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By

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MOLYBDENUM DISULFIDE, ITS PROPERTIES AND APPLICATION

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Annotation

The booklet presents data on the effect of purity and powder particle size, material, and quality of machining of mating surfaces, functional conditions for friction points (temperature and ambient composition, slip rate, pressure, and so on) on properties of molybdenum disulfide as a lubricant.

Methods of introducing the lubricant into the friction zone are described and its application areas are pointed out. A list of references, numbering 270 entries of Russian and foreign authorities, is appended.

The work is intended for engineering-technical personnel, scientific staff members, and students at technical institutions of higher learning.

Chief Editor
Academician of the Ukrainian SSR Academy of Sciences
I. M. FEDORCHENKO

Introduction

Molybdenum disulfide, MoS_2, is classed among materials capable of separating rubbing surfaces by forming a film. This cuts wear and prevents seizure and sticking of rubbing surface materials.

Under ordinary conditions, a fluid lubricant performs this role, but under certain conditions, for example, at elevated temperatures and in vacuum, it loses its lubricating ability. Also, in several cases use of a fluid lubricant is impossible, so molybdenum sulfide must be used in dry powder form. It is applied on the friction surface by rubbing. It is also used as pastes and films deposited on surfaces, as a powdered additive to circulation lubricant and in conjunction with plastics and metalloceramic alloys /1-270/.

Effectiveness in using molybdenum disulfide depends on a number of factors, in particular, on purity, grain size, method of film deposition, its thickness, friction conditions, and so on.

These ways of using molybdenum disulfide do not always give stable and unambiguous results. Therefore, detailed study of its properties and critical evaluation of the expediency of using MoS_2, as a lubricant are extremely important, all the more so in that MoS_2 is in quite short supply and expensive.

The aim of this study is to sum up existing literature data, their critical interpretation, and where possible correction of prevailing contradictions. An extensive list of references on this problem is appended.

Physicochemical Properties of Molybdenum Disulfide

Preparation of Molybdenum Disulfide

Molybdenum disulfide (molybdenite) is a dark, glistening mineral, similar in external appearance and structure to graphite. The amount of MoS_2 in ore is only 0.5 percent /118/. In extracting it from ore, the latter is pulverized, crushed, and subjected to flotation to further treatment.

To use MoS_2 as a lubricant, it must be carefully purified from abrasive particles (especially silicon) and moisture. Therefore, molybdenum concentrates containing 12-15 percent impurities (including 5-7 percent silica) are purified in several stages. In the first stage, a product containing 97 percent MoS_2 is obtained, and in the next stage very pure MoS_2 is obtained, used for special suspensions /210/. Undergoing this purification, molybdenum disulfite becomes very expansive.

Molybdenum disulfide is prepared most advantageously by synthesis. Data of several studies /8, 128, 146/ reveal that synthetic MoS_2 is not inferior in properties to the natural compound, and, additionally, its cost is roughly half as much.

Several ways of preparing synthetic MoS_2 are described in studies /8-9/.

Reaction of MoO_3 with sulfur in its melt:

$$MoO_3 + Na_2CO_3 = Na_2MoO_4 + CO_2,$$
$$Na_2MoO_4 + 3S = MoS_2 + Na_2SO_4.$$

Optimal charge composition for this reaction is: 33.5 percent MoO_3; 40.7 percent Na_2CO_3; 25.8 percent S. The mixture is heated in a porcelain crucible covered with a lid, at 973° K for 1 hour. The sintered mass is leached several times with water heated to 333-343°K to remove alkali, sodium sulfate, and sodium molybdate not consumed in the reaction. After filtration, the product is dried at 363°K in a vacuum drying oven. The resulting disulfide contains 59.65 percent Mo and 39.95 percent S (theoretical composition: 60 percent Mo and 40 percent S).

Reaction of calcium molybdate with sulfur in soda melt:

$$CaMoO_4 + 3S \rightarrow MoS_2 + CaSO_4.$$

A mixture with a $CaMoO_4:Na_2CO_3:S$ = 37.8:33.1:29.1 ratio is heated in a porcelain crucible at 973°K for 1 hour. The resulting product is treated with water, and then with a 5 percent solution of hydrochloric acid and again with water. Molybdenum disulfide contains 59.1 percent Mo and 40.3 percent S.

Reaction of molybdenum pentachloride with hydrogen sulfide: components are synthesized in a quartz tube through which a gas mixture of argon, hydrogen sulfide, and molybdenum pentachloride vapor is swept. At temperatures of 973-1073°K, in the tube some of the molybdenum pentachloride reacts with hydrogen sulfide, forming molybdenum disulfide, which settles on tube walls. The product contains much elemental sulfur, which is removed by treating the powder with sodium sulfite solution. This molybdenum disulfide contains 58.3 percent Mo and 40.1 percent S.

Reaction of molybdenum trioxide with sulfur vapor:

$$2MoO_3 + 3\frac{1}{2}S_2 \rightarrow 2MoS_2 + 3SO_2.$$

The reaction proceeds at appreciable velocity at temperatures somewhat higher than 573°K. Components are synthesized in a vertical stainless steel tube with a porous partition on which a layer of powdered molybdenum trioxide is placed. Sulfur emanates from a vaporizer through the porous partition. The upper part of the tube is filled with argon through an outlet in the tube cover. The reaction occurs at 973°K. The resulting product has the following composition: 59.9 percent Mo and 40.1 percent S.

Reaction of molybdenum with sulfur vapor. Here the method of preparing molybdenum sidulfide in distinction to the preceding one involves placing not molybdenum trioxide, but pure molybdenum on the porous partition. The resulting product has 58.0 percent Mo and 39.1 percent S.

Reaction of ammonium molybdate with calcium carbonate and sulfur. Ammonium molybdate is calcined at 773-873°K for 4-5 hours in an electric furnace. Layer by layer, sulfur, molybdic anhydride, and potash is heaped into a quartz crucible, the mixture is fused for 1 hour at 1073-1173°K, and then the melt is poured out, precipitated, and dried in vacuum at 353°K. Then the product is treated with a 20 percent solution of hydrofluoric acid and dried once again at 373°K. In the course of preparation, molybdic anhydride and molybdenum sulfide are formed.

Physicochemical Properties of Molybdenum Disulfide

Physicochemical properties of MoS_2 are described in numerous studies /50, 59, 85, 88, 89, 100, 104, 118, 147, 148, 159, 187, 190, 217, 224-226, 239, 240, and others/. The density of natural molybdenum disulfide is

4.5 g/cm^3, and 4.16 g/cm^3 for synthetic MoS_2 /118, 210/. Thus, MoS_2 is twice as dense as graphite, but somewhat softer than it. The hardness of MoS_2 is 1.1-1.5 Mohs units /17, 210, 216, 219/. MoS_2 density rises to 4.99 g/cm^3 as temperature is raised to 623-673°K, due to the transformation of MoS_2 into the amorphous state /32/. MoS_2 melts at a temperature of 1458°K /255/; it crystallizes in a laminar type hexagonal lattice /8, 103, 104/ (Fig. 1). In the elementary cell six sulfur atoms surround molybdenum at the apices of a regular trigonal prism. In natural molybdenum disulfide the bond between the S-Mo-S layers is weakened, while within the layer molybdenum and sulfur atoms are firmly bound (Fig. 2). Lattice parameters of natural molybdenum disulfide are: a = 3.26 AU and c = 12.30 AU /9/.

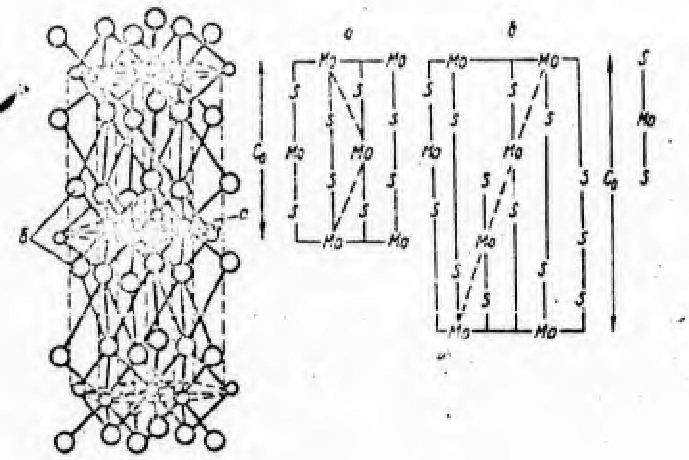

Fig. 1. Structure of molybdenum disulfide

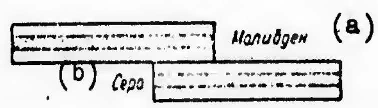

Fig. 2. Layers of sulfur and molybdenum in molybdenum disulfide

Key:
a -- Molybdenum b -- Sulfur

According to /87/, synthetic MoS_2 has a crystal lattice differing somewhat from the lattice of natural MoS_2 or molybdenite. It has a tetragonal lattice with a rhomic elementary cell and parameters as follows: a, equal to the corresponding parameter of natural molybdenite, and c = 1.5 times the natural molybdenite parameter.

Molybdenum disulfide is nonmagnetic, electroconductive /118, 233, 254/, and is resistant to nuclear radiation /226/. Below are listed its electroresistance values as a function of temperature /238/:

Temperature, ^{o}K	248	292.4	346.0	363.6
Electroresistance, ohms,	8.330	0.790	0.470	0.409

Molybdenum disulfide, MoS_2, is water resistant, stable and inert to oils, acids, and metal surfaces /168/, soluble in concentrated nitric and hydrochloric acids and aqua regia, and also in KCN solution. It reacts with fluorine and chlorine with mild heating. It does not react with bromine and sulfur vapor. MoS_2 combines with oxygen at room temperature, however MoS_2 is not oxidized in air /233/. Properties of MoS_2 remain unchanged at temperatures of 273-673°K /32, 104, 235, 238/. Oxidation of MoS_2 sets in at temperatures higher than 673°K and progresses thusly: at 673-700°K a thin oxide film forms on the surface; at 700-750°K -- slow, but appreciable oxidation; at 750-755° -- obvious oxide formation; at 775°K -- rapid oxidation; and at 838°K -- complete oxidation /235/. At 865°K, MoS_2 oxidizes totally to MoO_3.

