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INFLUENCE OF THE NORMAL FORCE ON THE SLIDING FRICTION UNDER ULTRASONIC OSCILLATIONS

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Natalie Milahin[1], Qiang Li[1], Jasminka Starčević[1,2]

[1]Berlin Institute of Technology, Germany
[2]National Research Tomsk State University, Russia

Abstract. *The paper is devoted to an experimental investigation of the sliding friction force between a rapidly oscillating sample and a rotating steel plate. The sliding friction force is studied experimentally as a function of the oscillating amplitude, the sliding velocity and the normal force. The results have proved the hypothesis that the coefficient of friction is a function of dimensionless oscillation amplitude and dimensionless velocity.*

Key Words: *Sliding Friction, Ultrasonic Oscillations, Tribospectroscopy*

1. INTRODUCTION

Ultrasonic vibration is widely used in manufacturing processes for the reduction of friction, such as tube and wire drawing, metal forming and drilling, etc. [1-5]. The effect of ultrasonic oscillation on the sliding friction has been studied for a few decades, including all possible directions of vibration with consideration of various frequencies and oscillation amplitudes [6-10]. The pioneer experimental studies of Godfrey [11] and Lenkiewicz [12] have found that the sliding friction reduction is due to vibration. Later the influence of oscillations on both friction and wear of metals was investigated by Weishaupt [13] and Goto et al. [14]. In the recent few years the theoretical models have been also developed to explain this reduction phenomenon for different directions of vibration [15, 6-7].

In the recent paper [10], the influence of ultrasonic oscillations for the basic configuration (in-plane-oscillations: oscillations in the contact plane along and perpendicular to the sliding direction; out-of-plane oscillations: oscillations perpendicular to the contact surface) is systematically studied in the relevant interval of the oscillation amplitudes and sliding velocities. The theoretical models are developed to support the experimental data. Its results show that the relation between the sliding velocity and the oscillation one is important for

Received: January 12, 2015
Corresponding author: Natalie Milahin
Technische Universität Berlin, 10623 Berlin, Germany
E-mail: natalie.milahin@tu-berlin.de

the reduction of friction for all these three basic configurations, and this effect can be expected to be significant when the sliding velocity is much smaller than the oscillation one. However, the work is carried out only under constant normal load (F_N = 9 N). Paper [16] has demonstrated that the normal load conditions also play an important role in the static friction force in the presence of ultrasonic oscillations. This effect is supposed to be observed in the sliding contact. Therefore, in this paper a complete experimental study for the out-of-plane configuration will be presented.

2. THEORETICAL ANALYSIS

We consider the dry contact of a sphere indenter pressed against a substrate moving with constant velocity v. Under normal load F_N, indentation depth $u_z^{(0)}$ is generated. After applying the ultrasonic oscillation, indentation depth $u_z^{(0)}$ becomes a periodic function of time t : $u_z = u_z^{(0)} + \Delta u_z \cos \omega t$, where ω is the circular frequency of oscillations. In paper [17], it is argued that that the main governing parameter in most of the contact and frictional problems is indentation depth $u_z^{(0)}$. The only velocity scale which can be produced using this characteristic spatial scale $u_z^{(0)}$ is combination $\omega u_z^{(0)}$. With these characteristic space and velocity scales, we can define dimensionless oscillation amplitude

$$\Delta \hat{u}_z = \Delta u_z / u_z^{(0)} \tag{1}$$

and dimensionless velocity

$$\hat{v} = v / (\omega u_z^{(0)}) \ . \tag{2}$$

According to general ideas of the paper [17], we can expect the resulting coefficient of friction μ in the presence of oscillations to be a function of only these two dimensionless variables:

$$\mu = f(\Delta \hat{u}_z, \hat{v}) \ . \tag{3}$$

Indentation depth $u_z^{(0)}$ is difficult to measure directly but it can be estimated if the normal force is known. It is shown in [18] that for a wide class of surface profiles, the indentation depth is a power function of the applied normal force

$$u_z^{(0)} = c \cdot F_N{}^{\gamma} \tag{4}$$

with c contact stiffness and $0 < \gamma < 2/3$, while $\gamma \approx 0$ for "very rough" surfaces (white noise) and $\gamma = 2/3$ corresponds to the Hertz solution for a single smooth asperity. For macroscopic profiles with superimposed roughness it is shown that there can be a crossover from a smaller value of γ to a larger one when the normal force is increasing [19]. Substituting Eq. (4) into Eq. (1) and (2), we can reformulate the hypothesis (3) in the form

$$\mu = \tilde{f}\left(\frac{\Delta u_z}{c F_N^{\gamma}}, \frac{v}{\omega c F_N^{\gamma}} \right) . \tag{5}$$

In this paper this hypothesis will be proved from experiment investigation.

