SCALING IN FRICTION EXPERIMENTS[1]

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Abstract

The tribological problems, which have to be taken into consideration in micromachines, micromechanisms, Micro Electro Mechanical Systems (MEMS) devices and components such as silicon micromotors, toothed gears, gas turbines etc. are discussed. In such systems appear entirely different problems as compared with tribological problems in macroscale machines. It was proved that the values of friction parameters in the devices where the contact area is some millimeters square cannot be applied to the situation when the realistic contact area is only some micro- or nanometers square as well when the geometrical dimensions are changed.

Keywords: Scaling of friction; Micro/nanoscale friction; Adhesion.

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1 INTRODUCTION

In the paper we are going to discuss problems of dry friction and the effect of scale on the results obtained in the measurement of friction. It means that we are going to analyze the friction without any third material (body) intentionally introduced between those two rubbing solids. In the technical literature the friction coefficient is treated as the measure of motion resistance and its value for a number of tribological combinations of materials is given in handbooks. Many, frequently published values of friction coefficients are proposed without precise description of the research background and the operational conditions of rubbing elements The use in the design process of these values is dissatisfying both when applied to design tribosystems embodied in large machines or miniature mechanisms . One of the authors has recognized this problem when tried to select the coefficient of adhesion between the wheel and the rail.(1) After tests it has appeared that the adhesion coefficients given in handbooks are much more higher than those observed during the investigations carried out in the laboratory with the use of real steel elements.

Very difficult problems connected with high friction are encountered in MEMS devices and magnetic recording systems. MEMS microdevices are fabricated using silicon planar technology, LIGA or other special techniques of manufacturing.(2-5) The frictional interactions between contacting surfaces in such systems result from very strong adhesive bonds what is caused by the activity of surface molecular forces. If the volume of a component decreases, the surface do the volume increases, so surface interactions dominate the frictional process. A large lateral force required to initiate relative motion between two smooth surfaces is referred to as „stiction" , which has been studied extensively in tribology of magnetic storage systems.(6) Friction/stiction (static friction), wear and surface contamination affect device performance and in some cases, can prevent devices from working.

The differences in geometry and size of the practical tribosystems needs intensive studies to find optimum models in experimental studies of friction and wear behavior of tribosystems. In every tribological test it is essential to assume the tribological model, which should form the adequate representation of realistic system. The scale of the model used in experiments and test conditions effect seriously on the applicability of the results obtained for the prediction of the tribological behavior of a realistic system.

In Europe has been carried out the research project with the objective to find methods of determination of the friction coefficient.(7) The aim was to compare the test results from different laboratories under rather limited test conditions accepted by the group of laboratories (31 various institutions and in this number the Institute of Terotechnology in Radom, Poland) participating in that international project called VAMAS (Versailles Project on Advanced Materials and Standards).The test conditions were:

-one type of tribological apparatus used in tests, materials delivered to all laboratories were of the same cast having the same structure and hardness; the friction between steel and the aluminum oxide Al_2O_3 samples was tested,

-surfaces of samples had the same roughness parameters, the ambient of every test was similar (special air conditioned rooms),

-the loads applied on samples (pressures) and sliding speed were the same ones.

It was very surprising to note that the values of the measured friction coefficient were different .These results suggest that the friction is not a simple phenomenon and the prediction of friction is a very hard task. The triboengineering is therefore difficult field of the engineering and science. It concerns also in particular the scaling problems of friction. The rules of friction are not the same for instance in the press shown in Figure 1 and the silicon micromotor depicted in Figure 2. Scaling in friction is very characteristic behavior of frictional contacts.(8-12)

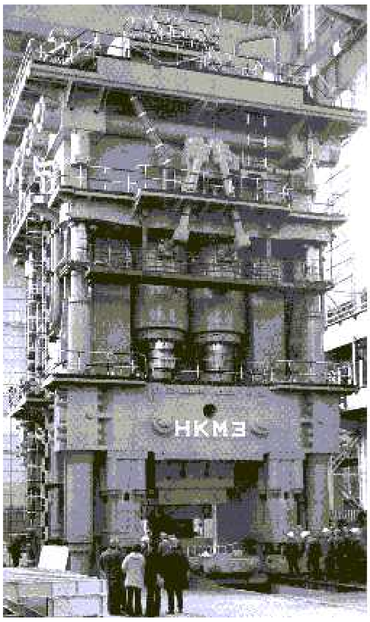

Figure 1. Press of 650 MN manufactured in former Soviet Union and mounted in France in 1978.