Molybdenum trioxide does not exhibit lubricating properties and is an abrasive, while the sulfide compounds liberated reacts with the surface of the contact metal, corroding it. In several cases corrosion is observed even when MoS_2 is present in the lubricant /235, 263/.

A most valuable property of MoS_2 is its use in vacuum and at low temperatures. Literature references list different data on the allowable temperature regime for MoS_2 use as a lubricant in vacuum, due to dissociation of molybdenum disulfide. Thus, according to /233/, this temperature is 1043-1373°K, in the report /139/ -- 1613°K, and in the report /34/ -- 1673-1879°K. Dissociation occurs in two stages according to the following reactions /34/:

$$4MoS_2 \rightarrow 2Mo_2S_3 + S_2\uparrow \text{ (gas)}$$

$$4MoS_2 \rightarrow 4Mo + 4S_2\uparrow \text{ (gas)}$$

In argon atmosphere the MoS_2 dissociation temperature is 1603-1813°K, while in hydrogen and hydrogen-containing media dissociation commences from 873°K and is culminated at 1073-1373°K /86, 172/(Table 1).

The rate of MoS_2 dissociation depends on powder particle size, which in turn determines working temperature and MoS_2 use as a lubricant. Thus, for powder size from 1 to 40 microns (mean particle size is 10 microns), the temperature adopted can be in the 358-723°K range /59, 84, 109, 267/, 203-973°K /168/, and 233-523°K /44, 94/.

TABLE 1

Dissociation of MoS_2 in Hydrogen-Containing Mixture as Function of Temperature /86/

T°, K	(A) Водород		(D) $H_2:N_2$, об. %			
			20:80		12:88	
	(B) Расчет	(C) Эксперимент	(B) Расчет	(C) Эксперимент	(B) Расчет	(C) Эксперимент
973	59,1	0,75	11,8	—	7,1	—
1073	100,0	3,75	35,2	0,47	21,7	—
1173	100,0	12,0	86,5	1,37	51,8	—
1273	100,0	29,0	100	3,91	100	1,2
1373	100,0	64,2	100	9,32	100	3,56
1473	100,0	95,4	100	24,6	100	12,1
1573	100,0	—	100	39,4	100	—

Key:

A -- Hydrogen
B -- Calculated
C -- Experiment
D -- Volume, %

Antifriction Properties of Molybdenum Disulfide

Molybdenum disulfide, like most other solid lubricants, is characterized by laminar structure, like graphite, though compared with graphite MoS_2 has a major advantage /45, 90, 156/. We know that graphite's lubricating properties are due to the presence of adsorbed films (of moisture) on the layer surfaces /15, 265/. The temperature during friction promotes desorption of these films and graphite loses its lubricating qualities. Therefore, in vacuum and at low temperatures graphite cannot be used as a lubricant /8/. MoS_2 does not suffer from these drawbacks.

The presence of layers of two different atoms in the MoS_2 structure provides conditions for facile slipping of its plates. The thickness of these plates, acting as if they were smeared on both sides with sulfur, is only 6.28 AU /249/. One micron of a molybdenum disulfide film contains 1630 layers of 1631 slip surfaces /159/, while a film 0.02 micron thick can include 40 layers or 39 slip surfaces. Use of films 5 microns thick is wholly adequate to ensure normal friction. For more prolonged service life, it is desirable to increase film thickness to 5-13 microns /159/.

Additionally, antifriction properties of molybdenum disulfide are quite markedly affected by orientation of its particles and slippage of layers /261/, and also by the ability of MoS_2 to form internal bonds with the surface on which it is deposited /89/.

As noted by many authors, use of molybdenum disulfide as a lubricant invariably leads to reduction of coefficient of friction, greater bearing capacity of friction pairs, reduction of temperature at points of contact, and prevention of seizure of surfaces even when the friction pair is made of similar metals.

Boyd and Robertson /63/ investigated frictional properties of various lubricants at high pressures and arranged them by increasing coefficients of friction:

Stearic acid	0.022	Animal oil	0.072
Tungsten disulfide	0.032	Calcium oxide	0.073
Molybdenum sidulfide	0.032	Soapstone	0.076
Graphite	0.036	Turbine oil containing 1 percent graphite	0.081
Silver sulfate	0.055	Turbine oil containing 1 percent stearic acid	0.087
Turbine oil containing MoS_2	0.060	Turbine oil	0.088
Lead iodide	0.061	Machine oil	0.099
Palm oil	0.063	Mica, powdered	0.257
Castor oil	0.064	Borax, powdered	0.482
Zinc oxide	0.071		

From this it follows that the coefficient of friction of molybdenum disulfide is a minimum value, inferior only to stearic acid. The coefficient of friction of MoS_2 together with turbine oil is also less (0.06) that for the same oil with graphite and stearic acid additives (0.081 and 0.087).

It must be noted that literature sources give contradictory data on the coefficients of friction, maximum loads, temperatures, rate of friction, and other parameters characterising antifriction properties of friction pairs when molybdenum disulfide is used. This evidently is due to the fact that the authors conducted studies under nonidentical conditions, not fully taking into account all factors affecting antifriction properties.

Let us look at these factors in greater detail.

Effect of molybdenum disulfide purity and powder particle size. The coefficient of friction and wear on the friction pair depend on the purity of the MoS_2 powder. MoS_2 powders of 99.4 and 98.4 percent purity have coefficients of friction, respectively, of 0.05 and 0.2, while powders less pure have higher values /64, 164, 242, 268/. The study /217/ points out that powder purity must not be less than 98.5 percent. Actually, it has been found /130/ that molybdenum disulfide 99.8 percent pure is required for lubrication. Various impurities of oxygen and silicon markedly deteriorate lubricating properties /35, 56, 210, 251, 253/. When silicon is present in MoS_2 powder up to a content of 0.5 percent, the coefficient of friction changes only slightly, but for higher silicon content use of MoS_2 is ineffective. It is assumed that if the lubricant powder contains SiO_2, then for a total content of 0.02 percent particle size of this powder must not be greater than 3 microns /57/.

Moisture contained in a lubricant adversely affects antifriction properties of MoS_2. The coefficient of friction and rate of wear on rubbing surfaces rise with increase in relative humidity /56/.

L. A. Chatynyan /35/ presents data from a study of the effect that purity of MoS_2 powders has on wear resistance of nickel alloys (Fig. 3), from whence it follows that wear on the friction pair is reduced with decreases in MoS_2 purity. This deviation from generally observed phenomena is accounted for by the present author as due to strenghthening of the nickel alloy owing to the abrasive action of impurities or oxidation of surfaces caused by higher frictional temperature. Here, as the author noted, the hardness of surface layers of the alloy rises by 196-294 meganewtons/meter^2 (200-300 kg/mm^2).

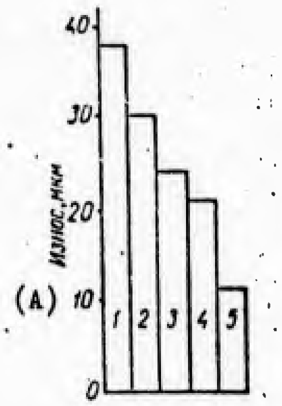

Fig. 3. Effect of Purity of Molybdenum Disulfide as a Solid Lubricant on Wear of Nickel Alloy for Different MoS_2 Purities:
1 -- without MoS_2 2 -- 98.5%
3 -- 99.4% 4 -- 97.8-98.9%
5 -- 96%
Key: A -- Wear, microns

As to MoS_2 powder particle size, most authors agree that the finer the powder, the higher its lubricating properties. However, in the view of the author of the study /81/, particle size must not be less than 1 micron, since for smaller particle size the powder loses its lubricating properties.

Different powder particle sizes, microns, have been recommended, depending on operating conditions and application of the lubricant: 0.5-1.0 [255]; up to 2 [258]: 0.5-2.0 [130]; up to 6.0 [238]; 10 [181]; 40 [217]; up to 70 [81]; and 75 [181].

Effect of lubricant layer thickness. Molybdenum disulfide is characterized by good covering power, so a small amount of the powder suffices to produce a lubricant layer on the friction surface. Authors of the study [210] claim that 5-8 grams of MoS_2 powder is enough to lubricate 1 square meter of surface.

For extended service life of the friction pair, as pointed out in the study [159], a lubricant layer 5-13 microns thick is needed. For a 16-micron film, a bearing can function for one hour at a slipping speed of $v = 1.7$ meters/second and pressure $p = 44$ kilonewtons/meter^2 (kg/mm^2) [210]. A film of dry lubricant 65.5 microns thick protects the surface of steel at high temperatures and pressures up to $1173^{\circ}K$ [225]. The thinner the molybdenum disulfide layer, the smaller the coefficient of friction [261]. Therefore, for normal functioning of friction pairs the optimal thickness of the friction pair must be chosen as a function of pressure, speed, temperature, method of introducing the molybdenum disulfide into the lubricant, and friction surface finish and preparation.

The effect of ambient or working environment on antifriction of molybdenum disulfide. This is determined by the nature of their chemical interaction and depends heavily on ambient temperature and composition.

It was pointed out above that molybdenum disulfide dissociates with temperature rise, as a result of which its lubricant properties are worsened. When functioning in an ordinary atmosphere with slight air exchange, MoS_2 can be used to a temperature of $903^{\circ}K$. Its coefficient of friction here is 0.02 [159]. Raising the temperature to $673^{\circ}K$ when MoS_2 is subjected to friction in air leads to formation of molybdenum oxides, due to which the coefficient of friction gradually rises [235]. Most data on the effect temperature has on the coefficient of friction of MoS_2 relate to tests of friction pairs in vacuum [4, 47, 82, 219].

