1. Introduction

In this paper we are going to discuss problems of dry friction which occurs between two metallic solids. It means that we 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 values frequently published 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 recognised 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 higher then 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 Micro Electro Mechanical Systems (MEMS) devices and magnetic recording systems. MEMS devices are fabricated using silicon planar technology, LIGA or other special techniques of manufacturing\(^2,3\). The frictional interactions between contacting surfaces in such systems result from very strong adhesive bonds caused by the activity of surface molecular forces. If the volume of a component decreases, the surface of the volume increases, so surface interactions dominate the frictional process. The 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\(^4\). Friction/stiction (static friction), wear and surface contamination affect device performance and in some cases can prevent devices from working.
Some special problems with friction appear in space devices when the lack of oxides on rubbing surfaces leads to very high friction. The heat transport from the rubbing area is another difficulty. The use of special coatings is one solution of such tribological problems.

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

In Europe has been carried out a research project with the objective of finding methods of determination of the friction coefficient. 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 Tero-technology in Radom, Poland, was included) 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$_2$O$_3$ 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.

It was very suprising to note that the measured friction coefficient values were different (Fig. 1).

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 a 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 Fig. 2 and in the silicon micromotor depicted in Fig. 3.

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) has been decreased considerably from one test to another and the effects of these changes in the friction coefficient were observed.

2. Experimental

The test rig used to carry out the friction experiments is presented in Fig. 4.

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 with rather low surface roughness were placed on the inclined polished
The Effect of Scale in Tribological Testing

Fig. 4 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

Fig. 5 Inclination angle ρ vs. applied load. 1 G = 1.28 N

steel plate (Fig. 4). Prior to the test both the sample surface and the inclined plane were carefully cleaned using cleaning solvents and finally by the use of petroleum spirit. The experiments started with the sample of gravity force 20 mN and additional weights up to the total load 1.28 N. The area of contact of the foil was 4.76 x 10^4 mm^2 and at the load of 2.4 μN, so the lowest load was 500,000 times smaller when 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 movement of the sample 3).

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. 5.

The friction coefficient, f, calculated as f = tan ρ as a function of the applied load, is presented in Fig. 6.

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. These dependences can be expressed as F = σ A + fp, or after dividing by the area, A, as S = F/A = σ + fp; where σ is the critical shear stress, f is the coefficient of friction, P is the local load, and p is the local pressure. The coefficient of friction, f, is given by the slope of the friction force vs. load curve, 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 (area of the used foil) is depicted in Fig. 7.

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

Fig. 6 Inclination angle ρ vs. applied load. 1 G = 1.28 N

Fig. 7 Friction coefficient f = tan ρ vs. averaged contact pressure (total load divided by contour area of contact (area of aluminium foil))
The curve surface-to-volume ratio, $k$, vs. the side of the square, $a$, is shown in Fig. 8.

The friction coefficient vs. the surface-to-volume ratio, $k$, is presented in Fig. 9.

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

The phenomena which occur between the rubbing surfaces can be analysed in different levels (Fig. 10)[10].

On the scale of a few millimeters the local pressure can be calculated from the geometrical shape and size of the contact area and compared with the bulk properties of the materials measured in conventional hardness and strength tests. The individual interfaces between the contacting bodies may be treated as micro-Hertzian contacts. Tribological behaviour is determined by the properties of a very small volume of material in the outermost surface layer alone in conjunction with environmental and loading parameters. As the volume stressed decreases, classical continuum mechanics becomes of doubtful applicability and surface properties differs substantially from the bulk properties of the material. At the nano- or atomic scale, crystal defects such as grain boundaries or dislocations, segregated atoms, surface films, and preferred crystal orientation affect friction. Interactions between the contacting surfaces through secondary (van der Waals) bonds or formation of primary bonds can play an important role. Cleanness of the surfaces on a molecular level influences adhesive strength and a monolayer of adsorbate can prevent intimate contact between the rubbing solids.

In our tribosystem, constructed of a flat, polished steel plate, and of an 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 contaminations, oxide layers, surface roughness etc.[11–13]. 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; a physical interaction involves the van der Waals bonds. Van der Waals forces are much weaker than forces that molecules undergo in 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.