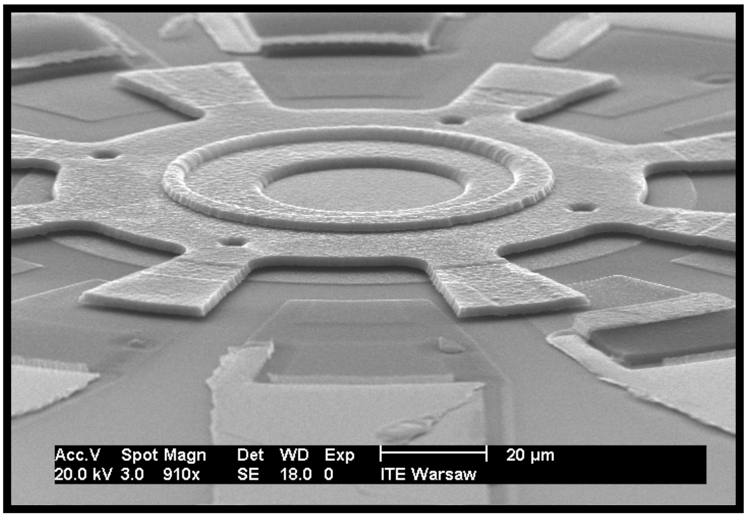

Figure 2. Silicon micromotor manufactured in Institute of Electron Technology in Warsaw (Poland).

This statement will be supported by the results obtained performing a very simple tribological experiment. The size of the rubbing/contacting surfaces (together with the magnitude of the applied load) have been decreased considerably from one test to another one and the effects of these changes on the friction coefficient was observed.

2 EXPERIMENTAL

The test rig used to carry out the friction experiments(13) is presented in Figure 3.

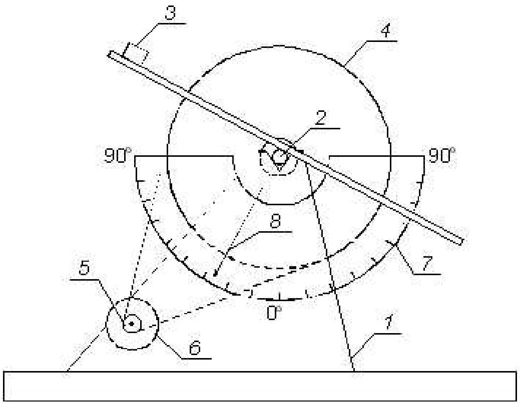

Figure 3. Test rig used in friction experiments. 1 – base, 2 – inclined plane, 3 – sample, 4, 5, 6 – two disks and string respectively, 7- protractor, indicator of the angle.(13)

The simple inclined plane to measure the static friction coefficient was very useful since the friction coefficient was estimated by the measurement of the angle of inclination of the plane to the horizontal plane. The gravity force was used to load the rubbing element.

The aluminum samples (15 µm thick foil, folded due to its large area) of the selected weight and having rather low surface roughness have been placed on the inclined polished steel plate (Figure 3). Prior to the test both the sample surface and the inclined plane have been carefully cleaned using cleaning solvents and finally by the use of petroleum spirit. The experiments have been started with the sample of gravity force 20 mN and additional weights up the total load 1.28 N. The area of contact of the foil was 4.76 x 10^4 mm^2. After each test (a few slides have been realized with one weight of the sample) the load has been decreased by half by taking out the weights and finally the foil has been cut off the folded foil. The experiments have been finished within the area of the foil 6 mm^2 and at the load 2.4 µN, so the lowest load was 500, 000 times smaller as compared with the highest load. The lowest load is similar to the loads applied in tribological tests performed with the use of Atomic Force Microscope (AFM).