As follows from Fig. 4 [4], the coefficient of friction of MoS_2 is minimal (0.2-0.3). But under the same set of conditions, the coefficient of friction of pure molybdenum has a much higher value, approximately 2.0. When water vapor, nitrogen, argon and helium are present, the coefficient of friction of MoS_2 rises. This is due, in all probability, to dissociation of molybdenum disulfide. The coefficient of friction depends on the method by which the MoS_2 film is formed on the friction surface (Table 2) [66].

A similar study was conducted by Deacon and Goodman (Fig. 5) [15, 82].

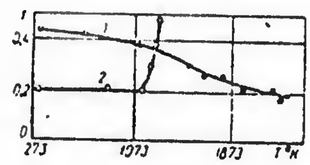

Fig. 4. Coefficient of Friction of Solid Lubricants as a Function of Temperature for Graphite (1) and Molybdenum Disulfide (2) /4_/

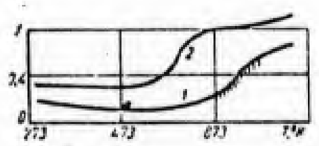

Fig. 5. Variation in Coefficient of Friction as a Function of Temperature and Method of MoS_2 Application on Friction Surface (Platinum):
1 -- by smearing MoS_2 powder
2 -- by deposition of MoS_2 powder /15, 82/

The coefficient of friction of MoS_2 film on platinum remains unchanged with temperature rise to 573°K, and when MoS_2 powder is smeared, the coefficient of friction is 0.2 (cf. Fig. 5, 1), but when the MoS_2 layer is deposited on the platinum surface, it is 0.3 (cf. Fig. 5, 2).

TABLE 2

Coefficient of Friction of MoS_2 Films Formed on Pure Molybdenum by Various Methods, in Relation to Ambient Temperature /66/

(A) Характеристика образца	(B) Температура, °К								
	295	873	973	1023	1073	1043	1213	1293	1423
(C) Mo, спеченный в парах MoS_2	0,9	0,45	0,3	0,2	0,2	0,2	0,3	0,45	—
(D) Mo, спеченный в парах CS_2	0,9	0,6	0,5	0,4	0,4	—	0,3	0,4	0,5
(E) MoS_2, нанесенный на молибден втиранием на воздухе	0,1	0,2	0,3	—	0,3	0,35	0,4	0,7	1,1
(F) MoS_2, осажденный на поверхность молибдена на воздухе	0,2	—	0,2	—	0,2	—	0,3	0,45	0,50
(G) Mo, спеченный в вакууме	2,0	—	2,1	2,3	2,5	—	2,8	3,6	(H) Схватывание

/Key on the following page/

Key:

A -- Characteristic of sample
B -- Temperature, ^{o}K
C -- Mo sintered in MoS_2 vapor
D -- Mo sintered in CS_2 vapor
E -- MoS_2 applied on molybdenum by smearing in air
F -- MoS_2 deposited on molybdenum surface in air
G -- Mo sintered in vacuum
H -- Seizure

When the temperature is higher than 573°K, the coefficient of friction for MoS_2 deposited on platinum surfaces rises. Thermographic analysis shows that in the 573-623°K range, oxidation of MoS_2 commences. Total sublimation of MoS_2 sets in at 1023°K.

The effect of slipping speed and specific pressure. A small variation in slipping speed has but little effect on the coefficient of friction of MoS_2, however, at high speeds the coefficient of friction does depend heavily on speed. A reduction in coefficient of friction with rise in slipping speed has been observed for molybdenum disulfide /6, 33, 56, 235/. Thus, when the slipping speed of a bearing rises from 4 to 40 meters/second, the coefficient is reduced by 1.5 times /235/. With an increase in speed from 10 to 35 meters/second, the coefficient of friction changes from 0.11 to 0.06 for specimens of chrome bronze lubricated with dry MoS_2 powder /6/.

Investigations /33/ conducted with artificial molybdenum disulfide revealed that the coefficient of friction drops from 0.25 to 0.1-0.16 as the slipping speed goes up fron 11 to 33.5 meters/second, depending on the lubricant powder particle size (Fig. 6). When the speed of friction was raised above 35 meters/second, the coefficient of friction of molybdenum disulfide rises, due to the higher temperature at the friction surface and decomposition of molybdenum disulfide, causing an abrupt increase in wear (Fig. 7).

For finer (70 microns) molybdenum disulfide powder, the total specific surface is greater. Due to this, oxidation of the powder occurs more intensively, causing much greater surface wear and a rise in the coefficient of friction.

When pressure is raised, the coefficient of friction also rises /33, 235/. However, data in these studies fail to agree with other data. The report /210/ states that effective functioning of friction pairs lubricated with MoS_2 requires that the specific pressure be not less than 9.8 kilonewtons/meter^2 (10 kg/cm^2). Here an increase in load to 6870 kilonewtons/meter^2 (7000 kg/cm^2) is allowable. When the speed is 2.5 meters/second and the pressure is 687 kilonewtons/meter^2 between polished steel surfaces lubricated with MoS_2, the coefficient of friction is 0.07 /258/. MoS_2 powder particle size markedly affects allowable load on the friction surface. For example, introducing MoS_2 with particle size of 40 microns allows this load to be doubled, while for powder with 0.5 micron particle size, a fourfold increase is afforded /31, 218/. The paper /6/ states that when the load is raised from 44.5 to 238 kilonewtons/meter^2 (45.4-242 kg/cm^2), a drop in coefficient of friction from 0.07 to 0.04 is observed. In this case, the lubricant was deposited on the rubbing surfaces of chrome bronze in the form of dry MoS_2 powder with particle size less than 10 microns.

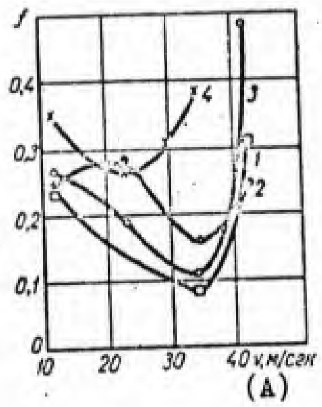

Fig. 6. Variation in Coefficient of Friction of Molybdenum Disulfide as a Function of Slipping Speed at Given Pressures Listed Below:
1, 2, 3 -- 0.69 kilonewtons/meter^2 4 -- 1.28 kilonewtons/meter^2
Powder particle size: 1 -- 40 microns 2 -- 75 microns
3,4 -- 100 microns

Key: A -- v, meters/second

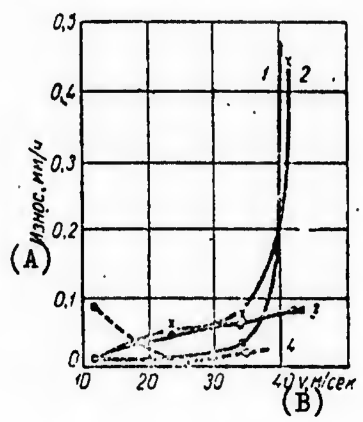

Fig. 7. Wear on Layer of Molybdenum Disulfide as a Function of Slipping Speed at Pressure Given Below:
1, 2, 3 -- 0.69 kilonewton/meter^2 4 -- 1.28 kilonewtons/meter^2
Powder particle size: 1 -- 40 microns 2 -- 75 microns
3,4 -- 100 microns

Key: A -- wear, mm/hr B -- v, m/sec

Table 3 lists data /104/ on the effect that pressure has on coefficient of friction and on the temperature reached at the friction surface with a lubricant of SAE-20 mineral oil containing 1 percent by weight colloidal MoS_2. It is clear from these data that the coefficient of friction diminishes with greater load, while the temperature at the friction surface rises. Similar conclusions have been reached by other researchers as well /6, 174, 177/.

When there is an absence of lubricant on the friction surface, and for higher slipping speeds and lower pressures, greater coefficients of friction are observed (cf. Fig. 6), as is the case for a slight rise in load. Use of liquid lubricant when there is friction on a molybdenum disulfide layer applied on steel ensures a reduction in the coefficient of friction with pressure rise even under conditions of higher slipping speeds (Fig. 8)/33/.

TABLE 3

Coefficient of Friction as a Function of Pressure When a Liquid Lubricant Containing MoS_2 Is Used /104/

(A) Давление, кн/м² (кг/см²)	(B) Коэффициент трения	Температура поверхности трения, °K (C)
208 (222)	0,24	296
1080 (1100)	0,27	324
2080 (2200)	0,22	351
3240 (3330)	0,189	371
4350 (4440)	0,186	371
5400 (5550)	0,148	388
6100 (6200)	0,130	406
6320 (6450)	0,124	407
6570 (6700)	0,120	407

Key:

A -- Pressure, kilonewtons/meter^2 (kg/cm^2)
B -- Coefficient of friction
C -- Temperature of friction surface, °K

Effect of material of surfaces in contact. Material used in friction pairs affects antifriction properties of the molybdenum disulfide film. MoS_2 has a most beneficial effect on friction of steels and alloys whose composition includes molybdenum. Bearings made of these materials function stably at a slipping speed of 166.6 rps and temperatures up to 811°K.

When an 0.01-0.02 mm thick film of powdered MoS_2 is used for friction pairs of dissimilar materials, different coefficients of friction result /242/ (Table 4). Choice of friction pairs of steel-on-steel with MoS_2 as lubricant showed that replacing one steel by another leads to a drop in the coefficient of friction from 0.05-0.2 to 0.05-0.095 /128/. For the same lubricant formulation, the coefficient of friction for the steel-on-steel pair is 0.06-0.04, but for aluminum on steel it is already up to 0.08 (Table 5).

Good results have come from using MoS_2 as an additive to oils for tin-based alloys (89 percent Sn, 7.5 percent Sb, and 3.5 percent Cu) and cadmium-based alloys (0.5 percent Cu, 0.75 percent Ag, balance Cd) /216/. Stable functioning at ambient temperatures up to 973°K decomposition point of iron sulfide) is afforded by lubricating sulfidized steel surfaces with molybdenum disulfide. When nickel is present in the steel, a nickel-molybdenum disulfide combination can result, since the free energies of MoS_2 and NiS are numerically close /118/.

