using the oil 'Industrial 20' at a sliding velocity $V = 3.14 \cdot 10^{-2}$ m/s. In all experiments, the contour pressure was calculated for the surfaces excluding the area of micro grooves and was equal to $p_0 = 0.61$ MPa.

The duration of the micro running-in was determined according to the time it took for the friction factor to stabilize (Fig. 12). During the process of the micro running-in lubricant excess was provided, as evidenced by its appearance in the inlet area of friction.

The boundary lubrication mode was controlled by the electric resistance in the contact area and by the oscilloscope displays. The diagrams in figure 13 confirm the dependence of the micro running-in duration on the relative area of micro grooves $F_k$, which allows making conclusions about an engagement of micro asperity projections with the edges of micro grooves.

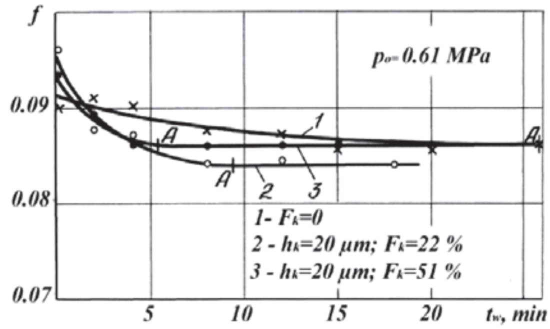


Fig. 12. Determining the time of the micro running-in completion $t_w$ according to the stabilized friction factor f (point A)

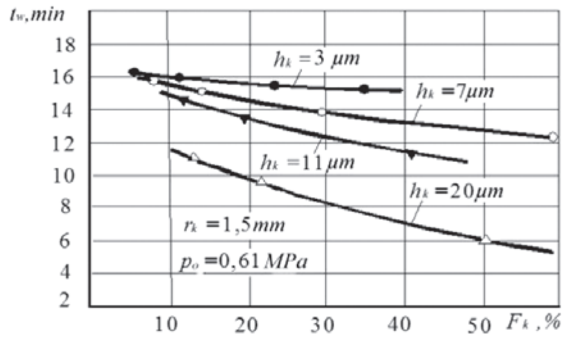


Fig. 13. Dependence of the time of the micro running-in completion $t_w$ on the relative area of micro grooves $F_k$

It should be noted that a micro running-in the range of $h_k$ = 7–20 μm is more intensive than in the range of 3–7 μm. If the micro grooves are shallow, the deformation component of the friction force that appears as a result of the engagement of micro asperity projections with the edges of micro grooves will be reduced. This can be explained by the fact that the lubricant from shallow channels is removed better and the lubricant film thickness increases at the edges. This means that, if the depth of micro grooves $h_k$ is less than 3 μm, there is a probability of transformation into mixed lubrication at the same values of sliding velocity, pressure and viscosity of the lubricant, which are typical for the boundary lubrication mode. It was not possible to check the friction mode $h_k$ of less than 3 μm, and $F_k$ of more than 50% due to some difficulties of sample preparation.

The rate of the micro running-in is also affected by the loading cyclicity of micro asperity projections, which causes their fatigue failure. The greater the relative area of micro grooves $F_k$ at a constant width $b_k$ is, the faster the micro running-in is finished. Under sliding friction in the boundary lubrication mode the loading cyclicity of micro asperity projections can lead to more extensive wear of a friction surface mated with the surface where micro grooves are formed. However, this is compensated by the decrease of wear resulting from the formation and destruction of adhesive welding bridges, and most importantly from the elimination of the probability of seizure.

Fatigue wear can be considered to be the growth of a wear value under normal friction in the mode of boundary or mixed lubrication when the relative area of micro grooves $F_k$ increases and its value exceeds the optimum value $F_k$ = 25–45%.

The value of the deformation component of the friction force should increase in the case of micro seizure because the break of adhesive welding bridges is accompanied by the removal of metal micro particles welded to the mating surface projections from the friction surface. This leads to the formation of higher projections with increased hardness which engage with the edges of micro grooves and significantly deform them (Fig. 14) (Dmitriyev *et al.* 2005).

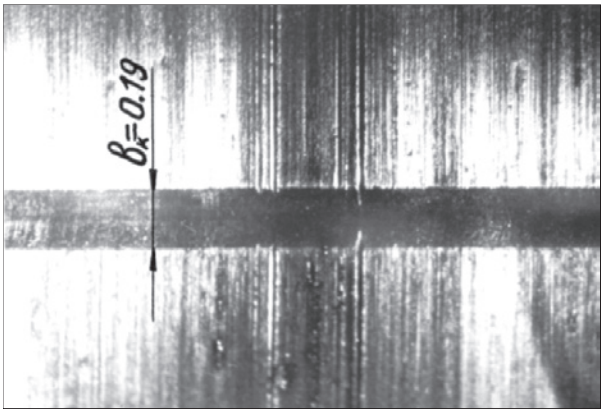


Fig. 14. Traces of penetration of micro asperity projections into the edges of micro grooves, which formed as a result of a micro seizure ($h_k$ = 3 μm, $r_k$ = 1.5 mm)

The decrease in the deformation component of the friction force reduces the energy cost for friction during the steady state mode of friction, as well as improves the smoothness of movement. The latter is indicated by the decrease in the variations of the friction force when tape surface roughness is reduced from Rz = 5–7 μm to Rz = 2–3 μm. At the same time, in order to accelerate the process of running-in it is necessary to increase the deformation component of friction.