The friction coefficient f was calculated as f= tan ρ (where ρ is the angle of inclination of the plane during starting to movement of the sample 3).

We studied also the effect of the size of contacting element and the size of contact on the frictional behavior. In this case we used atomic force microscope (AFM) equipped with MikroMasch cantilever NSC35 type C with force constant 4.2N/m.

The samples were polymeric resist ultrathin films with thicknesses 75,100,150, 250 and 300 nm spin-coated on silicon substrate.

3 RESULTS AND DISCUSSION

The values of the inclination angle ρ needed to start the sliding of the sample down along the steel plate as a function of the load are shown in Figure 4.

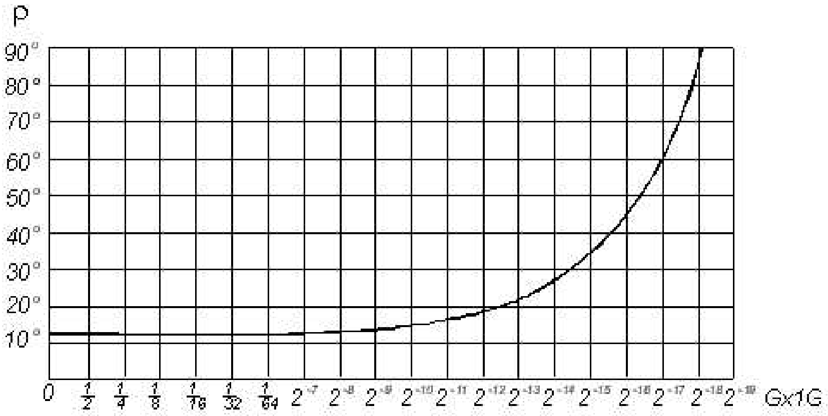

Figure 4. Inclination angle ρ vs. applied load. 1 G = 1.28 N.

The friction coefficient f calculated as f= tan ρ as a function of the applied load is presented in Figure 5.

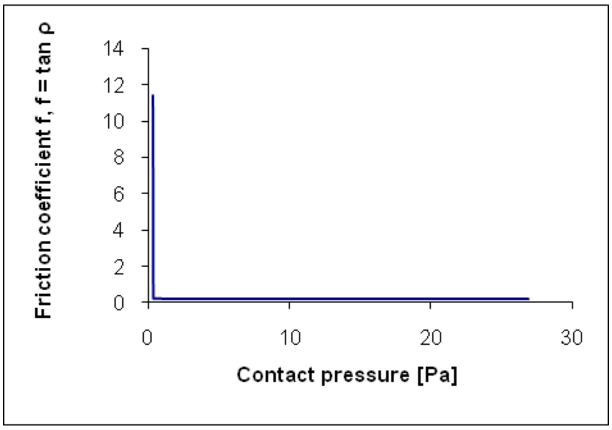

Figure 5. Friction coefficient f=tan ρ vs applied load.

It is evident from this characteristic curve that at least two quite separate contributions to the friction force between these two used smooth surfaces undergoing wearless sliding: one associated with the intrinsic adhesion between two surfaces (at low loads) and the other with the externally applied load (at high loads). The „adhesion controlled" contribution to the total friction force F is proportional to the real (molecular) contact area , A; the „load controlled" friction is proportional to the load P.(8).These dependences can be expressed as F=σ A + fP, or after dividing through by the area, A as S=F/A = σ + fp ; where σ is the critical shear stress, f the coefficient of friction, P – local load, and p the local contact pressure. The coefficient of friction f i given by the slope of the friction force vs. load cure, dF/dP, rather than the absolute value of F/P; the latter is the more traditional definition of f as defined by Amonton`s law.