Effect of treatment of surfaces of friction pairs. Treatment of friction pair surfaces when MoS_2 must ensure uniform deposition of the lubricant and its good adhesion to the material.

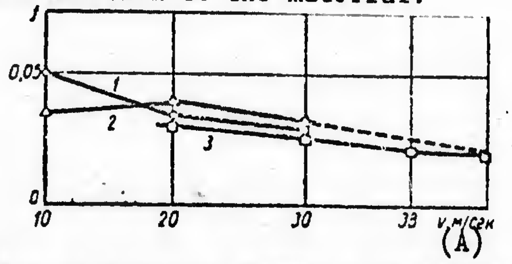

Fig. 8. Effect of Slipping Speed on Coefficient of Molybdenum Disulfide Layer When a Liquid Lubricant is Present, at Pressures Indicated Below:
1 -- 0.67 kilonewton/meter^2 2 -- 1.28 kilonewtons/meter^2
3 -- 1.96 kilonewtons/meter^2
Key: A -- v, meters/second

The specific technological process of preparatory operations is chosen in relation to the method of lubricant deposition and the material used in the friction surfaces. It has been established that film obtained chemically have excellent bonds /66/. Proper choice of lubricant deposition conditions and form of lubricant ensure high load capacity of the friction pair. Thus, the following data are given in the reports / 52, 181/: an MoS_2 film formed on the friction surface via a chemical reaction accepts a load on the specimen of 23.5 kilonewtons (2400 kg), while an anodized surface of the same specimen material accepts a load of 6.7 kilonewtons (681 kg), sulfidized surface -- 12.8 - 13.56 kilonewtons (1300-1362 kg), and an untreated steel surface -- only 3.55 kilonewtons (362 kg).

The reports /46, 66/ cite another example of the effect of surface treatment on coefficient of friction. A specimen made of molybdenum, degasified in vacuum at 1673°K, and then sulfidized in hydrogen sulfide atmosphere has a coefficient of friction of 0.9. After baking this specimen at 1073-1173°K in the same atmosphere, the coefficient of friction was reduced to 0.2.

TABLE 4

Effect of Materials of Rubbing Pair on Coefficient of Friction of Molybdenum Disulfide /242/

Материал образца (A)	Коэффициент трения (B)	Количество рабочих циклов (C)
Ag	0,032	103,68
Ni	0,045	73,44
Cr	0,040	43,20
Cu	0,036	38,88
Pb	0,110	360

Key:

A -- Material of specimen
B -- Coefficient of friction
C -- Number of working cycles

A very strong wear-resistant lubricant film on bearing surface is obtained by deposition of MoS_2 followed by heating in a special autoclave /104/. The report /19/ recommends applying molybdenum disulfide in paste form, and then heating it to a temperature below the point at which the lubricant can function. To improve coating of the friction surface with molybdenum disulfide, it undergoes complex treatment by parkerizing or nitriding, using ultrasound /23/. The following methods of surface treatment are recommended: sandblasting, shot-peening, oxide coating, anodizing, mild etching, chrome-plating, and so on /118/. Thus, when lubricating with molybdenum disulfide for friction along an aluminum surface, the aluminum surface is chrome-plated, while stainless steel suiface is parkerized. If stainless steel is in contact with nickel for copper, and manganese is in contact with copper, then their surfaces are subjected to special electrolytic treatment.

TABLE 5

Coefficient of Friction as a Function of Material Used in Friction Pair and Lubricant Composition /201/

Material of Pair	Lubricant Composition	Coefficient of Friction	Remarks
Steel on steel	90% MoS_2, with 2% graphite bound with resin	0.06-0.04	n = 1.2 rps, p = 5500 kilonewtons/m^2 (5624 kg/cm^2)
As above	100% MoS_2	0.045-0.038	Coefficient of friction, kinetic
As above	90% MoS_2, with 2% graphite (small amount of resin)	0.04-0.03	As above
Steel on aluminum	100% MoS_2, with lubricant	0.08	As above
Steel on steel	50% MoS_2, with 50% C	0.087	As above
As above	90% MoS_2, with 10% graphite	0.0715	p = 5500 kilonewtons/meter^2 (5624 kg/cm^2)

TABLE 6

Recommended Methods of Surface Treatment Prior to Applying Dry MoS_2 Lubricant /107/

Aluminum and Its Alloys	Steel (With Exception of Stainless)	Stainless Steel, Chrome-plated and Nickel-plated Surfaces
Removal of contaminants and corrosion traces	Removal of containinants and corrosion traces (organic solvents)	Removal of contaminants
↓	↓	↓
Anodizing	Parkerized	Sandblasting
↓	↓	↓
Quality control	Control	Control
↓	↓	↓
Application of dry lubricant	Application of dry lubricant	Application of dry lubricant
↓	↓	↓
Quality control	Control	Control
↓	↓	↓
Drying for 2 hours at 453°K	Drying for 1 hour at 498°K	Drying for 1 hour at 498°K
↓	↓	↓
Control	Control	Control

The surface of cadmium rubbing on zinc is parkerized, while the surface of titanium is degasified in vacuum /20, 240/. It is also recommended that parkerized be used for inconel and titanium /81/. A MoS_2 layer is retained on a parkerized surface 81-150 hours, while only for 0.12-0.3 hour on a nonparkerized surface /18, 162/. For friction of medium hard steel along mild steel and lubrication with mineral oil, corrosion of the friction surface sets in after 25 hours, when MoS_2 coating is used -- after 1200 hours, but when MoS_2 coating in a resin base is used -- in 0.5 hour /118/.

Gramp /107/, concentrating on preliminary treatment of surfaces and on methods of film deposition, found that the coated surface must have a finish of 80-160 microns, which corresponds to finish classes 10-12 (GOST /State Standard/ 2789-51). The author gives a treatment scheme which ensures high quality coating for different metals (Table 6).

As follows from this overview, factors enumerated have a marked effect on antifriction properties of friction pairs. Strictly speaking, they cannot be viewed in isolation from each other. When selecting both material of friction pairs and method of introducing MoS_2 into the zone of contact, these factors must be considered all together.

Methods of Introducing Molybdenum Disulfide Lubricant and Its Application

Molybdenum disulfide is used as a finely pulverized powder, colloidal, or quasicolloidal suspension of powder in petroleum oils, synthetic lubricating liquids, in different plastics as fillers, or coatings, and also as a constituent of metalloceramic alloys.

Choice of any particular method of introducing molybdenum disulfide into the friction zone is determined by operating conditions and material of the rubbing surfaces.

The chief purpose of MoS_2 use lies in improving antifriction properties of friction pairs operating at high contact loads, at elevated and reduced temperatures, in different gaseous media, and in vacuum, particularly in outer space [263].

Use of Dry Molybdenum Disulfide Powder

A layer of MoS_2 is applied by smearing or by compacting through compression or impact onto metal surfaces previously carefully cleaned. To improve the bond of MoS_2 with the metal, the surface on which the powder is applied is heated. An excess MoS_2 layer is quite difficult to remove mechanically, but is washed off with hydrochloric acid. In actual practice, the surface cannot be wholly freed of the powder without surface damage.

When dry powder is rubbed in, microirregularities become filled, due to which the total contact area increases and thus higher bearing capacity of the friction pair ensues [6, 35, 22]. Thus, a thin layer of MoS_2 ensures functioning of a friction pair at a specific pressure up to 6870 kilonewtons/meter^2 [118].

Study of the friction surface using electron microscopy revealed formation of a continuous lubricant layer and a high degree of orientation of the foliate MoS_2 particles on the metal surface. In the course of friction, the degree of orientation of powder particles of other lubricants as a rule decreases with temperature rise, but MoS_2 is characterized by retention of particle orientation, even when MoO_3 is formed /15, 43, 82/. This orientation of lubricant particles on the slip surface leads to a reduction in work of friction and a reduction of coefficient of friction /107/.

MoS_2 powder introduced into the zone of friction as a lubricant is employed in practically all fields of technology: aviation, automobile construction, in screw-cutting, in press and cutting tools, for drilling and boring refractory materials /92/, in precise machine building, railway car construction, turbine construction, and in the food and chemical industries /13, 89, 129, 210, 256/. MoS_2 enjoys particularly extensive use in marine transport and in installations functioning in water: floating docks, marine motors, sluices, bridges, revolving cranes, blocks, ship pulleys, and so on /171/.

Use of MoS_2 powder for lubricating rubbing parts of engines promotes their superior cooling and greater power due to reduction of the coefficient of friction /45, 247/. When lubricating with molybdenum disulfide, noise is reduced in functioning of bearings, force of twisting in threaded and screw connections is reduced by 50 percent. Due to use of MoS_2 powders in machining, the service life of broaching is raised by 50 percent, that of supporting hard-alloy tools -- by 100 percent, and that of copper-coated saws -- by 360-800 percent /200/. Wear resistance of press molds is 25 percent greater with MoS_2 use as lubricant /199/. In this case there is no need to use VK type alloys for steel working /89/.

Study of the effect of lubricating with dry MoS_2 powder parts of textile machines in contact with cotton filaments revealed that filament breaks here is reduced by 60 percent, and fiber breakage is also reduced /10/.

Use of MoS_2 powder at the Staupfwerkes plant /210/ in lubricating rail car bushings meant a replacement of bronze bushings with cast iron counterparts and increase in their service life from 8-10 days to 6-7 months.

Lubricating with MoS_2 powder increases antifriction properties of such materials as rubber, asbestos, leather, synthetic fibers, and so on /225, 249/.

