

ФІЗИКА ТА ХІМІЯ МАСТИЛЬНИХ МАТЕРІАЛІВ

UDC 621.891:681.6-633

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Solid Lubricants and Coating for Operation in Vacuum

I. Solid Lubricants

These are materials that ensure lubrication between two surfaces rubbing with dry or boundary friction under extreme conditions. Solid lubricants may belong to neither of the rubbing parts (e.g., solid lubricants in powdered form), or they may fill the composite material or coating of one or both rubbing parts. High heat resistance, good adhesion to metals, and low rate of evaporation in vacuum qualify solid lubricants for efficient use in vacuum, optical, and electronic systems. These lubricants are gaining recognition in general engineering, instrument making, and vacuum metallurgy.

Lamellar solid lubricants pertain to anisotropic compounds in which the strength of interatomic bonds is substantially different in different directions. The theoretical principles of solid lubricants are treated in numerous works [1, 3, 7, 8, 14].

Molybdenum disulphide (α – MoS₂) is crystallized in a hexagonal system. The molybdenum atoms are situated between two layers of the sulphur atoms. The distance between the nearest molybdenum and sulphur atoms is 0.241 nm, and the shortest distance between the sulphur atoms in parallel layers is 0.3 nm.

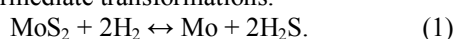
Main properties:

density, g/cm³ – 4.8;
mohs hardness – 1.0 to 1.5;
sublimation point, °C – 450;
melting point, °G – 1.185;
linear expansion coefficient within 50-700°C,
1/°C – $7 \cdot 10^{-6}$;
thermal conductivity, kcal/(cm s °C) – $4.9 \cdot 10^{-3}$;
magnetic properties – diamagnetic;
chemical stability – dissolvable in aqua regia,
oxidizes in concentrated H₂SO₄ and HNO₃.

In air, MoS₂ oxidizes to MoO₃ and S or SO₂. Such oxide films begin forming at 350°C, and rapid oxidation of MoS₂ takes place at temperatures of over 480°C. In vacuum, MoS₂ remains stable up to 1,100°C.

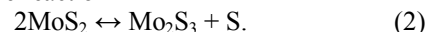
Fluorine reacts vigorously with MoS₂, chlorine turns MoS₂ into MoCl₂ on heating, whereas bromine practically does not react with MoS₂.

Hydrogen reduces solid MoS₂ directly to metal, without intermediate transformations:



Molybdenum disulphide is highly stable against radiation: when exposed to a dose of $5 \cdot 10^9$ rad, it shows no signs of damage.

A moderate heating of MoS₂ in an electric furnace in the absence of air results in Mo₂S₃ formed according to the reaction



Friction in air at surface temperatures above 400°C leads to a partial oxidation of MoS₂ to MoO₃.

Values of specific characteristics τ_0 and β for sintered bronze specimens coated with MoS₂ films of different thickness in rubbing against steel Grade ІІХ15 are given in Table 1.

Tungsten disulphide is crystallized in a hexagonal system. The crystal lattice of WS_a is similar to that of MoS₂ where the molybdenum atoms are replaced by the tungsten atoms. Tungsten disulphide has a greater thermal stability (up to 510°C in air) and resistance to oxidation than molybdenum disulphide (Table 2). Its loadcarrying capacity is 3 times that of MoS₂.

Tungsten disulphide is chemically neutral, it is insoluble in almost all media, including water, oils, alkalis and nearly all acids. The few chemicals it is sensitive to are free gaseous fluorine and hot sulphuric and hydrofluoric acids. WS₂ is a non-toxic material and it does not cause corrosion to metals.

The limitation to the use of WS₂ is its cost, which, according to some British sources, is three times the cost of MoS₂.

The use of tungsten disulphide as an additive to oils for producing colloidal suspensions is somewhat difficult because of its high density ($\rho = 7.4$ g/cm³), which is 8 times that of mineral oils. For instance, in an oil-base suspension containing 50 percent (by mass) of graphite, MoS₂ or WS₂, the volume of these components will be 36,15.5, and 11 percent, respectively.

At atmospheric pressure and temperatures of over 400°C use is recommended of WS₂, whereas at lower temperatures MoS₂ is to be preferred as a cheaper material. In vacuum, WS₂ and MoS₂ exhibit practically the same properties, and possess lubricating ability at up to 1,320°C.

In a vacuum of 10^{-10} mm Hg, molybdenum disulphide is stable at up to 1,100°C; its decomposition takes place at temperatures above 1,400°C.