An atomic model for the formation of adhesive bonds is shown in Fig. 11[10]. On static contact, vacancies are formed in the interfacial area owing to the different orientation terraces on the two surfaces (Fig. 11a). Atoms across the interface are relatively widely separated, which leads to low attractive forces between the contacting asperities. Under an applied load, some atoms may change their positions slightly (Fig. 11b). Substantial rearrangement of surface atoms, and hence greater attractive forces, are achieved by local high pressure and/or by tangential relative motion between the contacting surfaces and/or at temperatures sufficient to give greater atomic mobility by surface or volume diffusion (Fig. 11c). Depending on the contact tem-
pear and the materials involved, diffusion process (Fig. 11d) can substantially enhance the strength of the adhesive bonds.

A detailed calculation of van der Waals forces for the estimation of the adhesion of two surfaces being in contact is difficult. A simpler approach is to use the concept of free surface energy. Because the atoms at the surface have some unused energy, they can interact with each other, with other atoms from the bulk, and with species from the environment. Free surface energy influences adhesive bonds for solids in contact and, hence, friction. When the bond is formed between two materials (having free surface energy per unit area $\gamma_1$ and $\gamma_2$) in contact, the surface energy of the interface per unit area changes to $\gamma_{12}$. A simplified estimate of the tendency to adhere may be obtained therefore from a modified Dupre equation, $W_{ad} = \Delta \gamma = \gamma_1 - \gamma_2 - \gamma_{12}$.

Thus, $\Delta \gamma$ represents the energy that must be applied to separate a unit area of the interface or to create new surfaces. For two similar materials, $\Delta \gamma$ becomes the work of cohesion, equals to $2\gamma (\gamma_2 = 0)$. In our case, the work of adhesion, $W_{ad}$, assuming that the real contact is between iron oxides and aluminium oxide, can be estimated to be about 2,000 mJ/m$^2$.

Because both the surface energy and the mechanical strength of a material depend on the strength of its bonds, it would be expected that the high surface energies are associated with high strength parameters. It was found[14] that the correlation between penetration hardness, $H$, and surface free energy is indeed a close one. The good correlation between coefficient of adhesion and $W_{ad}/H$ for metal-metal pairs exists where $H$ is the hardness of the softer metal[16,17]. The better surface interaction behaviour, namely lower friction and less adhesion, is associated with lower $W_{ad}/H$.

When two adhering surfaces are moved across each other, even in the absence of a load, a finite force or energy must be exerted that goes into breaking the adhesive intermolecular bonds across the shearing interface[18]. Let $n$ be the number of bonds broken and let $w$ be the energy per bond. After the surfaces have moved a small lateral distance, $x$, these bonds may reform, fully or partially, but the energy recovered is never the same. If the fraction of energy “lost” is $\varepsilon (0 < \varepsilon < 1)$, then the kinetic friction force will be given by the following energy balance: $F_x = nw \varepsilon$ and thus, $F = nwx / x$. For the ideal surface, $nw$ can be associated with $W_{ad}$ and $\varepsilon$ can be associated with the irreversible (non-equilibrium) part of the adhesion-separation process - the “adhesion energy hysteresis”, which depends on the details of the molecular-scale rearrangements that occur during sliding[16]. Thus, it is possible to write $F = W_{ad} A / x$ and note that it suggests a contribution to the total friction force that is proportional to the “real” contact area of the junction, but strictly to the number of bonds sheared at the junction. In the general basic equation for wearless friction $F = \alpha A + f P$, the area $A$ represents the number of bonds participating in the shearing process rather than a true area. At high loads, according to Hertz and JKR theories[18], $A = P^{1/3}$, which means that the second term in the equation dominates over the first. Thus, the friction force is adhesion controlled ($F = \alpha A$) at low loads but load controlled ($F = fP$) at high loads, which was verified experimentally in the described experiment.

Let us consider now a single atom strongly interacting with a rough surface displaced in a tangential direction[19]. Such atom 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 contaminant, 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 $327 \text{ kJ/mol}$, which corresponds to $5.4 \times 10^{-19} \text{ J/atom}$ and a lattice spacing of $4.1 \times 10^{-10} \text{ m}$, so the friction force per atom is about $1.3 \times 10^{-4} \text{ N}$.