In addition to the above method of applying MoS_2 powder on rubbing surfaces, it is also deposited from suspensions. The suspension medium is water or oil. Here several drops of an aqueous suspension of solid lubricant are applied to the friction surface. After drying, excess lubricant is wiped off the surface with a clean cloth and the specimen is washed with gasoline. For the MoS_2 to precipitate from the colloidal suspension in vaseline oil, the specimen is immersed in the suspension. Then it is washed in benzene. Lubricant layers deposited from the colloidal suspension do not give the particle orientation when powder is smeared, and the coefficient of friction of these layers is higher than for lubricating with dry powder /15, 82/.

Among the drawbacks of these methods of applying MoS_2 into the friction zone must be included the large consumption of powder, the impossibility of monitoring and regulating thickness of the lubricant layer or the uniformity of its distribution on the friction surface.

Use of Molybdenum Disulfide Additive in Lubricating Liquids

Powdered MoS_2 additives in lubricating oils are employed to prevent seizure when there is sudden cessation of lubrication, and also to increase the specific loads, slipping speeds, and allowable temperatures of the friction assembly. The literature contains almost no studies explaining the effect of MoS_2 additive to oils on operating properties of friction pairs. Data presented dealing with formulation of lubricant components apply to specific cases. The report [71] recommends that a mixture of two parts MoS_2 and one part aircraft lubricant be used for lubricating bronze, cast iron, and nylon bearings; only one part MoS_2 per 10-12 parts spindle oil, or one part MoS_2 for each 300 parts oil can be employed for some friction assemblies of machines [48]. When lubricating bearings, it is sufficient to add 2-5 percent MoS_2 in order to increase pressure by three to four times [217].

A mixture of petroleum oil containing 2-3 percent MoS_2 is used to accelerate running-in of internal combustion engine parts. Normal engine performance is afforded by adding 1 percent MoS_2 powder to the liquid lubricant [152]. If a lubricant consiting of molybdenum disulfide and kerosene is used for blooming bearings made of phosphor bronze, blooming productivity is extended from 7000 tons of rolled stock to 10,700 tons [179]. A suspension of 70 percent MoS_2 and petroleum oil with a stabilizer additive is used successfully in lubricating heavily loaded exposed worm gears, in metals drawing, in molding of parts, and so on [14, 139].

The British company, William Jackson, Son and Self, [175] investigated cutting properties of saws treated with solutions of MoS_2 in alcohol and toluene. Productivity of these saws rose by 50-60 percent compared with untreated saws, due to the fact that the MoS_2 film resulting from the suspension impeded "greasing" of teeth.

Molybdenum disulfide powder is used in coolants; here kerosene is employed as the solvent. The stability of this solution is estimated to be two to three days. Use of MoS_2 solution with alcohol and oils in ratios of 1:100 and 1:300 is also possible [172].

R. B. Campbell [15] employed cellulose acetate dissolved in acetone (ATs-A) as a binder for a molybdenum disulfide lubricant. The coefficient of friction of the rubbing pairs he attained was 0.12, even though no film formed on the surface.

It is recommended that a lubricant based on lithium soap or fat with MoS_2 additive be used for worm gear reducers and other rubbing parts operating at elevated temperatures (the decomposition point of this lubricant is 466°K) /99, 177, 182, 213/. A film 0.25-3 micron thick is produced at the area of contact of the reducer teeth as a result of orientation of MoS_2 particles. After final running-in of the teeth, the height of the micro-irregularities of the teeth surfaces is, from data in /213/, 0.2 micron.

Depending on the composition of oils and liquids, the limits of working temperatures for application of lubricants containing molybdenum disulfide are extremely varied. Thus, a lubricant containing MoS_2 in an oil thickened with lithium soap is employed at temperatures from 255 to 373°K; in polyethylene glycol -- from 228 to 450°K; in silicone liquid -- from 224 to 505°K; in complex ester -- from 200 to 394°K; and in mineral oil -- from 239 to 402°K /99/.

Use of MoS_2 as a constituent in liquid lubricants is not always effective and is often hampered. For example, MoS_2 powder is not retained on rubbing surfaces and settles on the bottom of the circulating lubricant system when subjected to force of gravity or due to flocculation. Here much expensive MoS_2 powder is used up. Additionally, lubricating properties are strongly affected by particle size, powder purity, viscosity of oil, and so on, which even up to the present time have not been well enough explored.

Use of Molybdenum Disulfide in Complex Lubricants, Pastes, and Surface Films

Molybdenum disulfide is often employed in mixtures with other solid lubricants /31, 144, 166, 201, 220/. MoS_2 additive in graphite improves graphite's lubricating properties in dry friction all the way to 773°K /201/, though for bearings functioning in vacuum it is less effective /166/.

Good antifriction properties characterize a mixture of 67 percent MoS_2 and 33 percent PbS, used successfully at temperatures above 743°K. It is recommended that additional graphite be added to this lubricant to ensure its functionability at room temperature /166/. To reduce wear on friction pairs by 30-50 percent, it is recommended that 1-2 percent of substances such as the following to be added to MoS_2: carbonates of Na, K, Ba, and Ca, Na chromate, starch, camphor, and others, although the chemistry of additive action here is unknown /242/.

Pastes whose formulation includes MoS_2 powder are employed to produce an antifriction layer on rubbing surfaces. Depending on the operating conditions of the friction pair, different additive binders are used. Usually the pastes are based on phenolformaldehyde or epoxide resins or kerosene /21, 151, 166, 238/. A paste containing MoS_2, just like powdered MoS_2, is deposited on the friction surfaces by smearing with a soft cloth or briquetting /10/, and it is prepared by mixing a disperse MoS_2 powder with the binders. After deposition on the rubbing surfaces of the part, the paste is dried at 473-1073°K, depending on base properties /151/. It can be deposited on metal surfaces, and also on natural and synthetic rubber, leather, and other materials. Coating with the paste ensures good coefficients of friction, in particular, for friction of phosphor bronze on steel /151/. It can be deposited on metal surfaces, and also on natural and synthetic rubber, leather, and other materials. Coating with the paste ensures good coefficients of friction, in particular, for friction of phosphor bronze on steel /151/.

Authors of the report /6/ recommend, for example, the following paste formulation with MoS_2 additive: 75 percent MoS_2 and 25 percent NaOH. The amount of MoS_2 in these formulations can vary from 20 to 90 percent by weight.

The following optimal paste composition has been suggested: MoS_2 (6-7 micron powder particle size) -- 70 grams; graphite (325 mesh powder) -- 7 grams; sodium silicate -- 50 grams; water -- 60 grams. Sodium metaborite and sodium hexametaphosphate have been tested as binders, in addition to sodium silicate. Studies revealed that sodium silicate is the longest-lived binder.

The paste is applied by spraying or immersion, depending on coating requirements. Film thickness is regulated to a precision of 1 micron by varying the content of solid constituents in the paste and by varying pressure. Optimal film thickness ensuring good wear resistance must be 5-12 microns. The polymerization temperature of this film must be regulated strictly and depends on the properties of the binders, since adhesion and endurance of coatings are directly proportional to the degree of polymerization.

The paper /107/ lists coefficients of friction for pastes containing molybdenum disulfide and deposited on different metals (Table 7).

Concentration on surface films that reduce friction, improve performance, and prevent seizure, authors of the study /15/ list interesting data on lubricating properties of different films (Table 8). As evident from the study /15/, the following films proved ineffective: $NiCl_2$; $Ca(OH)_2$; $Mo(OH)_2$. Effective films, besides MoS_2, included: $Zn(C_{18}H_{35}O_2)_2$; graphite; CdI_2; $CdCl_2$; WS_2; and others.

To form a film with desired properties and thickness, it must be deposited several times. Additionally, film properties can be upgraded by special treatment of surfaces prior to film deposition, this resulting in lower wear rate and improved adhesion of film to base metal.

When these films are deposited, the best results come from parkerizing of surfaces. Conditions for producing the phosphate layer, crystal sizes, and layer thickness affect properties of the deposited film containing lubricant (Table 9) /107/. In this case, the thickness of the noncemented film is taken as equal to phosphate layer thickness. The thickness of the phosphate layer affects properties of uncemented films, but has almost no effect on properties of cemented films. For coating

TABLE 7

Coefficient of Friction of Friction Pairs Using Molybdenum Disulfide-Based Pastes /107/

(A) Тип покрытия	(B) Вращающийся образец	(C) Нагрузочный блок	(D) Кинетический коэффициент трения
4396	Специальная нержавеющая сталь 52100 (E)	Специальная нержавеющая сталь 4130* (N)	0,23
4396	То же (F)	Алюминий 755Т (O)	0,4
4396	Нержавеющая сталь 303 (G)	Специальная нержавеющая сталь 4130* (N)	0,32
4396	Алюминиевая бронза (H)	То же (F)	0,35
4396	То же (F)	Алюминий 355Т (P)	0,32
4396	Титан 140 А (I)	Специальная нержавеющая сталь 4130* (N)	0,35
4396	Хромированная поверхность (J)	То же (F)	0,33
4396	То же (F)	Алюминий 755Т (O)	0,45
4396	Никелевое покрытие на стали 52100 (K)	Специальная нержавеющая сталь 4130* (N)	0,30
4396	То же (F)	Алюминий 755Т (O)	0,34
4396	Алюминий 7075 Т6 (L)	Специальная нержавеющая сталь 4130* (N)	0,35
4396	Специальная нержавеющая сталь 52100 (M)	То же (F)	0,75**
4356	То же (F)	• • (F)	0,87
4856	• • (F)	• • (F)	0,9

* Steel hardness: HRC = 60

** Static coefficient of friction is given.

Key:

A -- Coating type
B -- Rotating specimen
C -- Load block
D -- Kinetic coefficient of friction
E -- Special stainless steel 51200
F -- As above
G -- Stainless steel 303
H -- Aluminum bronze
I -- Titanium 140 A
J -- Chrome-plated surface
K -- Nickel coating on steel 51200
L -- Aluminum 7075 T6
M -- Special stainless steel 51200
N -- Special stainless steel 4130*
O -- Aluminum 755T
P -- Aluminum 355T

TABLE 8

Indicators of the Effect of Solid Lubricants (Test Conditions: p = 0.26-1.0 newtons (269-1017 grams); v = 0-32.6 m/sec; medium -- dry air)