The required depth of micro grooves should be maintained in order to ensure a good running-in of the friction surfaces, which results in light surface wear and the reduction of groove depth. The profile of grooves is also changed: one of the edges becomes more rounded. Upon completion of the running-in the grooves with less depth and rounded edges of micro grooves provide a reduction of the adhesion and deformation components of friction and decrease wear on the friction surfaces in comparison with the period of running-in.

## 4. Conclusions

1. The formation of micro grooves of 3–20 μm on the friction surface reduces the adhesion component of the friction force under boundary lubrication if the friction surfaces do not have micro cavities to reserve lubricant. This friction pair ought to have minimum clearance, high accuracy of shape (round surface, longitudinal section profile) and have a minimum surface roughness of less than Rz = 0.8–1.0 μm).
2. Micro grooves increase the deformation component of the friction force under boundary lubrication, especially when the mating friction surface has increased roughness.

Thus, the formation of micro grooves on friction surfaces under boundary lubrication is highly applicable for precision friction units, for example, in the boxes of the odolites, in the friction units of telescopes and other precision devices.

The effect of micro grooves under boundary lubrication appears when the friction surfaces are unable to provide normal modes of friction and lubrication. If a friction pair is run in and operates without deviations, it will be inappropriate to form micro grooves on contacting surfaces in order to improve the mechanism of lubrication and increase their wear resistance, except in cases when structural errors were made during the process of a new friction pair design.

## References

Chernyshev, V.; Shatokhin, B.; Khaibullin, P. 2010. *Increasing the Longevity of Cylinder Liners of an Internal Combustion Engine Using Regular Microrelief Formation*. Vol. 53. Moscow: Press of Russian Scientific Research Institute, 91–94.

Dmitriyev, S.; Koudrin, A.; Labunets, A., *et al.* 2005. Functional coatings application for strengthening and restoration of aviation products, *Aviation* 9(4): 39–45. http://dx.doi.org/10.1080/16487788.2005.9635917

Golubchikov, M.; Kuzmin, Y. 2010. *Modeling Process of Vibration Rolling Over,* 53(8). Moscow: University press "Priborostroyeniye".

Kragelskyi, I.; Gitis, N. 1983. Probability of 'lack of film' in plastic lubricants, *Friction and Wear* 4(1): 12–17.

Morgounov, A.; Pogodaev, V.; Masyagin, V. 2004. Relative area of a surface with partially regular microrelief while rolling with a rotating tool, in *New Materials and Technologies: Proceedings of All-Russian Scientific and Engineering Conference.* Rubtsovsk, 34–36.

National Aeronautics and Space Administration. 1971. *Lubrication, friction, and wear* [online]. Langley Research Center, Hampton, Virginia [cited 25 August 2013]. Available from Internet: http://www.surface.mat.ethz.ch/education/courses/surfaces_interfaces_and_their_applications_II/NASA_Wear_UA

Popov, M.; Avanish, A. 2002. *Final Processing of Precision Surfaces with an Oscillating Tool.* Press of Donskoy State University, 2(1): 40–50.

Radionenko, A. 1987. *The Tribometer to Study the Influence of Surface Quality on the Condition of Lubricant Film.* Moscow: Mashinovedeniye, 93–97.

Radionenko, A. 2005. Lubricant mechanism of surfaces with a partially regular microrelief*, Problems of Tribology* (4): 203–206.

Radionenko, A.; Kindrachuk, M. 2005. Friction model and technological support of surfaces with a partially regular microrelief, *Problems of Tribology* (1): 59–68.

Schneider, Yu. 1982. *Operational Properties of Details with Regular Microrelief.* Leningrad: Mashinostroyeniye. 248 p.

Schneider, Yu. 1998. *Technology of Final Processing Using Pressure*: Handbook. St. Petersburg: Politekhnika. 414 p.

Schneider, Yu. 2001. *Operational Properties of Parts with a Regular of Microrelief. Series "Outstanding Scientists of Information Technologies"*. St. Petersburg. 264 p.

Shaikhutdinov, R. 2010. Methods of increasing oil absorption of friction surfaces of cylinder liners, *Bulletin of the Kazan State Agrarian University* 13(2): 110–111.