The friction coefficient as a function of applied averaged pressure defined as the total load divided by the contour area of contact (are of the used foil) is depicted in Figure 6.

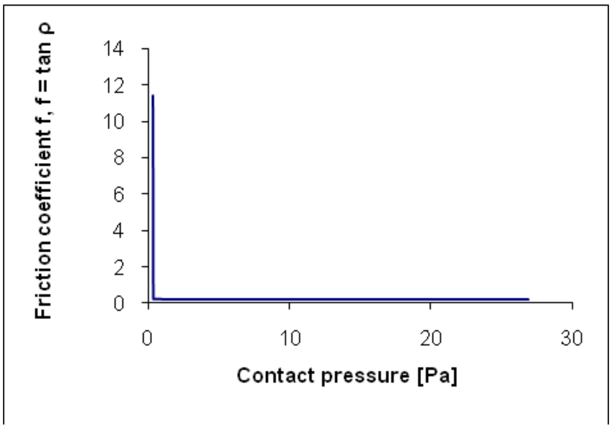

Figure 6. Friction coefficient f=tan ρ vs. averaged contact pressure (total load divided by contour area of contact (area of aluminum foil)).

Since the size of the rubbing element (aluminum foil) was decreased 10, 000 times in the experiments the surface-to-volume ratio was increased significantly, so the surface activity was stronger and stronger as the size (area) of the foil was decreasing. This is characteristic situation in contacting the microcomponents in MEMS devices. The surface-to-volume ratio k was calculated from the formula $k= A_f /V = (2a^2 + 4ah)/a^2h = (2/h) + (4/a)$; it was assumed square size of the foil, a – is the square`s side, h – thickness of the foil.

The curve surface-to–volume ratio k vs. the side of the square a is shown in Figure 7.

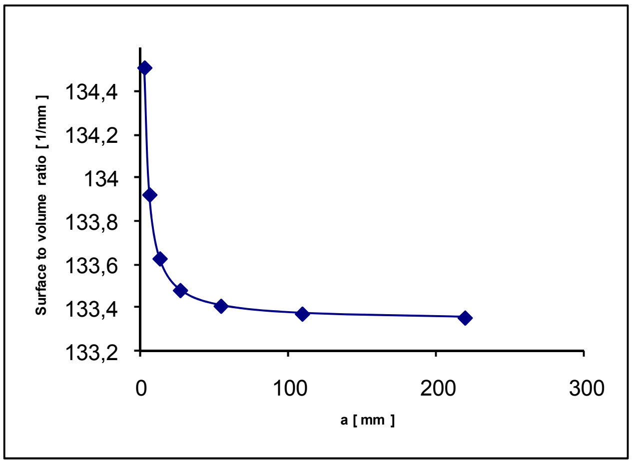

Figure 7. Surface-to-volume ratio k vs. side of square a of aluminum foil.

The friction coefficient versus the surface-to-volume ratio k is presented in Figure 8.

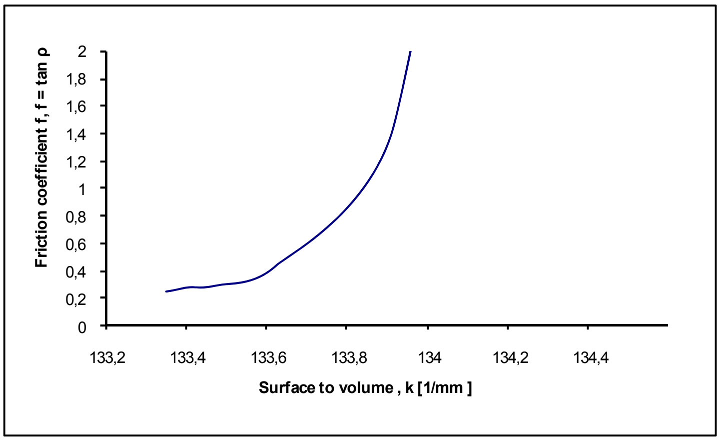

Figure 8. Friction coefficient f=tan ρ vs. surface-to-volume ratio k.