(A) Материал	(B) Чистота смазки	(C) Коэффициент трения после работы в течение 30 мин	(D) Площадь износа ползуна, мм²
MoS_2	(E) Возможно наличие MoO_3	0,05	1,03
CdJ_2	Химически чист (F)	0,06	1,48
$CdCl_2$	То же (G)	0,07	1,23
WS_2	Наличие окиси (H)	0,08	1,16
Ag_2SO_4	Химически чист (F)	0,14	Незначительная (K)
PbJ_2	То же (G)	0,28	1,18
Графит (I)	Очищенный, с малым размером частиц (L)	0,11	2,2
$Zn(C_{18}H_{35}O_2)_2$	Химически чист (F)	0,11	2,06
$CoCl_2$	Обезвоженный (M)	0,10	1,29
HgJ_2	Химически чист (F)	0,18	1,25
CuBr	—	0,06	1,25
AgJ	Химически чист (F)	0,25	2,13
Машинное масло (для сравнения) (J)	—	0,11	1,29

Key:

A -- Material
B -- Purity of lubricant
C -- Coefficient of friction after functioning for 30 minutes
D -- Area of slider wear, mm^2
E -- Presence of MoO_3 is possible
F -- Chemically pure
G -- As above
H -- Presence of oxide
I -- Graphite
J -- Machine oil (for comparison)
K -- Slight
L -- Purified, small particle size
M -- Degreased

with a single phosphate layer without MoS_2, increased wear is observed, compared with films containing only molybdenum disulfide. Various cementing agents have been studied /107/; organic, thermoplastic, epoxide, phenolic resins, urea-based resins, and so on. Purified MoS_2 powder is used in forming films, but when liquid cementing agents are employed, a colloidal-disperse MoS_2 in alcohol or water is used.

It has been established that the best results come from using polyfluoroethylene purified with molasses and resercine resin (Table 10). All other materials disintegrate in two hours of testing under a load of 39.24 newtons (4 kg) and a slipping speed of 2 meters/second.

Good film properties are obtained when polytetrafluoroethylene is used as binder. This is because the binder material is extremely effective,

TABLE 9

Effect of Phosphate Layer Thickness on Properties of Cemented and Uncemented Molybdenum Disulfide Films (p = 2.06 kilonewtons/meter^2 (2.1 kg/mm^2); v = 0.48 meters/second

(A) Характеристика фосфатного слоя	(B) Толщина слоя, мкм	(C) Пленки скрепленные патокой		(F) Пленки нескрепленные	
		Время до разрушения, ч (D)	Скорость износа, мм/ч × 10^{-3} (E)	Время до разрушения, ч (D)	Скорость износа, мм/ч × 10^{-3} (E)
(G) Слоя нет, толщина пленки MoS_2=40 мкм	—	11,5	3,3	—	—
(H) Тонкий, крупнозернистый (зерна пирамидальной формы)	8	44	1,5	2	3,8
(I) Средний, мелкозернистый неравномерный	15	46	1,4	15	1,0
(J) Средний, мелкозернистый (зерна игольчатой формы)	30	49	1,3	20	1,4
(K) Толстый, крупнозернистый (зерна пирамидальной формы)	46	57	1,0	43	1,0
(L) Слой фосфата	1000	0,2	—	—	—

Remark. To cement film cleaned with molasses, specimens are heated at 579°K. A suspension of MoS_2 in alcohol is used for noncemented films. Total thickness of cemented MoS_2 film of 60 microns is kept constant, as far as is possible.

Key:

- A -- Characteristic of phosphate layer
- B -- Thickness of layer, microns
- C -- Films cemented with molasses
- D -- Time to failure, hours
- E -- Rate of wear, mm/hr x 10^{-3}
- F -- Uncemented films
- G -- No layer, MoS_2 film is 40 microns thick
- H -- Thin, coarse-grained (pyramidal grains)
- I -- Medium, fine-grained, nonuniform
- J -- Medium, fine-grained (needle-shaped grains)
- K -- Thick, coarse-grained (pyramidal grains)
- L -- Phosphate layer

and in all probability improved mechanical properties of the composition. Below are listed mean wear values of cemented film, purified with molasses, in relation to sintering temperature [107]:

Sintering temperature, °K	513	523	543	563	573	583	603	633	673
Mean wear values, microns	14.4	3.2	2.4	3.5	3.9	4.2	8.8	Film breakdown	

TABLE 10

Wear Resistance of Film Containing MoS_2 With Different Cementing Agents /107/

(A) Скрепляющие вещества	(B) MoS_2, об. %	(C) Толщина пленки, мкм: 25 — (D) Длительность работы до разрушения, ч	25 — (E) Температура, °K	40 — (D) Длительность работы до разрушения, ч	40 — (E) Температура, °K	75 — (D) Длительность работы до разрушения, ч	75 — (E) Температура, °K	(F) Длительность работы до разрушения, ч, при испытании без MoS_2*
(G) Политетрафторэтилен	40	80	453	—	—	80	433	12
		59	454	—	—	43	453	8
(H) Резерциновое масло	30	15	358	—	—	40	353	8
		13	363	—	—	18	353	9
(I) Очищенная патока	25	22	403	39	303	63	363	1,5
		5	388	24	398	33	413	1,0

* Film is 75 microns thick; temperature at friction surface is unstable.

Key:

A -- Cementing agents
B -- MoS_2, % by volume
C -- Film thickness, microns
D -- Time to failure, hours
E -- Temperature
F -- Time to failure, hours, when testing without MoS_2
G -- Polytetrafluoroethylene
H -- Resercine oil
I -- Purified molasses

The conclusions drawn in the study /107/, based on thorough study of MoS_2-containing lubricants, are of interest:

1) use of films of solid lubricants permits employment of similar materials for the friction pair;

2) the softer surface of friction pair constituents must be coated with dry lubricant, for wear resistance of the pair depends more on metal hardness than on similarity of friction pair materials;

3) if both surfaces are coated with a film, the coefficient of friction and wear resistance of the surfaces is higher than for the case when one surface is coated with film.

Advantages of the method of using molybdenum disulfide as a lubricant in the form of films and pastes must include the direct introduction of MoS_2 onto the friction surfaces; one drawback of the method is poor adhesion of pastes with working surfaces.

The method of introducing MoS_2 ontc surface films of rubbing parts provides a distinct advantage compared with other methods, due to improved heat transfer, ease of forming films on parts, the possibility of protecting large slip surfaces against wear, as well as lower consumption of MoS_2, and so on.

However, in several cases certain binders adversely affect antifriction properties of friction pairs.

Use of Molybdenum Disulfide in Plastics

Good lubricating properties and continuous replenishment of lubricant with wear of surface, the molybdenum disulfide film must be of a specific thickness and unite strongly with the material of the friction assembly. This is quite a complicated task, since use of binders in the form of lacquers and paints is ineffective in a number of cases. At elevated temperatures lacquers soften and smear out over surfaces. Poor adhesion of coatings with the material used in the parts is observed in this case.

Since 1947, wide use has been made of uniform distribution of MoS_2 powder in the carrier material, along with the method of depositing thin films on friction surfaces.

D. K. Mitchell and B. V. Fulford /15/ presented results of studies on wear of plastic specimens containing molybdenum disulfide as filler, and on wear of specimens with deposited MoS_2 in film form of a specially prepared surface.

Fine MoS_2 powder, when used as filler, is mixed in different proportions with powdered plastic, phenolic resin, or nylon. Then the mixture is molded into specimens. These materials exhibit adequate mechanical strength, heat resistance, wear resistance, and a low coefficient of friction.

It follows from the data in Tables 11 and 12 that tensile strength, temperature at friction surface, and coefficient of friction for both compositions are reduced with rise in MoS_2 content. The coefficient of friction for nylon materials is somewhat less than for phenolic resins with the corresponding MoS_2 content. For MoS_2 content greater than 20 percent, the coefficient of friction is practically the same for both compositions. It has been established that with rise in load and slipping speed, wear of plastic materials rises (Table 13).

The Dupont Company /135/ makes extensive use of composition obtained by sintering nylon or perlon with fillers: graphite, silver, copper, and molybdenum disulfide in different formulations (10 percent by weight). Best results come from sintering nylon with molybdenum disulfide (Tables 14 and 15). There are also other similar compositions, for example, nylon-6 and MoS_2, so-called nylatron GC /145/, nytrolon of grade IC, and others.

TABLE 11

Characteristics of Compositions Based on Phenolic Resins and Molybdenum Disulfide (Service Life Is Determined by 0.125 mm Surface Wear)

(A) Количество MoS_2, об. %	(B) Предел прочности на растяжение, $Мн/м^2$	(C) Коэффициент трения	(D) Результаты испытания при давлении и скорости трения							
			(E) p=2,06 $кн/м^2$ (2,1 $кг/мм^2$)				(J) p=4,12 $кн/м^2$ (4,2 $кг/мм^2$)			
			(F) v=0,48 $м/сек$		(I) v=0,96 $м/сек$		(F) v=0,48 $м/сек$		(I) v=0,96 $м/сек$	
			(G) Длительность до разрушения, ч	(H) Температура, °К	(G) Длительность до разрушения, ч	(H) Температура, °К	(G) Длительность до разрушения, ч	(H) Температура, °К	(G) Длительность до разрушения, ч	(H) Температура, °К
0	12,5	0,25*	—	—	—	—	0,5*	—	0,4*	—
5	6,85	0,20	70	313	48	328	55	323	1	—
11	6,75	0,15	161	323	126	333	112	348	66	348
20	5,77	0,17	66	317	46	343	73	351	51	358
33	3,58	0,15	79	323	36	339	37	346	30	343