Table 1

Adhesion of MoS₂ coatings, depending on their thickness

Sample No.	Coating thickness, μm	Mean contact stress, kgf/mm^2	τ_n , kgf/mm^2	f_{adh}	τ_0 , kgf/mm^2	β
1	Uncoated bronze	65	4.65	0.078	0.03	0.049
2	2-16	60	3.30	0.055		
3	14-18	56	3.06	0.054		
4	60-64	35	1.69	0.051		
5	74-85	29	1.51	0.052		
6	MoS ₂ in bulk	3.8	0.19	0.050		

Table 2

Characteristics of solid lamellar lubricants

Solid lubricant	d, nm	c, nm	c/d	Density, g/cm^3	Compressibility-modulus, kgf/cm^2	Temperature, °C			Electrical conductivity	Friction coefficient***
						oxidation in air	decomposition in vacuum	melting		
Graphite	0.246	0.675	2.74	1.4-1.7	50.500	455	-	3.652**	High	0.04
BN	0.252	0.669	2.66	2.25	22.800	800-900	-	3.000**	Low	0.67
MoS ₂	0.316	1.232	3.90	4.8	85.000	400	1.100	1.185	Semi-conductor	0.03
MoSe ₂	0.3288	1.290	3.92	6.9	-	400	-	1.200		0.02
WSe ₂	0.3290	1.297	3.94	9.22	-	350	-	1.200		0.02
WS ₂	0.3187	1.2525	3.9	7.4	-	510	1.400			-
NbSe ₂	0.3439	2.5188	7.32	6.25	-	350	-	800	High	0.06
CdJ ₂	0.426	0.686	1.61	5.7	-	-	-	388	-	-
PbJ ₂	0.455	0.689	1.51	6.16	-	-	-	412	-	-
BiJ ₃	0.750	2.065	2.75	5.7	-	-	-	408.439	-	-
Sb ₂ S ₃	0.4589	0.75	1.2	5.67	-	-	-	552	-	0.17
AgJ	0.3838	1.1223	2.92	4.64	-	-	-	550	-	0.14

* Found in pressed specimens.

** Material begins subliming.

*** Tests were conducted in nitrogen at 71°C, sliding speed 1.1 m/s, pressure 10.5 kgf/cm²; boron nitride was tested at 538°C.

II. Seif-Lubricating Materials

In accordance with the molecular-mechanical theory of friction, low friction and wear are ensured if the rule of the positive gradient of mechanical strength is observed, that is, the strength of the emerging molecular bonds must be lower than that of the underlayers: $\text{grad } \sigma_x > 0$ [7, 11, 16].

This rule is always realized when oils or greases are introduced between rubbing surfaces, because the shear strength of the lubricant is much lower than that of the metal it covers. In a pair of rubbing surfaces a positive gradient can be achieved by coating with a film (metallic or nonmetallic) and by using a self-lubricating monolithic material which in the process

of friction also ensures a positive gradient of mechanical strength, owing to its active filler or to squeezing out a lubricant (Maslyanit) [9]. Still another method is the use of a resin with a solid lubricant (Grade АФ-3ам). All these phenomena are intensified with rising friction temperature which, in turn, produces structural changes in the surface layers, selective diffusion, evaporation and, hence, a change in the coefficient of friction and wear.

Analysis of the data of Table 1 indicates that the adhesion component of the friction coefficient remains practically unchanged (variation within 10 percent) with a change in film thickness δ of from 2 to 85 μm , whereas the tangential strength of the adhesion bond changes sharply from 3.3 kgf/mm²

(with $\delta = 2$ to $6 \mu\text{m}$) to 1.51 kgf/mm^2 (with $\delta = 74$ to $85 \mu\text{m}$), that is, more than by a factor of two. The reason for this decrease is a change in the normal contact stresses.

From the production standpoint, the advantages of self-lubricating polymer materials over metals are unlimited sources of basic materials, reduced (by a factor of 2 to 5) capital investments, reduced (by a factor of 5 to 10) labour consumption in making parts without chip removal on a batch or mass production basis, and reduced (by a factor of up to 5) losses of material.

As compared with liquid lubricants, self-lubricating materials are capable of operating over a wider range of temperatures and ensure permanent lubrication during storage.

The drawbacks to self-lubricating polymer materials are the poor transfer of heat generated in friction for lack of liquid-lubricant circulation, and a friction coefficient exceeding that in hydrodynamic friction.

The main trend in developing self-lubricating polymers is towards multicomponent materials [7, 9, 11].

The content of the components in these materials is determined by the service properties, working temperatures, friction conditions, service life, load

capacity, working medium, manufacturing feasibility, and cost effectiveness of a given material.

Self-lubricating polymers feature a higher rate of evaporation in vacuum than metal-ceramics and materials with a solid-lubricant surface layer.

The evaporation of material must be taken into account when selecting self-lubricating materials for operation in a high vacuum. In some cases self-lubricating polymers having a high rate of evaporation are not fit for vacuum applications.