The friction force is affected by the normal load since this force dictates the number of 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 $P/H$[16] ($P$ = 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 $\mu$m by the nanoindentation technique using TriboScope® instrument of Hysitron Inc.) the real area of contact is $4.3 \times 10^5 \text{ m}^2$, 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 $7 \times 10^{-11} \text{ m}^2$. The lowest load 2.4 $\mu$N could result in $8 \times 10^{-14} \text{ m}^2$, approximated value of the real area of contact. The estimated numbers of atoms corresponding to these values of the area of contact are $1.55 \times 10^8$ and $1.8 \times 10^8$ atoms, respectively.

- Using the friction force per atom $1.3 \times 10^{-4} \text{ N}$ 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 $\mu$N the estimated values, by this method of friction force, are 200 mN and 234 $\mu$N, respectively. These values of the total friction forces cause the values of the friction coefficient be higher than the experimental values (0.21, 0.23, and about 100, respectively). Prediction of
such 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.\(^{[10]}\)

During the experiments the water could condense from vapour into cracks and pores on surfaces in particular in the form of an annular-shaped capillary condensate in the contact zone. The spontaneous condensation and formation of adhesive bridges or menisci is due to a phase separation induced by the proximity of two surfaces.\(^{[21–24]}\) The presence of the liquid films of the capillary condensates can significantly increase the adhesion between solid bodies.\(^{[23]}\) Liquid-mediated adhesive forces can be divided into two components: meniscus force due to surface tension and a rate-dependent viscous force. These forces increase for smaller gaps and smoother surfaces so that the adhesion of ultra-flat surfaces can be extremely strong. The viscous component of the adhesive force is significant for more viscous liquid (dynamic viscosity ~1 Pa s\(^{[21]}\)).

Let us assume for our case a random rough surface in contact with smooth surface without continuous liquid film on the smooth surface but with some menisci at the contact zone or near the enough high near-contacting microasperities (Fig. 12).

A wetting liquid that has a small contact angle or wet, such as water, condenses from vapour in places between and around two contacting bodies (microasperities) which results in the formation of curved (concave shaped) menisci (liquid bridges). The attractive meniscus force occurs because of the negative Laplace pressure inside the curved (concave) meniscus arises as a result of surface tension effects. The product of this pressure difference and the immersed surface area is the attractive meniscus force. In contact of two rough surfaces, meniscus force increases with an increase in relative humidity and/or liquid film thickness and decrease of surface roughness of the interface.\(^{[21–23]}\)

Let us estimate the meniscus force for contacting and noncontacting asperities according to the model shown in Fig. 13. The meniscus force can be calculated by using the meniscus force formulae presented in Fig. 13.\(^{[21–23]}\)

According to Bowden and Tabor, the meniscus force formula is applicable only for isolated meniscus, i.e., for the situation in which a droplet of liquid is introduced between surfaces in contact. The formula given by Israelachvili was derived from the Bowden and Tabor’s model by assuming that the liquid volume of meniscus remained constant as the sphere was moved with the respect to the flat plate. These two cases are therefore valid only for the case of an isolated meniscus.

The normal force on the aluminium-steel interface is the externally applied normal force plus meniscus force. Therefore, during sliding, the force \(F\) required to initiate or sustain sliding is equal to the sum of the intrinsic (true) friction force \(F_\text{f}\) and the stiction force \(F_\text{st}\), a combination of the friction force due to the meniscus effect and the viscous force.\(^{[21]}\) The viscous force \(F_v\) is the true coefficient of friction in the absence of meniscus, and smaller than the measured value of \(f = F/P\). The sum of \(P\) and \(F_m\) is the total normal load; \(F_m\) is the meniscus force in the normal direction; and \(F_v\) is the viscous force in the sliding direction. The friction force \((f, P)\) depends on the material properties and surface topography, while \(F_m\) depends on the roughness parameters as well as the type of liquid. For static calculations, as in our case, the viscous effect can be neglected; therefore, the measured static coefficient of friction, \(f_m\), including the effect of the meniscus force, is given by \(f_m = F/P = f_s (1 + (F_m/P))\).

