SCIENTIFIC PROBLEMS
OF MACHINES OPERATION
AND MAINTENANCE
3 (163) 2010

Z. RYMUZA*, S. PYTKO**

Scaling in friction experiments[1]

K e y w o r d s

Scaling of friction, micro/nanoscale friction, adhesion.

S ł o w a k l u c z o w e

Skalowanie przy tarciu, tarcie w mikro/nanoskali, adhezja.

S u m m a r y

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, and others are discussed. In such systems entirely different problems appear as compared with tribological problems in macroscale machines. The research 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.

1. Introduction

In this 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

* Department of Mechatronics (Institute of Micromechanics and Photonics), Warsaw University of Technology, Warsaw, Poland.

** Department of Machine Design and Exploitation of the Science and Technology University (AGH), Cracow, Poland.

[1] Paper presented during the First International Brazilian Conference on Tribology TriboBr, 24th to 26th,210, Rio de Janeiro, RJ, Brazil.

are going to analyse 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 a 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 recognised this problem when the author tried to select the coefficient of adhesion between a wheel and a rail [1]. After tests, it appeared that the adhesion coefficients given in handbooks are much 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 that are caused by the activity of surface molecular forces. If the volume of a component decreases, the ratio of the surface to volume increases, so that the 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 the tribology of magnetic storage systems [6]. Friction/stiction (static friction), wear, and surface contamination affect device performance and, in some cases, can prevent a device from working.

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

Research has been carried out in Europe with the objective of finding methods of the 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 as follows:

– One type of tribological apparatus were used in tests, and the materials delivered to all laboratories were of the same cast having the same structure and hardness, and the friction between steel and the aluminium oxide Al_2O_3 samples was tested.

– The surfaces of samples had the same roughness parameters, and the ambient temperature of every test was similar (special air conditioned rooms).
– The loads applied on samples (pressures) and sliding speed were the same.

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 difficult task. Tribological engineering is a difficult field of engineering and science. In particular, it also concerns the scaling problems of friction. The rules of friction are not the same in the press shown in Fig. 1 and the silicon micromotor depicted in Fig. 2. Scaling in friction is a very characteristic behaviour of frictional contacts [9–12].

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, and the effects of these changes on the friction coefficient was observed.

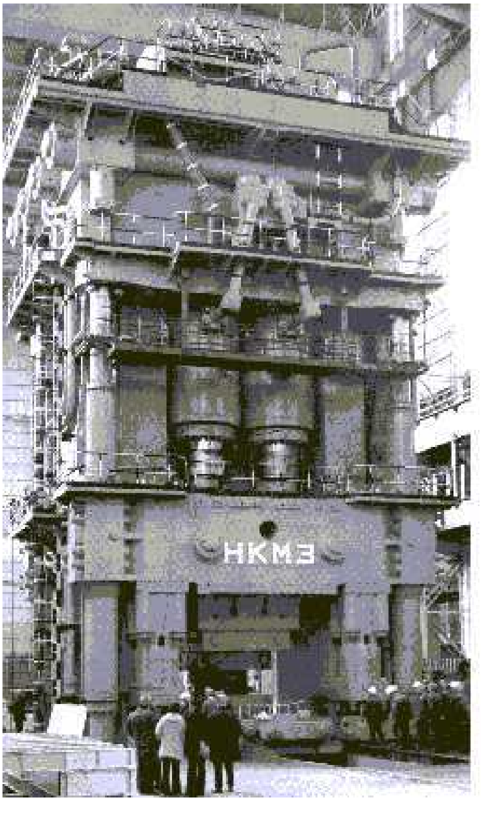

Fig. 1. Press of 650 MN manufactured in former Soviet Union and mounted in France in 1978
Rys. 1. Prasa o nacisku 650 MN wyprodukowana w dawnym ZSRR, zmontowana we Francji w 1978 roku