Metal-ceramic compositions with solid-lubricant components or coatings deposited onto the rubbing surface by various methods are more suitable for operation in vacuum.

There is a special group of heat-resistant materials in which a solid-lubrication surface layer is formed, e.g., by thermochemical treatment [10, 12]. High thermal stresses in tribological joints operating in vacuum impose limitation on wear, loads and clearances.

Metal-ceramic materials and materials with a solid-lubricant layer are preferable for high-vacuum applications.

Data on self-lubricating polymer materials for rubbing components are given in Table 3. The range of commercially available materials is much wider.

Table 3

Properties of self-lubricating materials

Properties	Unit of measurement	AФ-3ам	АМАН-2	АМАН-4	Esteran-33
Rate of linear wear in steady sliding (mean value)	-	$4 \cdot 10^{-7}$	$4 \cdot 10^{-9}$	$4 \cdot 10^{-9}$	$4 \cdot 10^{-8}$
Counterface material	-	Steel Grade 20·13	Steel Grade 20·13	Steel Grade 20·13	Steel Grade 20·13
Counterface roughness	-	Ra $\leq 0.32 \mu\text{m}$	Ra $\leq 0.32 \mu\text{m}$	-	-
Friction coefficient in steady sliding	-	0.12	≤ 0.12	≤ 0.1	0.08
Pressure	kgf/cm*	2	2	2	2
Sliding speed	m/s	2	2	2	2
Hardness of self-lubricating material, HB	kgf/mm ²	28-30	32-35	27-29	22
Hardness of counterface, HRC	kgf/mm ²	32-35		32-35	32-35
Compressive strength	kgf/cm ^a	-	1.500	900	1000
Impact strength	kgf cm/cm ^a	-	1.5	27-29	3
Linear expansion coefficient	$\alpha \cdot 10^{-5} 1/^\circ\text{C}$	-	1.2	2.0	-
Density	g/cm ³	2.1	3.7	3.2	3.2
Thermal conductivity	kcal/m h °C	0.25	-	0.516	-
Maximum permissible working temperature	°C	350	300	300	120

III. Frictional Characteristics of Solid Lubricants and Self-Lubricating Materials

When rubbing on a hard surface in air, graphite ensures good lubrication, but it is inefficient in vacuum, as shown in Table 4 [3]. The coefficient of friction for both natural and pyrolytic graphite is 2 times higher in vacuum than in air. The reason is the adhesion of graphite layers in each other.

As seen from Table 4, boron nitride, which is also lamellar in structure, in vacuum has a coefficient of friction of up to 0.70.

The lamellar structure as such is not enough to explain the difference in the lubricating efficiency of solid lubricants in air and in vacuum. One of the reasons is the presence of adsorbents coming to the sliding interface from the ambient air, and the lack of these in vacuum renders graphite and boron nitride inoperable.

The distance between the atoms in parallel layers of graphite (0.344 nm) is greater than this distance in the boron nitride lattice. For this reason, the interlayer bonds in graphite are weaker than in boron nitride. An indirect proof of this is the coefficient of friction for

graphite being lower than that for boron nitride as observed under identical test conditions. The effect of adsorbed surface films on the lubricating efficiency of lamellar structures has been extensively studied [2, 3, 8].

The relation between the coefficient of friction and temperature for tungsten molybdenum, niobium, and tantalum diselenides in air at different values of the relative humidity and in vacuum is shown in Fig. 1 [10]. The tests were run in air and in vacuum at two specific loads, 0.6 and 2 kgf/cm², at a sliding speed of 1.5 m/s. Friction was effected through the external cylindrical surface of a steel specimen (10 mm in diameter and 10 mm in length) and the end face of a cylindrical solid-lubrication insert (8 mm in diameter). The steel specimens were made of steel Grade 15X18H12C4TiO with a surface finish of from 0.63 to 0.32 $\mu m Ra$.

As seen, from Fig. 1, the frictional behaviour of the tungsten, molybdenum, niobium, and tantalum diselenides within the specified region of loads (0.2 to 12 kgf/cm²) and temperatures depends on adsorbed surface films. Fig. 2 shows the effect of temperature on the coefficient of friction for a thin molybdenum-disulphide film on molybdenum, tungsten, and copper substrates [5].