The surface activity has important effect on the observed inclination angle and friction coefficient.

In our tribosystem constructed of the flat, polished steel plate and the aluminum foil the formation of adhesive bonds can be crucial. The tendency for two surfaces to adhere is determined by surface and interfacial energies, which are influenced by the mated materials, surface contamination, oxide layers, surface roughness, etc.(14-30) .In a broad sense, adhesion can be considered to be either physical or chemical in nature. A chemical interaction involves covalent bonds, ionic or electrostatic bonds, metallic bonds, and hydrogen bonds; and physical interaction involves the van der Waals bonds. Van der Waals forces are much weaker that in the molecules that undergo chemical interaction. These forces are always present when two asperities are in close proximity. Adhesion is a function of material pair and interface conditions such as crystal structure, crystallographic orientation, solubility of one material into another, chemical activity and separation of charges, surface cleanliness, normal load, temperature, duration of contact, and separation rate.

Let us consider now a single atom strongly interacting with a rough surface displaced in a tangential direction.(21) Such atoms may need to be displaced permanently during contact sliding and such displacement of atoms can result from breakage of individual cohesive bonds or generation of defects such as dislocations and vacancies. In the simple analysis when we neglect the effects of surface oxides and contaminants a rough approximation for friction force can be obtained by dividing the energy required to break a cohesive bond by the distance slid, or the lattice spacing. The bond energy for the weaker material aluminum is 327 kJ/mol(22) which corresponds to 5.4×10^{-19} J/atom and a lattice spacing of 4.1×10^{-10} m so the friction force per atom is about 1.3×10^{-9} N.

The friction force is affected by the normal load since this force dictates the number of the atomic interactions. The prediction of the total friction force comes from the uncertainty of the number of atoms involved in the frictional interaction. The total friction force may be attempted to predict from the real area A of contact, which is typically expressed as P/H(18) (P-applied load, H – flow pressure or hardness of the softer material). For the highest applied load equal to 1.28 N and the hardness equal to about 0.3 GPa (the hardness of aluminum foil was measured on the depth about 1 μm by the nanoindentation technique by using TriboScope® instrument of Hysitron Inc.) the real area of contact is 4.3×10^{-8} m^2 which corresponds to a projected area of about 10^{10} atoms (the radius of A1 is 143 pm). At the load 20 mN (the full size of foil without additional weights) the real area of contact was estimated to be about 7 x 10^{-11} m^2. The lowest load 2.4 μN could resulted in 8 x 10^{-14} m^2 approximated value of the real area of contact. The estimated numbers of atoms corresponding to these values of the area of contact are 1.55 x 10^8 and 1.8 x 10^5 atoms, respectively.

Using the friction force per atom 1.3 x 10^{-9} N obtained previously, the total friction force comes to about 13 N for 10^{10} atoms (applied load 1.28 N). At the applied load 20 mN and 2.4 μN the estimated, by this way, values of friction force are 200 mN and 234 μN , respectively. These values of the total friction forces cause that the values of the friction coefficient are higher than the experimental values (0.21, 0.23, and about 100, respectively). Prediction of such a high friction coefficient may have resulted from overestimating the number of atoms involved and/or the critical shear stress. The number of atoms in contact may also have little to do with the frictional force observed during sliding. It is likely that atoms with the weakest cohesive energies will be displaced during sliding process. The crystal imperfections may cause that such energies may be orders of magnitude smaller than the ideal values. In similar context, the number of atoms involved in the breakage of cohesive bonds should be estimated not from the contact area but from the density of such imperfections within the volume of the interacting asperities.(19)

Very high friction coefficients obtained in the range of very low loads (and small area of aluminum foil) could be the effect of quite high liquid-mediated adhesive forces occurring because of the condensation of water from vapor on both contacting and near-contacting asperities. The foil was observed to be firmly sticked to the steel surface and no sliding occurred at the inclination angle 90 degrees.