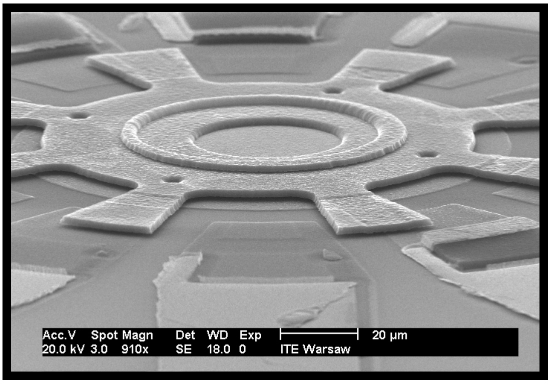

Fig. 2. Silicon micromotor manufactured in
Institute of Electron Technology in Warsaw (Poland)
Rys. 2. Silnik krzemowy wyprodukowany
w Instytucie Technologii Elektronowej w Warszawie

2. Experimental

The test rig used to carry out the friction experiments [8] is presented in Fig. 3.

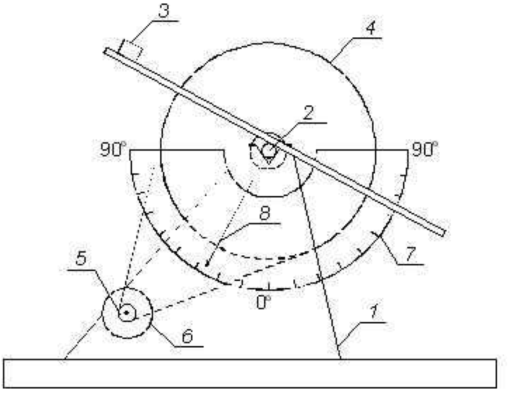

Fig. 3. Test rig used in friction experiments. 1 – base, 2 – inclined plane, 3 – sample,
4, 5, 6 – two disks and string respectively, 7 – protractor, indicator of the angle [8]
Rys. 3. Stanowisko badawcze użyte w eksperymentach tarciowych. 1 – podstawa, 2 – nachylona płyta, 3 – próbka, 4, 5, 6 – odpowiednio dwie tarcze i struna, 7 – podziałka do odczytu kąta

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 aluminium 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 (Fig. 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 spirits. The experiments have been started with a 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 were conducted with one weight of the sample), the load was decreased by half by taking out the weights and finally part of the foil was cut off the folded foil. The experiments finished within the area of the foil of 6 mm^2 and at the load of 2.4 μN; therefore, the lowest load was 500,000 times smaller than the highest load. The lowest load is similar to the loads applied in tribological tests performed with the use of an 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 of movement of the sample 3).

We also studied the effect of the size of the contacting element and the size of contact on the frictional behaviour. In this case, we used an atomic force microscope (AFM) equipped with MikroMasch cantilever NSC35 type C with a force constant 4.2 N/m. The sliding speed was 9 μm/s and the same normal load in the nN range was applied. The samples were polymeric resist ultrathin films with thicknesses of 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 Fig. 4.

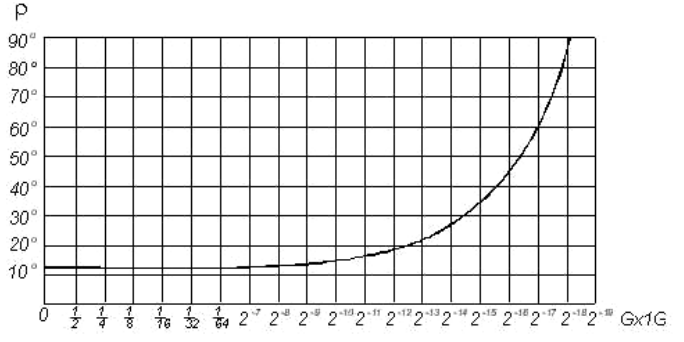

Fig. 4. Inclination angle ρ vs. applied load. 1 G = 1.28 N
Rys. 4. Kąt nachylenia ρ w funkcji obciążenia. 1 G = 1,28 N

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

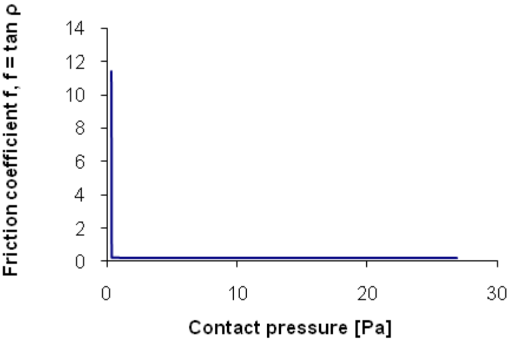

Fig. 5. Friction coefficient f = tan ρ vs applied load
Rys. 5. Współczynnik tarcia f = tg ρ w funkcji obciążenia

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, and the “load controlled” friction is proportional to the load P [9]. These dependencies can be expressed as $F = \sigma A + fP$, or after dividing by the area, A as $S = F/A = \sigma + fp$; 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 is 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 Fig. 6.