Table 4

Data on friction of graphite and boron, nitride [3]

Solid lubricants	Friction coefficient		Vacuum, mm Hg
	in air	in vacuum	
Natural graphite	0.19	0.44	$6 \cdot 10^{-9}$
Pyrolytic graphite	0.18	0.50	$2 \cdot 10^{-9}$
Hot-pressed boron nitride	0.25	0.70	$2 \cdot 10^{-9}$

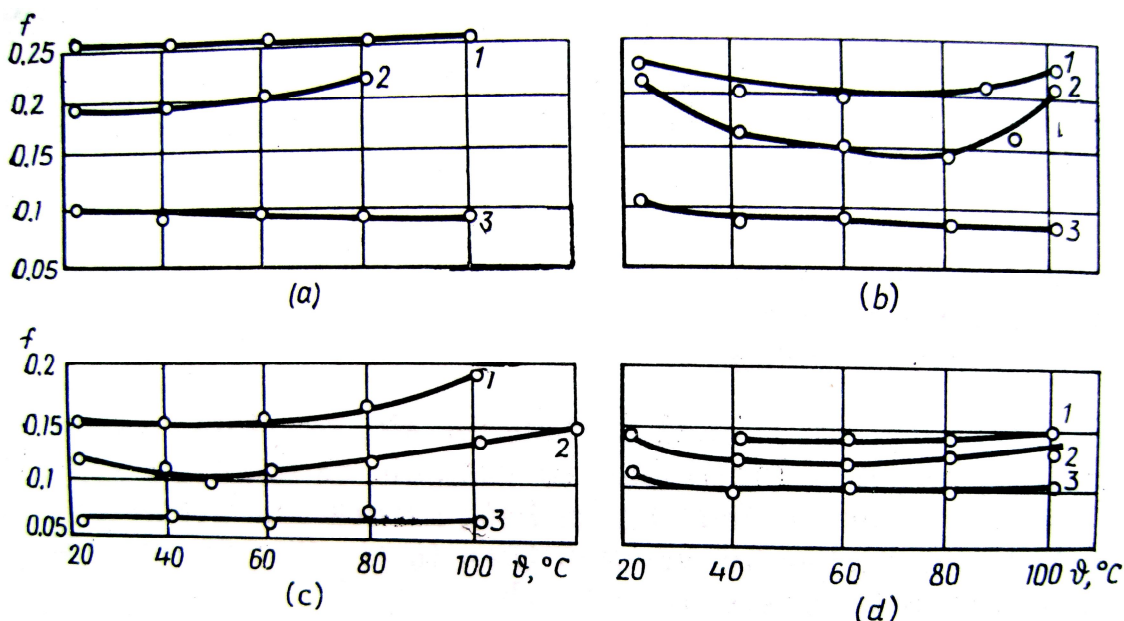


Fig. 1. Effect of temperature on friction coefficient for (a) tantalum diselenide; (b) molybdenum diselenide; (c) niobium diselenide and (d) tungsten diselenide 1 – relative humidity 100 %; 2 – relative humidity 50 %; 3 – vacuum 10^{-7} mm Hg.

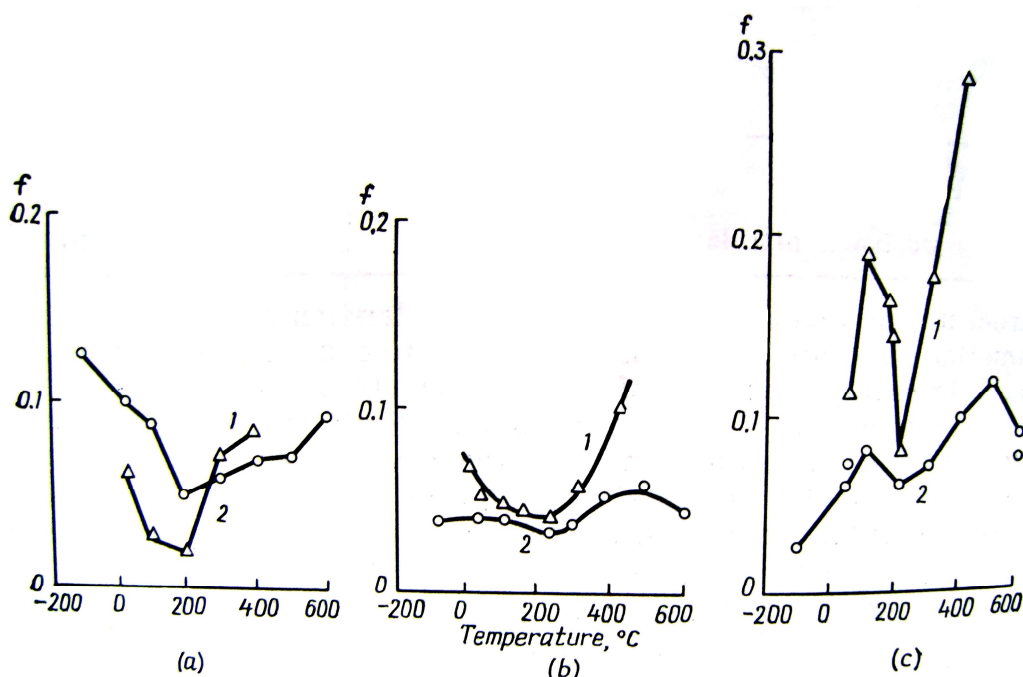


Fig. 2. Coefficient of friction of thin molybdenum disulphide film on (a) molybdenum, (b) tungsten, and (c) copper Δ – in air; \circ – in vacuum.