* Specimens failed at outset of tests

Key:
- A -- Amount of MoS_2, % by volume
- B -- Tensile strength, meganewtons/m^2
- C -- Coefficient of friction
- D -- Results of tests at pressures and friction rates indicated below
- E -- p = 2.06 kilonewtons/m^2 (2.1 kg/mm^2)
- F -- v = 0.48 m/sec
- G -- Time to failure, hours
- H -- Temperature
- I -- v = 0.96 m/sec
- J -- p = 4.12 kilonewtons/m^2 (4.2 kg/mm^2)

When molybdenum disulfide is added to nylon, its wear resistance doubles, its moisture resistance is improved, and the coefficient of friction is stabilized for slipping along steel without lubricant. Nylon-6 has a coefficient of friction of 0.2-0.3, while nylon GC has a coefficient of friction of 0.16-0.2 /179/. The strength of nylon resulting from introduction of MoS_2 rises markedly. Properties of nylon (σ_b = 6.87-9.70 meganewtons/meter^2 (703-990 kg/cm^2); $\sigma_{\text{in bending}}$ = 11.0-13.0 meganewtons/meter^2) (1120-1330 kg/cm^2)) allow its use as shafts in rolling mills, gears, and so on /112/. However, these materials do not exhibit good wear resistance and friction properties, evidently, due to their poor thermal conductivity /15, 28/

TABLE 12

Characteristics of Compositions Based on Nylon and Molybdenum Disulfide (Service Life Is Determined by 0.125 mm Surface Wear)

(A) Количество MoS_2, об. %	(B) Предел прочности на растяжение, Мн/м²	(C) Коэффициент трения	(D) Результаты испытания при P=2,06 кн/м², v=0,48 м/сек	
			(E) Время испытания, ч	(F) Температура, °К
0	16,6	0,17	6	—
5	15,2	0.17	30	377
20	12,45	0,15	37	369
35	10,2	0,13	47	360
50	8,8	0,15	56	362

Key:

A -- Amount of MoS_2, % by volume

B -- Tensile strength, meganewtons/meter^2

C -- Coefficient of friction

D -- Results of tests at P = 2.06 kilonewtons/meter^2 and v = 0.48 meter/second

E -- Testing period, hours

F -- Temperature

TABLE 13

Rate of Wear on Films Containing Molybdenum Disulfide and Phenolic Resin, for Different Loads and Speeds

(A) Условия испытаний		(D) Время износа поверхности на 0,125 мм, ч	(E) Скорость износа, мм/ч, ×10⁻³
(B) p, кн/м²	(C) v, м/сек		
2,06	0,48	94	1,3
2,06	0,35	69	1,8
4,12	0.48	69	1,8
4,12	0,35	37	3,3

Key:

A -- Test conditions

B -- p, kilonewtons/meter^2

C -- v, meters/second

D -- Time required for 0.125 mm of surface wear, hours

E -- Wear rate, mm/hr x 10^{-3}

TABLE 14

Comparative Properties of Zaytel'-102 Grade Nylon With and Without Filler

(A) Свойства	(B) Без наполнителя	(C) Наполнитель		
		(D) Графит	(E) Бронза	Дисульфид молибдена (F)
(G) Коэффициент теплового расширения, $град^{-1}$	$0{,}19 \cdot 10^{-5}$	$0{,}038 \cdot 10^{-5}$	$0{,}0254 \cdot 10^{-5}$	—
(H) Температура деформации, °К, при				
$p = 4{,}54$ $кн/м^2$ ($4{,}6$ $кг/см^2$)	477	—	—	536
$p = 18{,}1$ $кн/м^2$ ($18{,}2$ $кг/см^2$)	339	—	—	412

Key:

A -- Properties
B -- Without filler
C -- Filler
D -- Graphite
E -- Bronze
F -- Molybdenum disulfide
G -- Coefficient of thermal expansion, deg^{-1}
H -- Deformation temperature, °K at $p = 4.45$ kilonewtons/meter^2 (4.6 kg/cm^2) and $p = 18.1$ kilonewtons/meter^2 (18.2 kg/cm^2)

TABLE 15

Coefficient of Friction of Different Fillers Used With Teflon

(A) Материал наполнителя	(B) Коэффициент трения
(C) 20% стекловолокна и 20% MoS_2	0,17
(D) 40% графита	0,19
(E) 85% меди	0,29
(F) 40% бронзы	0,27
(G) Без наполнителя	$0{,}21 \pm 0{,}02$

Key:

A -- Filler material
B -- Coefficient of friction
C -- 20% glass fiber and 20% MoS_2
D -- 40% graphite
E -- 85% copper
F -- 40% bronze
G -- Without filler

V. F. Platonov /26/, studying the shortage status and limited distribution of certain starting materials, recommended more accessible lubricants for mass-produced plastics-based bearings. These lubricants, in spite of relatively high coefficients of friction, would give better results in many cases.

Of materials based on polyamide resins and used as bearings, best results are shown by resin p-68 and polycaprolactam B in pure form and when containing fillers (talc and MoS_2). The range of reliable, stable performance for bushings made of polyamide resins with fillers is limited by maximum slipping speed -- 0.5-0.6 meter/second and by specific load -- 49-68.5 kilonewtons/meter^2 (50-69 kg/cm^2), and maximum allowable friction assembly temperature of 358-363°K. The coefficient of friction of these materials in dry friction regime is 0.3-0.48, while the mean coefficient of friction (excluding running-in considerations) is 0.08-0.15.

Under dry friction conditions, wear on bushings made of polyamide is 60-80 times less than wear of bronze bushings, but under conditions of semidry friction -- 6-8 times less /12/. Molybdenum disulfide is recommended as the basic filler in all combinations with plastics for replacement of worn parts in agricultural machines and tractors /3/.

The following polymeric compositions containing fillers were tested in this study:

a) ED-5 epoxide resin with 3.5 and 10% MoS_2;
b) ED-5 epoxide resin with 15% styrene and 10% MoS_2;
c) 20% cresolformaldehyde resin with mixture of 80% nitrile rubber and 20% MoS_2;
d) 80% cresolformaldehyde resin with a mixture of 20% nitrile rubber and 20% MoS_2;
e) E-116 resin and 10% MoS_2;
f) a mixture of the copolymer of furfurolacetic resin with epoxide resin and 20% MoS_2.

It has been established that epoxide resins cannot be used as binder in antifriction coatings of bushings in internal combustion engines due to inadequate heat resistance and low impact toughness. The best results were secured using cresolformaldehyde resin and nitrile rubber. A coating 20 microns thick has adequate hardness and heat resistance, but due to insufficient impact toughness it cannot bear up under dynamic loads.

To increase impact toughness of materials, glass fiber and asbestos flocs are added to them. This results in a rise in impact toughness of material to 294.3 kilojoules/meter^2 (330 kg/cm^2), a rise in heat resistance to 523°K and in hardness to 29.4 kilonewtons/meter^2 (30 kg/cm^2). When subjected to static load of 98.1 kilonewtons/meter^2 (100 kg/cm^2), the surface of an asbestos-containing composition failed, but a load of 490 kilonewtons/meter^2 (500 kg/mm^2) does not result in failure of a material with glass fiber as filler.

Filled plastics can be deposited on the friction surface in the form of a thin layer, for example, a layer of a mixture of teflon with 40-50% by volume MoS_2. This material is called DU /29/. For better adhesion of the layer to the surface and good antifriction properties under dry friction conditions, the layer is deposited on a previously parkerized mild steel surface. The layer can be deposited on a steel surface containing up to 10% alloying elements. Optimal layer thickness for steel is 65 microns, but for the other materials used it is 50 microns.

Also recommended is an antifriction material not requiring lubrication and consisting of a mixture of 35-55 parts rubber, 14-40 parts plastic, and 5-50 parts (by weight) MoS_2. It is deposited on the working surfaces of support bearings (layer thickness is 0.1-2% of shaft diameter) and is cemented thereto with Desmodur brand cement /14/.

The eddying method of depositing films on friction surface has been widely received at enterprises in our country /7, 11, 16/ as the most progressive compared with gas-flame deposition or the extrusion method. Essentially, this method consists of immersion of the metal part, heated to a temperature exceeding the melting point of the plastic, in a swirling layer of powdered material in a special dusting container. The powder spreads over the part surface, fuses, and coats it with an even film. After application of the film, it must be fused in a heating oven. This method ensures uniformity of coating, economy of materials, and the possibility of producing multilayer coatings with diffentiated properties, depthwise.

Currently, extensive use is made of the method of introducing molybdenum disulfide-filled fluoroplastics into a porous layer of spherical bronze sintered onto a metal strip -- a blank for bearings.

A key disadvantage of plastics containing fillers is limited slipping speeds, since a rise in this factor means a marked increase in temperature of surface layers, leading to softening and disintegration of plastics.

Use of Molybdenum Disulfide in Metalloceramic Antifriction Materials

Advances in powder metallurgy have opened up broad prospects for forming materials with predesired properties. An extremely promising method improving antifriction properties of materials is introduction of sulfur and sulfur-containing materials, particularly MoS_2, into metalloceramic materials. Present in the structure of the material as a distinct phase, MoS_2 can function as a solid lubricant. The technological process of fabricating metalloceramic articles affords retention of surface layers firmly wedded to the base metal and exhibiting different physicochemical properties, in this case, more strongly saturated with molybdenum disulfide.

Reports on the use of MoS_2 as a constituent in metalloceramic antifriction alloys /4, 20, 21, 52, 53, 64, 87, 129, 160, 173, 179, 224, 258, 262/ are found in the literature.

However, these reports are incomplete, affording only an idea of the properties of the resulting materials. Eisenkolb et al /87/ has patented a method of fabricating self-lubricating antifriction materials. The role of lubricant here is played by 4-6% MoS_2 or graphite. Materials are prepared from powder with particle size of 60-40 microns by cold pressing at a pressure of 5900 kilonewtons/meter^2 (6 tons/cm^2) and are sintered at 1273°K with subsequent final pressing at a pressure of 5900-6850 kilonewtons/meter^2 (6-7 tons/cm^2). Gaseous mixtures of nitrogen and carbon monoxide are used as the protective atmosphere during sintering.