3. EXPERIMENT MEASUREMENT AND RESULTS

The experimental measurements are carried out on the ultrasonic pin-on-disk tribometer (set-up in Fig. 1). To investigate the sliding friction force as a function of the normal force under the ultrasonic oscillations, we have used a specimen made of steel with build-in piezo elements with natural frequency $\omega = 30$ kHz and a small steel bearing ball (100Cr6) fixed on the one side. The rotation speed of the disc made of structural steel is controlled by the step motor and the specimen is installed as perpendicular to the disc. During the measurements the specimen is pressed against the rotating disc under different normal forces and the specimen performs oscillations perpendicular to the sliding direction (so called out-of-plane-mode). The variable amplitude of the oscillations is controlled by the ultrasound generator and measured by the high-precision laser vibrometer. The friction and normal forces are measured by the force sensor.

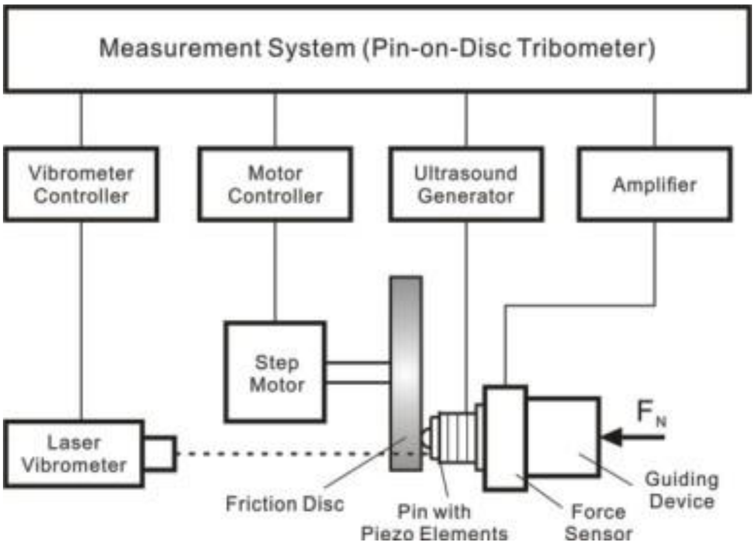

Fig. 1 Experimental Set-up, schematic view on the pin-on-disc-tribometer [10].

The sliding friction force is measured for five different excitation states, oscillation amplitude $\Delta u_z = 0$, 0.04, 0.08, 0.16 and 0.27 μm, four different normal loads F_N = 4, 9, 18 and 32 N, and also for different sliding velocities v ranging from 0.001 to 0.009 m/s. With these small velocities, the maximum influence of ultrasonic oscillation can be achieved. Each measurement (constant sliding velocity, constant normal load and constant amplitude) lasts for 1 minute and the frictional force is averaged by 60 measured values during this time. The coefficient of friction is obtained from the division of averaged frictional force by the applied normal force.