In the case of the studies of ultrathin polymeric resist films we observed the effect of the film thickness which was connected with the different size contact at the same load effected by the different deformation in the area of contact. The results of these studies are presented in Figure 9.

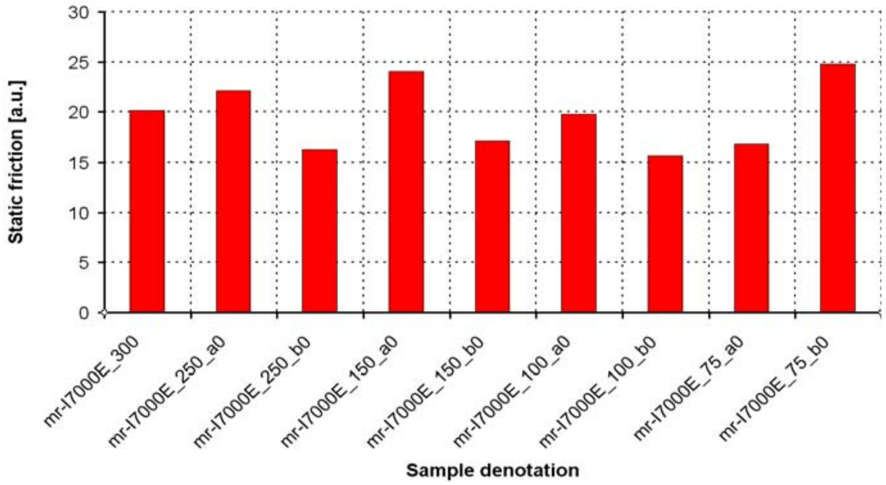

Figure 9. Static friction vs. film thickness

In this case probably the most important was the effect of deformation (mechanical) component of friction force on observed friction. The optimum thickness of the film can be found for decrease (minimization) of friction in the studied contacts.

4 CONCLUSIONS

The results of the described simple experiment performed by using an aluminum foil sliding on the flat steel surface confirm the general basic equation for wearless friction describing that at low loads the friction force F is adhesion controlled ($F=\sigma A$) (σ – critical shear stress, A – real (molecular) contact area) but it is load controlled ($F=f\ P$) (f-friction coefficient, P-applied load) at high loads. The friction force is proportional to a purely load-dependent term and a purely adhesion-dependent term, the latter being proportional to the number of bonds being sheared at the junction nw (n – number of bonds broken, w – energy per bond) which may be associated with $\Delta\gamma A$ ($\Delta\gamma$ is the thermodynamic (equilibrium) surface energy or work of adhesion W_{ad}).

At low loads strong adhesion or bonding across the interface between the aluminum foil and the flat steel surface occurred which required a finite normal force, called adhesive force, to pull the two solids apart. This effect was demonstrated by very high values of the inclination angle needed to start to slide the aluminum foil. Such effect was observed in particular when the values of the measured inclination angle were over 20˚ what corresponds to the situation of the applied loads being below 260 µN.

When the size of the rubbing elements decreases from 1 cm to 1 mm, the area decreases by a factor of million and the volume decreases by a factor of a billion. As a result, surface forces such as friction, adhesion, meniscus forces, viscous drag and surface tension that are proportional to area, become a thousand times larger than the forces proportional to the volume, such as inertial or electromagnetic forces.(28,29)

The increase in resistive forces such as friction and adhesion because of the increase of the surface-to-volume ratio was observed in our experiments. This is in particular important effect in MEMS devices which are designed for small tolerances, so the physical contact becomes more likely. The high adhesion between adjacent components leads to the appearance of a large lateral force required to initiate relative motion between two smooth surfaces referred to as „stiction", which have been studied extensively in tribology of magnetic storage systems.(6)

The effect of the thickness of the polymeric resist films in the range of thicknesses 75-300 nm was observed during studying of friction with the use of AFM equipped with silicon cantilever.

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