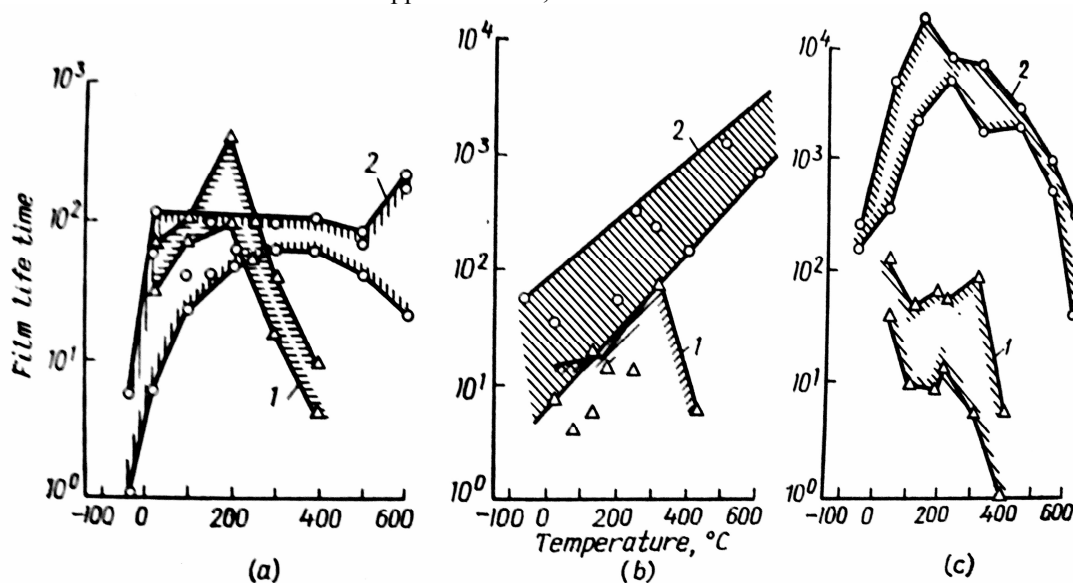


Fig. 3. Life time of thin molybdenum disulphide film on (a) molybdenum, (b) tungsten, and (c) copper at different temperatures 1 – in air; 2 – in vacuum.

These data demonstrate the influence of the substrate and, therefore, the influence of interaction between a solid lubricant and a metal. The service life of a thin molybdenum-disulphide film on molybdenum, tungsten, and copper substrates, depending on temperature in air and in vacuum, is shown (in semi-logarithmical coordinates) in Fig. 3. The substrate hardness also has an effect on the coefficient of friction, so that with greater hardness of the substrate the coefficient decreases. The distinguishing features of MoS_2 are its strong adhesion to the substrate and its exceptionally high compressive strength.

The layer of MoS_2 withstands dynamic pressures of up to 10^4 kgf/cm² and static pressures of up to $3 \cdot 10^4$

kgf/cm², which allows it to be used up to the yield point of many metals. A new class of solid lubricants with still further improved stability in vacuum and reduced rate of evaporation has more and more often been reported upon in the literature. The solid lubricants WSe_2 and MoS_2 exhibit high thermal stability in air and in vacuum and high resistance to corrosion. Relationships between the friction coefficient and temperature for MoS_2 , MoSe_2 and MoTe_2 are shown in Fig. 4 [3].

With molybdenum disulphide, the coefficient of friction remains low up to 550°C, and beyond this point it begins rising sharply. At 730° in vacuum, molybdenum disulphide begins dissociating into

molybdenum and sulphur. The rise of the friction coefficient at 550°C points to the effect of additional heating due to friction, which is typical of the testing procedure. Molybdenum diselenide is more stable against heating than molybdenum disulphide.

With self-lubricating materials in vacuum applications, the moment of friction in the movable joints rises after their prolonged stand-still. Hence, the design of low-power vacuum mechanisms involves the selection of materials with a minimum increase in the starting friction coefficient.

The AMAH-2 Grade material [7] has a stable and low coefficient of friction in vacuum, but its starting friction coefficient can be as high as 0.44. For sliding bearings, the AMAH-2 Grade material is used in combination with steel Grade 20X13 hardened to HRC 35 and finished to not worse than 0.32 μm Ra. The bearing bush is finished to 1.25 to 2.5 μm Ra.

The M-801 Grade material is a solid-lubricant diffusion coating of MoS₂ 35 to 40 μm thick on a molybdenum substrate, obtained by thermochemical treatment [12].