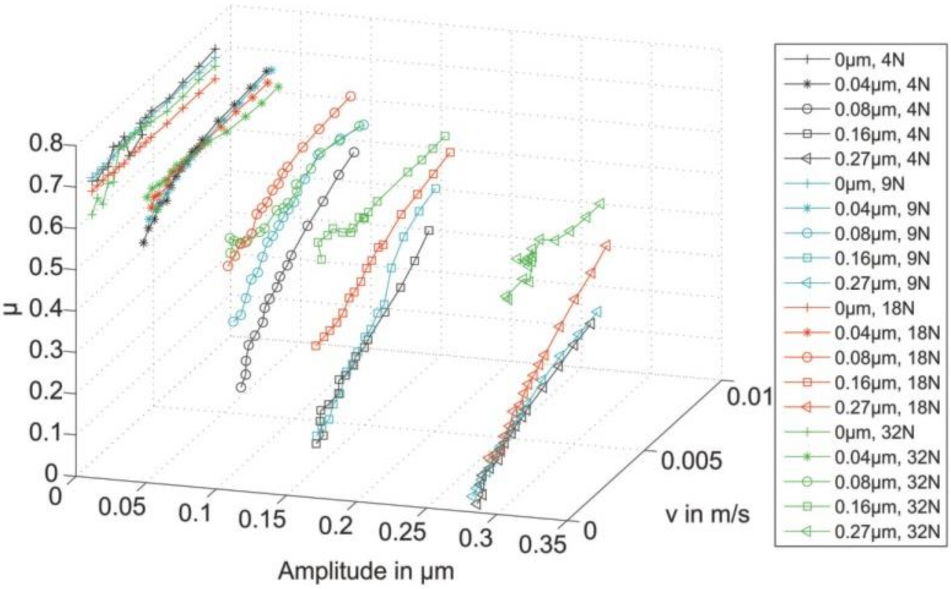

Fig. 2 The coefficient of sliding friction as a function of oscillation amplitude Δu_z and the sliding velocity for four different normal loads: $F_N = 4, 9, 18, 32$ N .

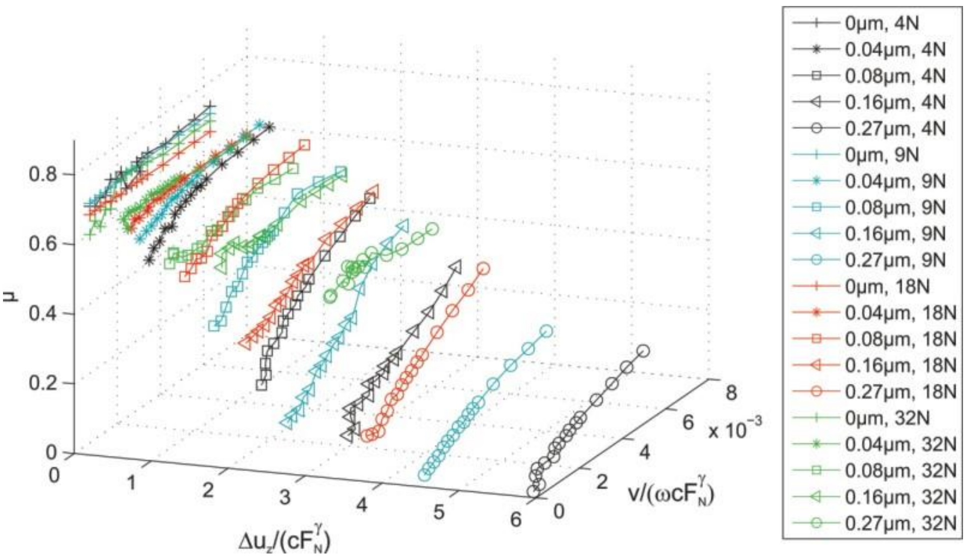

Fig. 3 The coefficient of sliding friction in the axes ($\Delta u_z / cF_N^{\gamma}$, $v / \omega cF_N^{\gamma}$).

The measurement results are shown in Fig. 2. The coefficient of friction μ is plotted as a function of oscillation amplitude Δu_z and sliding velocity v, the colors representing different normal loads. The sliding coefficient of friction can become even zero, if the sliding velocity is very small and the oscillation amplitude very high. When the oscillation amplitude is larger, the sliding friction is reduced, but with an increasing normal load this reduction effect becomes less for the same oscillation amplitudes and sliding velocities.

Now we come to prove the hypothesis (5). We have plotted experimentally measured values of μ in the axes ($\Delta u_z / cF_N^\gamma$, $v / \omega cF_N^\gamma$) with $\gamma = 1/3$, as shown in Fig. 3. It is found that in these variables, the data indeed are placed on one surface thus defining a function of the form Eq. (5) (with exception of the case of very high forces, which can be related to the above mentioned crossover).