The base of these materials is 76% Fe and 19% Pb; 80% Cu and 13% Ni; Ni:Cu = 1:6 (in weight ratio) with additive of 1% Be; Ni:Fe:Cu = 1:2:4. Materials with this formulation exhibit good corrosion resistance and are employed for piston rings.

Molybdenum disulfide is added to a mixture of the following composition: 75-85% Cu, 8-14% Sn, and 1-3% MoS_2 /20/. Here tin powder particle size must be one-fourth as large as those for copper and molybdenum disulfide powder particle size. The mixture is molded under a pressure of 1.97-3.42 meganewtons/meter^2 (2-3.5 tons/cm^2) and sintered at 1073-873°K in carbon atmosphere. Articles made by this process are quite strong, but for superior antifriction properties, MoS_2 powder is additionally rubbed into their working surfaces. Materials based on silver, containing 5% copper and up to 35% MoS_2 /56/ are known.

Addition of 4-10% finely pulverized (from 25 to 50 microns) MoS_2 powder into metalloceramic alloys based on iron, copper, bronze, and aluminum obtained by the ordinary sintering method or using hot-pressing promote a reduction in coefficient of friction and higher wear resistance of the materials /24, 25, 53, 58, 129, 173, 205/.

The phenomenon of seizure of friction pairs is eliminated when 5% MoS_2 is added to materials.

An increase in the MoS_2 content in an alloy leads to lower coefficients of friction and lower material wear (Table 16). However, low MoS_2 content in an alloy does not afford the needed antifriction properties, while a rise in MoS_2 content results in materials losing their strength properties.

In addition, obtaining metalloceramic materials containing more than 10% MoS_2 is technologically cumbersome /217/. Using sintering under pressure, materials containing up to 50-68% MoS_2 /258/ can be produced. This requires that molybdenum disulfide powders with particle size of about 70 microns be used /81/.

Metalloceramic materials based on iron, copper, and other materials containing MoS_2 are marked by high bearing capacity, high endurance, and high antifriction properties over a wide temperature range -- from 233 to 473°K, and in some cases -- from 473 to 773°K (Table 17) /205, 206/.

TABLE 16

Coefficients of Friction of Metalloceramic Compositions in Relation to Ambient Temperature /206/*

(A) Материал	(B) Коэффициент трения						
	(C) исходный	(D) после неоднократного скольжения	(E) при температуре				
			288° K	373° K	473° K	573° K	673° K
(F) Спеченный молибден	0,4	0,45	0,45	0,5	0,5	0,5	0,55
(G) Спеченный молибден с дисульфидом молибдена	0,1	0,1	0,1	0,08	0,06	0,06	0,07
(H) Спеченная медь	0,3	0,8	0,3	0,7	0,8	1,2	1,2
(I) Спеченная медь с дисульфидом молибдена	0,15	0,13	0,13	0,14	0,13	0,14	0,2
(J) Литая медь (для сравнения)	1,3	1,3	1,3	1,0	1,0	1,0	1,0

* Material of counterbody is steel.

Key:

A -- Materials
B -- Coefficient of friction
C -- Starting value
D -- After repeated slipping
E -- At temperatures listed
F -- Sintered molybdenum
G -- Sintered molybdenum with molybdenum disulfide
H -- Sintered copper
I -- Sintered copper with molybdenum disulfide
J -- Cast copper (for comparison)

TABLE 17

Approximate Properties of Metalloceramic Alloys / 205/

(A) Сплав	(B) Плотность, г/см³	(C) Твердость, кн/м²	(D) Предел прочности, Мн/м²	(E) Пористость, %
I	6,3—6,7	37,3—43,2	7,35—9,35	18—22
II	6,9—7,35	47,2—54	9,35—10,3	7,5—10
III	7,85—8.15	88,5—103	4,7—16,7	0,5—2

Key:

A -- Alloy
B -- Density, grams/cm^3
C -- Hardness, kilonewtons/meter^2
D -- Strength, meganewtons/meter^2
E -- Porosity

The high density of these materials is attained by sintering under pressure in dry ammonia atmosphere. It is recommended that these alloys be used for bearings of textile machines and household electrical appliances, that is, where liquid lubricant cannot be used.

In those cases when introduction of MoS_2 into materials is impeded, the metalloceramic articles are impregnated with a suspension. Here a suspension of MoS_2 and a volatile organic liquid is used. Bearings made of this material are used in automobile, tractor, and other sectors of industry. However, metalloceramic materials MoS2 are recommended for use in producing parts rotating at low speeds (parts of textile machines, bicycles, and so on) /53/.

With higher slipping speeds as well as with temperature rise, MoS_2 is oxidized to MoO_3. Molybdenum trioxide, like silicon, deteriorates antifriction properties of alloys. So use of antifriction alloys containing MoS_2 is limited by temperature conditions of molybdenym disulfide application.

MoS_2 is also introduced into friction compositions intended for aircraft brake shoes and other friction parts operating under severe conditions. The following compositions are recommended for these purposes:

1) 10% graphite, 15% MoS_2, balance Fe;
2) 5-15% graphite, 5-20% MoS_2, up to 10% MoS_2 /sic/, balance Fe;
3) 10% graphite, 15% $MoSi_2$, 5% MoS_2, 70% Fe, and so on /109/.

Friction material of the following composition exhibits the ability to function in the 243-433°K temperature range with a coefficient of friction of 0.23-0.30: 67% iron-nickel alloy (with 32-40% Ni); 10-30 parts by weight graphite, additives of copper, bismuth, zinc, mullite, or molybdenum disulfide /22/.

Other Methods of Obtaining Molybdenum Disulfide

To prevent microseizures in dry friction, formation of a solid solution between metals of rubbing surfaces must be impeded. This requires that the following physicochemical conditions be observed: metals in contact must not interact with each other; metals must have atomic radii differing by more than 7% (Hume-Rothery rule) /62/.

These requirements are satisfied by lead. It is a good antifriction material, has low modulus of elasticity, low hardness, readily conduct heat, exhibits good fluidity, and is readily wetted with metals.

Lead loses its positive properties with pressure rise, while, in contrast, MoS_2 can be used successfully at elevated temperatures and pressures. Based on this fact, authors of the study /62/ have proposed a new method of increasing wear resistance of friction parts -- deposition on one of the surfaces of a coating consisting of a Pb-MoS_2 film. This coating ensures necessary surface qualities in the zone of high pressures with good adhesion. Pb-MoS_2 film 5 microns thick are deposited on cemented and annealed specimens at temperatures below 303°K over a 45-minute period. For greater longevity of thin film, it is recommended that it be deposited on previously prepared surface of the friction assembly /243/.

For greater longevity of cast bearing alloys, it has been suggested that 0.1-0.55 percent MoS_2 be introduced into the molten metal during teeming after its complete deoxidation (the previously added MoS_2 powder undergoes heat treatment in dissociated ammonia at 1283-1393°K for 2 hours) in order to form on the surface of each powder particle a protective layer of metallic molybdenum due to dissociation of MoS_2.

Conclusion

Based on literature on use of molybdenum disulfide as a lubricant, the following conclusions can be drawn.

1. Physicochemical properties of MoS_2 allow its use as a lubricant in the 123-698°K temperature range in air. In vacuum the temperature range in air. In vacuum the temperature range is extended to 1373°K, and in inert gas atmospheres -- to 1813°K.

2. The structure of MoS_2 ensures its good adhesion with metal surfaces and high antifriction properties of friction pair contact schemes, slipping speeds, and pressures, as well as methods of introducing MoS_2, researchers have invariably arranged at the lowest coefficient of friction with total absence of seizure even for similar materials. Use of MoS_2 means higher bearing capacity of friction pairs, a rise in pressure, speed, and increased temperature of the ambient environment.

3. Antifriction properties of friction pairs in which molybdenum disulfide has been used are strongly affected by the following factors: purity of MoS_2 and powder particle size; thickness of lubricant layer; ambient medium and its temperature; slipping speed and pressure; material of friction pairs; condition of friction pair surfaces; and method of introducing lubricant onto rubbing surfaces.

Powders not less than 98.5 percent pure and with particle size of 0.5-75 microns ensure the best antifriction properties.

Good wear resistance values for friction pairs using MoS_2 necessitate that all the factors be given due consideration and that the optimal MoS_2 content be found based on specific operating conditions of the friction pair.

4. Molybdenum disulfide is used as dry powder as an additive to oils, jointly with plastics as a filler, and in metalloceramic compositions.

Use of MoS_2 as a powder and as an additive to oils does not ensure uniform and stable film thickness and leads to overconsumption of the expensive powder.

Use of MoS_2 in plastics is not effective enough. Higher preference must be given to coatings of plastics with MoS_2 as filler. However, employing MoS_2 in plastics reducing the limits of the working temperatures, whose values depend on properties of plastics.

5. The most promising method for superior wear resistance of friction assemblies must be deemed as the formation on the friction surface of layers with differentiated properties, containing molybdenum disulfide and exhibiting the predesired properties. This can be afforded by using powder metallurgy. They make it possible to formulate metalloceramic materials with required physicochemical and high antifriction properties. Use of this method means obtaining molybdenum disulfide both in the surface layers of material as well as in its structure.

6. The studies we have looked at represent an empirical choice of more rational friction pairs without investigation of processes occurring at rubbing surfaces. Therefore, metallographic, X-ray, and other physicochemical methods of research must be widely employed for profound analysis of the ongoing processes. Only if the problem is faced in this way, can all the advantages of molybdenum disulfide as a solid lubricant be rationally employed.

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13. ABSTRACT

Information is given ~~in this~~ brochure of the effect of the purity and size of powder particles, of the material and quality of machining of a friction pair, and operating conditions for a friction part (temperature and composition of the surrounding medium, sliding speed, pressure, etc.) on the properties of molybdenum disulfide as a lubricant. The means of introducing the lubricant into the friction zone are described and the regions where it is applied are indicated. The brochure is intended for technical-engineering and scientific workers, and students of vuzes. [AM9010848]

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