The high thermal stability in vacuum and nearly equal thermal expansion coefficients of the materials of rubbing parts and the coating (e.g., the Mo-MoS₂-Mo system) present interesting possibilities for many vacuum applications. In addition to these advantages, the Mo-MoS₂-Me (or Mo-MoSe₂-Mo) system have a low rate of evaporation in vacuum and a small difference between the starting and sliding friction coefficients (see Table 5).

Figure 5 illustrates the change of friction coefficients with temperature for sulphides and selenides, as these were heated up to 600°C. Powders of these lubricants were rubbed onto the surface of a specimen obtained from a powdered iron, Grade ПДК1М1, by pressing and sintering in a hydrogen medium. The layer of the lubricants, was 80 to 100 μm thick, the counterface was copper Grade М1, the pressure, 10 kgf/cm², sliding speed, 0.004 m/s, and vacuum, 10⁻⁵ mm Hg.

The lubricating action is interpreted with respect to the atomic structure of the tested substances [13].

IV. Solid-Lubricant Coatings with Polymer Binders

Solid-lubricant coatings commercially produced for use in air and in vacuum are given in Table 6.

The physico-mechanical properties of solid-lubricant films are largely determined by their structure which can be modified for best results by various methods, namely, by changing the binder, by introducing fillers, by heat treatment, by changing the orientation, etc. In all the materials of Table 6 the filler is molybdenum disulphide Grade MBH (TsMTU 06-1-68) with a grain size of 1 to 7 μm . The optimal ratio between the binder and the filler varies with different materials. The substrate material is steel (Grades 20X13, 45), cast iron (Grade ВПЧ), etc. The optimal underlayer finish is 1.6 to 3.2 μm Rz, with the film thickness being 20 to 30 μm . The properties of a number of solid-lubricant coatings are described in [15]. The kind of binder has a significant bearing on the thermal stability of solid-lubricant films.

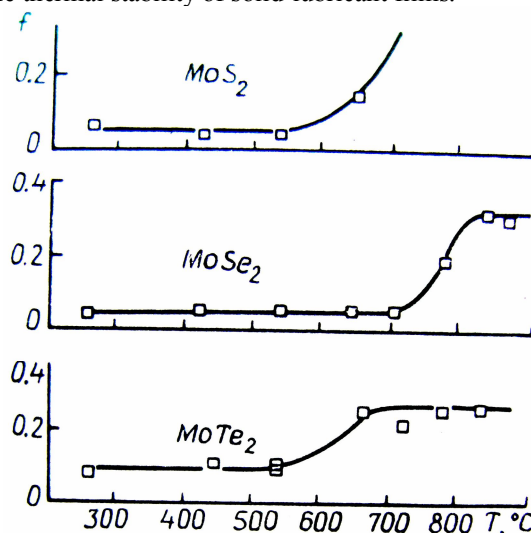


Fig. 4. Coefficient of friction as a function of temperature for thin films of MoS₂, MoSe₂, and MoTe₂ in vacuum of 10⁻⁸ to 10⁻⁶ mm Hg at a sliding speed of 2.0 cm/s a load of 100 gf.

Frictional characteristic of materials with solid lubricant films

Table 5

Material	Friction conditions	760 mm Hg, 20°C		(2 to 3)·10 ⁶ mm Hg		Source (Reference No.)
		f_{st}	f_{kin}	f_{st}	f_{kin}	
AMAH-2	$P = 2 \text{ kgf/cm}^2$ $v = 4 \text{ m/s}$	0.44	0.18	0.1	0.1	[7]
M-801 (Mo-MoS ₂ -Mo)	$P = 78 \text{ kgf/cm}^2*$ $v = 0.265 \text{ m/s}$	0.4-0.5	0.1	0.15	0.05	[12]
Mo-MoSe ₂ -Me	$P = 0.3-3 \text{ kgf/cm}^2*$ $v = 0.02 \text{ m/s}$	0.13	0.12	0.1	0.1	[10]