The value of \(f_s\) is the friction due to liquid-mediated adhesion. The maximum possible value is equal to \(f_m = (4\pi R \cos \phi N_i + 2\pi R \cos \phi N_j)\), where \(N_i\) is the total number of real contacts (peaks) in the nominal contact area and \(N_j\) is the number of asperities which have only meniscus bridges with the counterface. The formulae for the meniscus force are shown in Fig. 13. It was assumed that \(D = S\). When the arealasperity density is assumed to be of 7 mm\(^2\) (100 times smaller as compared with such value

<table>
<thead>
<tr>
<th>Meniscus Geometry</th>
<th>Meniscus force (f_m) and Major Assumptions</th>
<th>Sources</th>
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<tbody>
<tr>
<td>Small (\phi), uniform (r), (S=2R\cos \phi)</td>
<td>(f_m = 4\pi R \cos \phi(1+D/S))</td>
<td>Bowden and Tabor</td>
</tr>
<tr>
<td>Small (\phi), uniform (r), constant meniscus volume</td>
<td>(f_m = 4\pi R \cos \phi)</td>
<td>Israelachvili</td>
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Fig. 13 Different meniscus geometries and formulae for calculation of the meniscus force for a single asperity in contact with liquid of surface tension \(\gamma\). In two cases shown in the schematics contact angle \(\phi\) is assumed to be the same for the liquid in contact with either surfaces (if the contact angles are different, \(\cos \phi\) should be replaced by \((\cos \phi_1 + \cos \phi_2)/2\))\(^{[21–23]}\).
for the magnetic head hard disk interface for an apparent area of 5 mm$^2$ [23]) for an apparent area of contact of 6 mm$^2$ (the minimum size of the aluminium foil), the total number of asperities is $N = 42$. For liquid properties $y = 0.073$ N/m (surface tension of water) and $\theta = 60\degree$ for water, and critical peak radii 5 $\mu$m, the total meniscus force for the contactingasperities is 100 $\mu$N. This force is much higher than the applied external load 2.4 $\mu$N. 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 of 90$\degree$.

4. Conclusions

The results of the described simple experiment performed by using an aluminium foil sliding on the flat steel surface confirms the general basic equation for wearless friction describing that at low loads the friction force $F$ is adhesion controlled ($F = \alpha A$) (where $\alpha$ = critical shear stress; $A$ = real (molecular) contact area), but it is load controlled ($F = \frac{f}{P}$) ($f$ = 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 $\delta A\gamma$ ($\gamma$ is the thermodynamic (equilibrium) surface energy or work of adhesion $W_A$).

At low loads, strong adhesion or bonding across the interface between the aluminium foil and the flat steel surface occurred. This 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 effect was observed in particular when the values of the measured inclination angle were over 20$\degree$, which corresponds to the situation of the applied loads being below 260 $\mu$N.

Adhesion occurs both in solid-solid contacts and when the two solids were interposed with liquids or tacky solids. In our case, for the thoroughly clean aluminium and steel surfaces, the adhesion could be strong. Since the detailed calculation of van der Waals forces is difficult, the concept of the surface energy (which values for aluminium and steel are about and over 1,000 mJ/m$^2$, respectively) was used to estimate the adhesion. The high surface free energies of these two contacting materials led to the formation of the strong bonds. For metal-metal pairs the coefficient of adhesion correlates well with $W_A/\gamma$ ($\gamma$ is the hardness of the softer materials) [16], so the low hardness of the aluminium foil and the high value of the work of adhesion, $W_A$, favoured the formation of the strong adhesive junctions and the high static friction observed in the investigated tribosystem.

During the experiments in the used materials with high surface free energies, the condensation of water, that wets the surface of metals, occurred at the assumption that the formation of an annular-shaped capillary condensate in the contact zone and around noncontacting asperities occurs, the liquid-mediated adhesive meniscus forces for small gaps and smooth surfaces in a humid environment can be extremely strong. In our case the estimated total meniscus attractive force could be much higher than the applied external load, which explains that even at the inclination angle of 90$\degree$ the aluminium foil did not slide but stuck firmly to the flat steel counterpart.

When the size of the rubbing elements decrease 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 [26,27]. 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 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 [5].

Most studies of real surfaces suggest that the contact between individual asperities involves contact regions that are a few micrometers in diameter, so millions of atoms are involved (as also shown by results from our rough estimation) when the surfaces are placed together and slide on one another. If it is even possible to know how individuals atom behave (by using e.g. AFM) but in terms of atoms it is necessary to recognize the relative gross nature of the frictional process [28].

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