4. Conclusions

A recent paper [17] shows that sliding friction coefficient μ in contact with oscillation will be a function of the oscillation amplitude, the sliding velocity and the indentation depth. Due to the measurement difficulty of indentation depth, we have proposed an empirical model of frictional contact so that the sliding friction coefficient will be a function of the dimensionless oscillation amplitude and the dimensionless velocity where the normal force is involved because the indentation depth is a power function of the applied normal load for a wide class of surfaces [18]. Therefore, an experimental investigation of steel-steel contact is carried out using the pin-on-disc apparatus to measure the coefficient of sliding friction for different oscillating amplitudes, sliding velocities and especially the normal forces. The results show that the effect of friction reduction decreases with the increasing normal force for the same oscillation amplitudes and sliding velocities, and our hypothesis is proved with these experiment data. Furthermore, we are looking forward to investigating the influence of contact geometry on sliding friction. Also the possibility of a temporary loss of contact which is assumed to appear at large amplitudes, lower normal forces and sliding velocities, will be analyzed in detail.

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References

1. Siegert, K., Ulmer, J., 2001, *Superimposing Ultrasonic Waves on the Dies in Tube and Wire Drawing*, Journal of Engineering Materials and Technology, 123(4), pp. 517-523.
2. Murakawa, M., 2001, *The utility of radially and ultrasonically vibrated dies in the wire drawing process*, J. Mater. Process. Technol. 113(1-3), pp. 81–86.
3. Ashida, Y., Aoyama, H., 2007, *Press forming using ultrasonic vibration*, J. Mater, Process. Technol. 187–188, pp. 118–122.
4. Siegert, K., Ulmer, J., 2001, *Influencing the friction in metal forming process by superimposing ultrasonic waves*, Annals of CIRP, 50 (1) , pp. 195–200.
5. Egashira, K.,Mizutani, K, 2002, *Ultrasonic vibration drilling of microholes in glass*, Annals of CIRP, 51 (1), pp. 339–342.

6. Littmann, W., Storck, H., Wallaschek, J., 2001, *Sliding friction in the presence of ultrasonic oscillations: superposition of longitudinal oscillations*, Arch. Appl. Mech. 71, pp. 549–554.
7. Tsai, C.C., Tseng, C.H., 2005, *The effect of friction reduction in the presence of in-plane vibrations*, Arch of Appl Mech 75, 164–176.
8. Chowdhury, M., Helali, M., 2006, *The effect of frequency of vibration and humidity on the coefficient of friction*, Tribol. Int. 39, 958–962.
9. Kumar, V.C., Hutchings, I.M., 2004, *Reduction of the sliding friction of metals by the application of longitudinal or transverse ultrasonic vibration*, Tribology International, 37(10), pp. 833-840.
10. Teidelt, E., Starcevic, J., Popov, V.L., 2012, *Influence of ultrasonic oscillation on static and sliding friction*, Tribology Letters, 48, pp 51-62.
11. Godfrey, D., 1967, *Vibration reduces metal to metal contact and causes an apparent reduction in friction*, Tribol. Trans. 10, pp 183–192.
12. Lenkiewicz, W., 1969, *The sliding friction process: effect of external vibrations*, Wear 13, pp 99–108.
13. Weishaupt, W., 1976, *Reibungsverminderung durch mechanische Schwingungen*, Technisches Messen 11, pp 345–348
14. Goto, H., Ashida, M., Terauchi, Y., 1984, *Effects of ultrasonic vibration on the wear characteristics of a carbon steel: analysis of the wear mechanism*, Wear 94, pp 13–27.
15. Thomsen, J., 1999, *Using fast vibrations to quench friction-induces oscillations*, J. Sound Vib. 228, pp 1079–1102.
16. Milahin, N., Starcevic S., 2014, *Influence of the normal force and contact geometry on the static force of friction of an oscillating sample*, Physical Mesomechanics, 17(3), pp. 228-231.
17. Popov, V.L., Psakhie, S., Popov, M., 2014, *On the Role of Scales in Elastomer Friction*, International Conference on Physical Mesomechanics of Multilevel Systems, AIP Conf. Proc. 1623, pp. 507-510.
18. Pohrt, R., Popov, V.L., 2013, *Contact stiffness of randomly rough surfaces*, Scientific Reports, 3, 3293.
19. Pohrt, R., Popov, V.L., 2013, *Contact Mechanics of Rough Spheres: Crossover from Fractal to Hertzian Behavior*, Advances in Tribology, 974178.