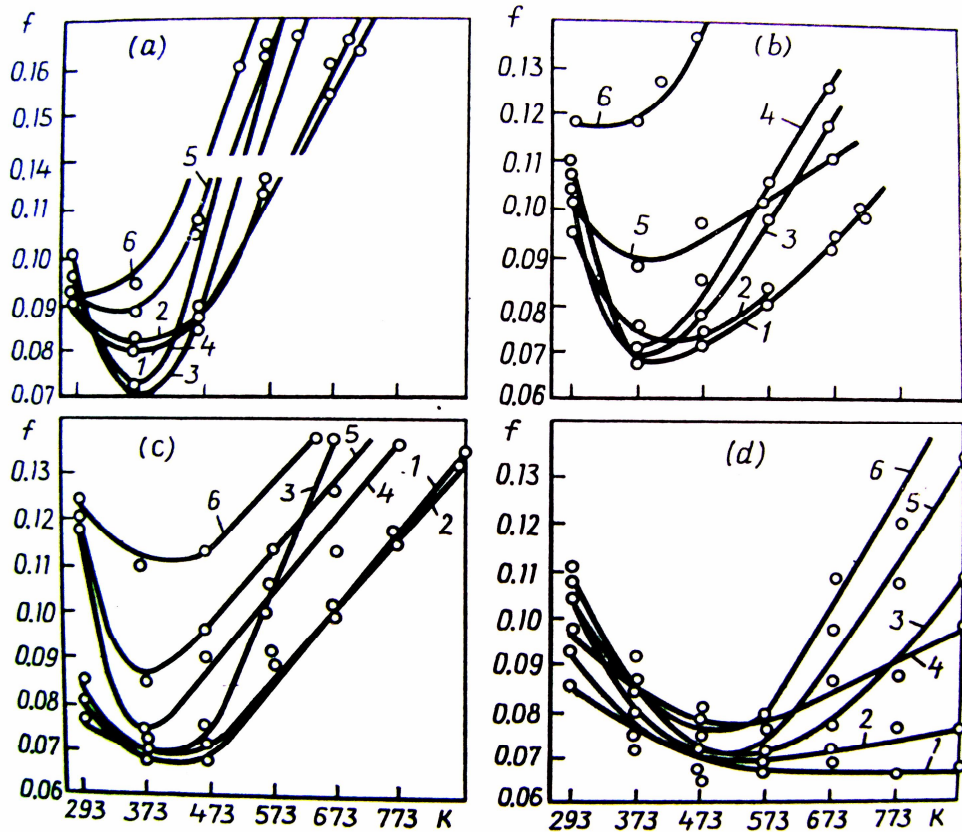


Fig. 5. Coefficient of friction as a function of temperature in friction of sulphides and selenides of high-temperature metals in (a) air, (b) nitrogen, (c) argon, and (d) vacuum 1 – native MoS_2 ; 2 – MoS_2 ; 3 – WS_2 ; 4 – MoSe_2 ; 5 – WSe_2 ; 6 – NbSe_2 .

The lubricity of MoS_2 -base films at high temperatures depends, among other things, on the extent of their oxidation. The following binders are generally used: inorganic (sodium silicate, ceramics, compounds of aluminium, lead, etc.), organic (based on epoxy, phenolformaldehyde, butyral, polyurethane and other resins), and organosilicon. The maximum thermal stability (up to 800°C) is provided by inorganic binders; organosilicon binders are stable against heat in air (up to 300°C), but their stability in vacuum is limited to 150°C . Organic binders operate within the temperature range from -100 to $+400^\circ\text{C}$; within this large class a binder with the required thermal properties can always be selected. The most favourable operating conditions for organic binders are those under which the binder undergoes transition into a highly elastic state.

Antifriction fillers can be represented by materials containing oxygen, chlorine, sulphates, phosphates, fluorine, sulphur, selenium, etc. The most efficient fillers are disulphides, diselenides, and chlorides, which provide high wear resistance, low friction coefficients, and stability in air and in vacuum. The wear life of solid-lubricant coatings is influenced by the nature of the binder and its resistance to tribocracking in vacuum, and by the presence of moisture in the material [16].

V. Soft Metal Coatings

These are used for lubricating purposes in precision tribological joints of optico-mechanical instruments and in sliding electric contacts operating in vacuum. A low evaporation rate and the possibility of providing high-accuracy fits allow these coatings to be employed in high vacuum within a wide range of working temperatures. Coatings of this type, functioning as solid lubricants, have also found application in movable joints operating within a wide temperature range at high specific loads.

Such coatings are disadvantageous in that they cannot regenerate as they wear unless special measures are taken, have high coefficients of friction, and are less efficient in the transfer of heat from the sliding interface than fluid lubricants. The frictional characteristics of rubbing surfaces with thin metal coatings are rather difficult to evaluate, because they depend substantially on the type of deformation in the contact [4, 6].

In friction of soft metal coatings in vacuum the following phenomena can be found on the specimens: plastic flow and tearing in depth. The first is characterized by stable friction (the coefficient of friction during testing did not vary in excess of 5 to 10 percent about its mean value) and by small surface roughness.