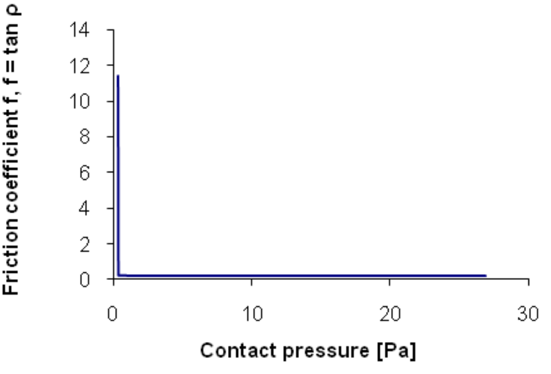

Fig. 6. Friction coefficient f = tan ρ vs. averaged contact pressure (total load divided by contour area of contact (area of aluminium foil))
Rys. 6. Współczynnik tarcia f = tg ρ w funkcji nacisku (całkowite obciążenie podzielone przez pole styku (powierzchnia folii aluminiowej))

Since the size of the rubbing element (aluminium 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 a characteristic situation in contacting the microcomponents in MEMS devices. The surface-to-volume ratio k was calculated from the formula $k = A_f / V = (2a^2 + 4ah)/a^2h = (2/h) + (4/a)$. A square size of the foil is assumed; 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 Fig. 7.

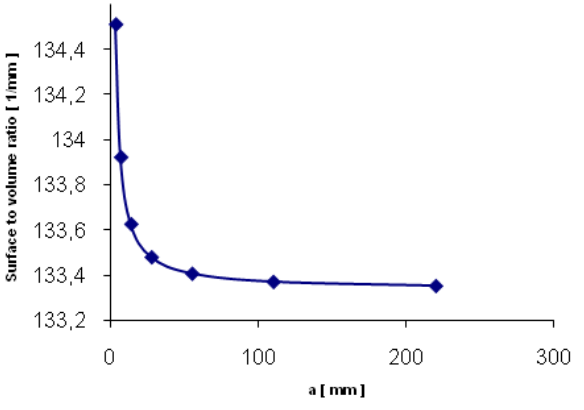

Fig. 7. Surface-to-volume ratio k vs. side of square a of aluminium foil
Rys. 7. Stosunek powierzchni do objętości k w funkcji wymiaru boku kwadratu z folii aluminiowej

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

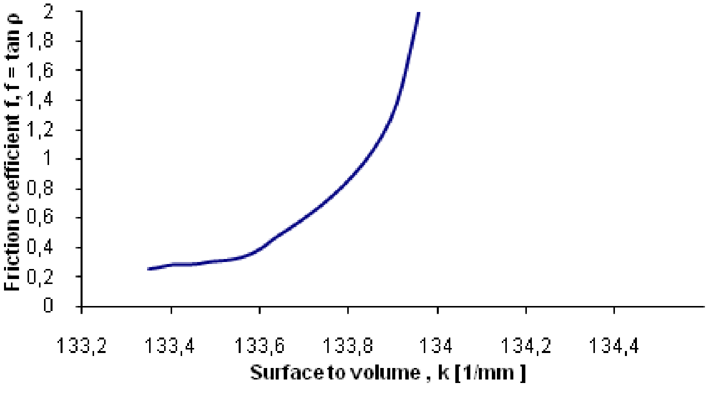

Fig. 8. Friction coefficient f = tan ρ vs. surface-to-volume ratio k
Rys. 8. Współczynnik tarcia f = tg ρ w funkcji stosunku powierzchni do objętości k