Table 6

Solid lubricant coatings with polymer binders (after L.N. Sentyurichina)

Coating	Standard	Binder material	In atmospheric conditions				In high vacuum				
			life, min	mean deviation, %	f	sliding distance, km	life, min	mean deviation, %	vacuum, mm Hg	f	sliding distance, km
ВНИИ НП-209	TU 38 10186-75	Organosilicon resin $k=1$	110	± 9	0.04- 0.09	5.8	15	± 6	$5 \cdot 10^{-9}$ - 10^{-7}	0.05- 0.08	0.78
ВНИИ НП-213	TU 38 10187-75	Organosilicon resin $k=0.5$	290	± 7	0.05- 0.09	15.2	50	± 10	$2 \cdot 10^{-8}$ - 10^{-7}	0.04- 0.08	2.6
ВНИИ НП-212	TU 38101594-75	Urea-formaldehyderesin $k=0.5$	380	± 10	0.06- 0.12	20	400	± 9	10^{-8} - $5 \cdot 10^{-8}$	0.02- 0.06	21
ВНИИ НП-229	OСТ 38 128-73	Sodium silicate $k = 0.5$	230	± 15	0.05- 0.12	12	350	± 12	10^{-8} - $8 \cdot 10^{-8}$	0.02- 0.05	18.5
ВНИИ НП-230	TU 38 101558-75	Epoxy resin $k = 0.5$	300	± 12	0.05- 0.12	15.7	270	± 15	$2 \cdot 10^{-8}$ - $8 \cdot 10^{-8}$	0.02- 0.06	14

Note, k – ratio between the amounts of MoS_2 and binder.

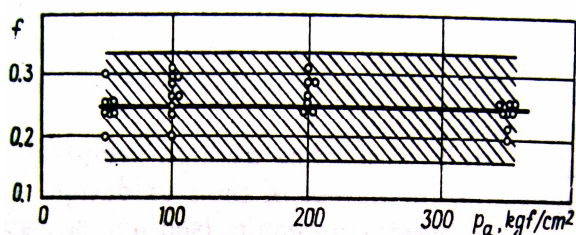


Fig. 6. Effect of pressure on the friction coefficient of gold-plated B-95 alloys specimens.

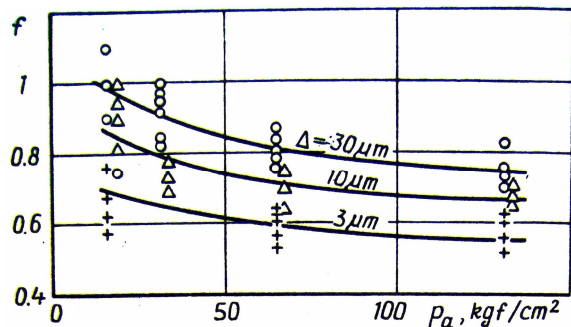


Fig. 7. Effect of pressure on the friction coefficient for a specimen of steel Grade 20X13 with a gold coating 3, 10 and 30 μm thick rubbing against a counterface of steel Grade 20X13 in vacuum.

For instance, the rubbing surfaces of tin and lead films on an underlayer of steel Grade 20X13 were found to have a surface roughness of 0.32 to 0.63 μm Ra and that of silver film, 0.08 to 0.16 μm Ra. No transfer of film particles onto the counterface was observed by visual inspection.

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transfer of film particles onto the counterface was observed by visual inspection.

Phenomena of the second type are accompanied with a significant variation in the coefficient of friction; the rubbing surface of the film becomes rough, with traces of pulls of film particles from it and smears on the counterface. Here, the surface roughness substantially depends on both the load and the film thickness.

Shown in Fig. 6 is the coefficient of friction as a function of the load on a specimen of steel Grade 20X13 with a gold coating 1 to 10 μm thick which rubbed against a counterface made of alloy Grade B95 in the plastic compression regime. The microhardness of the gold plating was 80 kgf/mm^2 . Within the range of pressures from 3 to 350 kgf/cm^2 , the coefficient of friction was found to depend neither on the coat thickness, which varied from 3 to 30 μm , nor on the load. The relationship obtained is typical of all the observed cases of friction in the plastic-flow conditions (with the coat thickness being $\geq 1 \mu\text{m}$), and it is characterized by the lack of any marked dependence of the friction coefficient on the coat thickness and load.

When tearing in depth takes place, the coefficient of friction substantially depends on the coat thickness and load. As the first is reduced and the second increased, the coefficient of friction decreases. Figure 7 shows how the friction coefficient depends on the specific load in friction of a specimen of steel Grade 20X13 with a gold coating 3, 10 and 30 μm thick against a counterface of the same steel. When the thickness of the coat is lowered under the point of transition from tearing in depth to plastic flow, the coefficient of friction levels off and no longer depends on the coat thickness and load.

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Стаття підготовлена до друку аспірантом Сулимою І.В. за виданням «Troyanovskaya G. I. Solid lubricants and coating for operation in vacuum // Friction, Wear, Lubrication / Edited by Prof. I. V. Kragelsky D.Sc (Eng.), V. V. Alisin Cand. Sc (Eng.) / Translated from the Russian by Felix Palkin and Valerian Palkin. – Moscow, Mir Publishers, 1981. – Vol. 1. – P. 352-367.