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

In our tribosystem constructed of a flat, polished steel plate and aluminium 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 than 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 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 the 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 aluminium 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. We may attempt to predict the total friction force 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 aluminium foil was measured on the depth about 1 μm by the nanoindentation technique by using a TriboScope® instrument of Hysitron Inc.), and 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 7×10^{-11} m^2. The lowest load 2.4 μN could have resulted in 8×10^{-14} m^2 approximated value of the real area of contact. The estimated number of atoms corresponding to these values of the area of contact are 1.55×10^8 and 1.8×10^5 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 values of friction force are 200 mN and 234 μN, respectively. These values of the total friction forces cause the values of the friction coefficient to be higher than the experimental values (0.21, 0.23, and about 100, respectively). The 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 the sliding process. The crystal imperfections may cause that such energies may be orders of magnitude smaller than the ideal values. In a 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 aluminium foil) could be the effect of quite high liquid-mediated adhesive forces occurring because of the condensation of water from vapour on both contacting and near-contacting asperities. The foil was observed to be firmly stuck 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 that 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 Fig. 9.

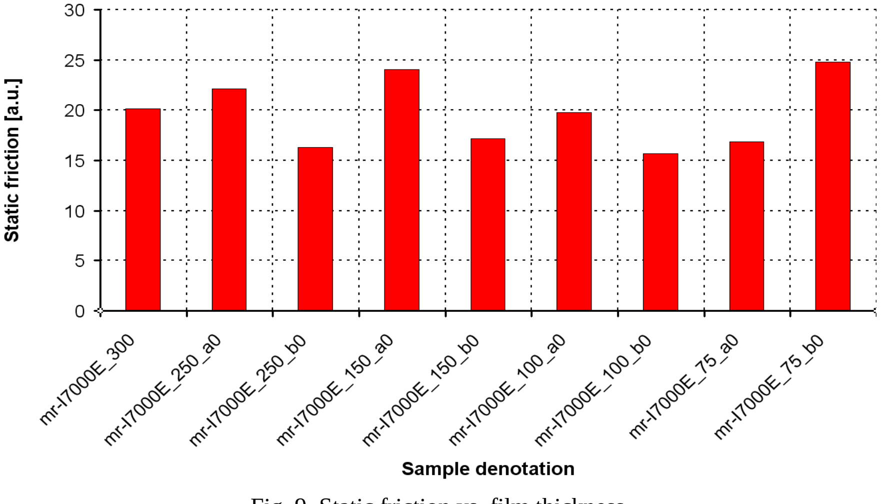

Fig. 9. Static friction vs. film thickness
Rys. 9. Współczynnik tarcia statycznego w funkcji grubości warstwy

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

4. Conclusions

The results of the described simple experiment performed by using an aluminium 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 aluminium foil and the flat steel surface occurred that 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 aluminium foil. Such an effect was observed when the values of the measured inclination angle were over 20˚, which 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 a 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 a particularly important effect in MEMS devices that 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 has been studied extensively in the 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 the study of friction with the use of an AFM equipped with a silicon cantilever.

Acknowledgement

The partial support from NaPa European 6FP Project related to study of the resist films is acknowledged.

References

[1] Pytko S., Furmanik K., Designing track and driving wheels in cranes, Przeglad Mechaniczny No.3 (1974) 89-93, in Polish.
[2] Madou M., Fundamentals of Microfabrication, 2nd ed., CRC Press, Boca Raton 2002.
[3] Gardner J., Varadan V.K., Awadelkarim O.O., Microsensors, MEMS and Smart Devices, J.Wiley, Chichester 2001.
[4] Elwenspoek M., Wiegerink R.J., Mechanical Sensors. Springer Verlag, Berlin 2001.
[5] B. Bhushan (Editor), Tribology Issues and Opportunities in MEMS, Kluwer Academic Publishers, Dordrecht 1998.
[6] Bhushan B., Tribology and Mechanics of Magnetic Storage Devices. 2nd edition, Springer Verlag, Berlin 1996.
[7] Czichos H., Becker S., Lexow J., Multilaboratory tribotesting: Results from the Versailles Advanced Materials and Standards Programme on Wear Test Methods, Wear 114 (1987) 109-130.
[8] Krajewski S., Remarks on „dry" friction, Manuscript in the possession of S. Pytko , in Polish.
[9] Israelachvili J., Tribology of ideal and non-ideal surfaces and fluids, in: B.Bhushan Editor, Fundamentals of Tribology and Bridging the Gap Between the Macro- and Micro/Nanoscales, Kluwer Academic Publishers, Dordrecht 2001, 631-650.
[10] Zum Gahr K.H., Microtribology, Interdisciplinary Science Reviews 18 (1993) 259-266.
[11] Bhushan B., Principles and Applications of Tribology, J. Wiley, Chichester 1999.
[12] Nosonovsky M., Bhushan B., Multiscale Friction Mechanisms and Hierarchical Surfaces, Springer, Berlin 2008.
[13] Popov V.L., Contact Mechanics and Friction, Springer , Berlin 2010.
[14] Mastrangelo C.H., Adhesion-related failure mechanisms in micromechanical devices, Tribology Letters 3 (1997) 223-238.
[15] Legtenberg R., Tilmans H.A.C., Elders J., Elwenspoek M., Stiction of surface micromachined structures after rinsing and drying: model of investigation of adhesion mechanisms, Sensors and Actuators A 43 (1994) 230-238.
[16] Neuman A.W., Spelt J.K. (Editors), Applied Surface Thermodynamics, Marcel Dekker, New York 1996.
[17] Zum Gahr K.H., Microstructure and Wear of Materials, Elsevier, Amsterdam 1987.
[18] Rabinowicz E., Friction and Wear of Materials, 2nd edition, J. Wiley, Chichester 1995.
[19] Bowden F.P., Tabor D., The Friction and Lubrication of Solids, Clarendon Press, Oxford 1986.
[20] Johnson K.L., Kendall K., Roberts A.D., Surface energy and the contact of elastic solids, Proceedings of the Royal Society of London A 324 (1971) 301-313.
[21] Kim D.E., Suh N.P., On microscopic mechanisms of friction and wear, Wear 149 (1991) 199-208.
[22] Kittel C., Introduction to Solid State Physics, 7th edition, J.Wiley, Chichester 1995.
[23] Bhushan B., Introduction to Tribology, J.Wiley, Chichester 2002.
[24] Bhushan B., Contact mechanics of rough surfaces in tribology: multiple asperity contact, Tribology Letters 4 (1998) 1-35.

[25] Gao C., Tian X., Bhushan B., A meniscus model for optimization of texturing and liquid lubrication of magnetic thin-film rigid disks, Tribology Transactions 38 (1995) 201-202
[26] Komvopoulos K., Surface engineering and microtribology for microelectromechanical systems, Wear 200 (1996) 305-327.
[27] Israelachvili J., Intermolecular and Surface Forces, 2nd edition, Academic Press, San Diego 1991.
[28] Sundararajan S., Bhushan B., Micro/nanoscale tribology of MEMS materials, lubricants and devices, in: B.Bhushan Editor, Fundamentals of Tribology and Bridging the Gap Between the Macro- and Micro/Nanoscales, Kluwer Academic Publishers, Dordrecht 2001, 821-850.
[29] Rymuza Z., Control tribological and mechanical properties of MEMS surfaces, Part 1: critical review, Microsystem Technologies, 5 (1999) 173-180.
[30] Tabor D., Tribology and physics, Journal of Physics: D:Applied Physics, 25 (1992) A1-A2

Manuscript received by Editorial Board, February 2nd, 2011

Problemy skali w badaniach tarcia

S t r e s z c z e n i e

Problemy tribologiczne spotykane w mikrourządzeniach, takich jak np. MEMS i w mikrosilnikach krzemowych, a także w przekładniach zębatych, turbinach gazowych, prasach itp. różnią się znacznie między sobą. Różnice te wynikają z różnych skali wymiarowych. Stwierdzono, że zidentyfikowane tarciowe opory ruchu, gdy powierzchnia kontaktu jest w skali milimetrowej, nie mogą być wykorzystywane do prognozowania takich oporów ruchu, gdy powierzchnia kontaktu jest w skali mikro- lub nanometrowej, a także wtedy, gdy wymiary elementów trących znacznie się różnią.