Technology of wear resistance increase of surface elements of friction couples using solid lubricants

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Abstract. Based on the results of experimental investigations in wear resistance increase using lamellar solid lubricants the technology of wear resistance increase of surface elements of friction couples by applying solid lubricants is developed with the following surface plastic deformation providing enough bond strength of solid lubricant with an element surface and increasing operational life.

1. Introduction
Films can be formed with submission of particles in the loaded contact rubbing in of particles in a surface or pressing of firm lubricant materials. Adhesion connected of a film produced by dispersion on a substrate of firm lubricant materials with addition organic or metal binding.

Savege has found out, that the film of graphite, drift on copper by a graphite brush, has the basic (base) crystal planes almost parallel a surface. Is shown, that this orientation makes 5...10° concerning a surface of a substrate in a direction of sliding. In the basic results are received for MoS₂. The more detailed research with the help x-ray diffraction films MoS₂, generated on copper, has shown, that they contain a monocrystal layer by thickness 2...5 microns with the basic planes parallel surfaces of sliding.

![Figure 1. Structure of a superficial film MoS₂.](image)

It is interesting, that this guided, layer settles down on unguided (not focused) (figure 1). The authors believe, that the high-energy connections of edges of crystals provide coupling a guided, layer with a surface and increase cohesive durability of a guided, film. The lubricant film by thickness 2.4 microns consists approximately of 300 separate layers S-Mo-S. With deterioration of a film the guided, layer approaches with a metal substrate. This rather thick (2 microns) the layer testifies that the process of sliding is accompanied by the advanced plastic deformation.
Film received rubbing, for the first time were studied Johnston and Moore [1]. The cylinder covered sated MoS₂ with a fabric, sated rubbing about a copper surface with a different roughness under various. After the first 100 passes the space near to rough nesses was filled by lubrication, that made a surface more smooth. With the subsequent passes the carry (MoS₂) was carried out already on MoS₂, and the thickness of a film continued to be increased even the after 7000 passes. However other researchers have shown, that there is a limiting thickness of a film, which depends on loading. Certainly, the rougher the surface is, the more material it is required for its covering. A completely different film were formed in a dry and damp atmosphere. In a normal atmosphere the more dense packing of particles was realized, that is caused by influence adsorbed of a moisture ensuring the best coupling of the basic planes MoS₂/MoS₂. Lancaster has shown, that on smooth surfaces fragments of a lubricant material by the size 10 microns were transferred on a film by thickness 0.05 microns. If the film formed rubbing of a surface, simultaneously is exposed frictional to influence, at the end it collapses as a result of wear process. Though solid lubricant the core wears out with rather large speed, but on a film is transferred of very poorly worn out material. Frequently meet difficulties of restoration of a film with the help of 'free particles; the degree of restoration depends, apparently, on character of distribution of pressure. Such impossibility to keep a film specifies that has a place superficial sliding, as shear can be realized only with strong adhesion in interphase area MoS₂/MoS₂.

Thus, at the first stage of functioning of firm lubrication on both surfaces the thin guided, film is formed. Then has a place sliding either between films, or between a substrate and film. The subsequent sliding results in gradual wear process of a film up to a complete exhaustion of a firm lubricant material, or to destruction of a film, that depends on atmospheric conditions and parameters of sliding. Fusaro in detail has studied wear process and destruction films MoS₂ and of fluorinated graphite. The deterioration is displayed as gradual reduction of thickness of a film caused radial and tangential by its replacement from the zone of contact. Last is caused normal and by frictional loadings.

The second kind of wear process is cracking and chipping of a film (similarly of weariness). It is interesting to note, that the same character of behavior is found out in soft materials with moderate deterioration (Ag/Fe). Deterioration of a film, in essence, same, as well as for volumetric materials. Moreover, is shown, as the intensity of wear process similar. Under these conditions more isotropic materials (metals, organic substances, the glasses) collapse by current, while MoS₂ and the layered materials tend to fatigue to destruction of a guided, external layer.

The process of wear process connected and untied films proceeds in two stages. The process described above, has a place until uncover of roughness of a substrate. In the further durability of a film depends on ability of a firm lubricant material in a vicinity of roughness to cover its top.

The destruction of a continuous film occurs for the different reasons. Conducting are two basic processes. First, the heat generated during sliding, softens a film and promotes its oxidation. Secondly, the interaction with an environment can change structure of a film. It, in particular, is fair for MoS₂, which oxidation in steam of water, on air or in environments of oxygen results to deformation of a film.

2. Formulation of the problem

Already in the first works on inorganic firm lubrication were mentioned layered screen structures serving with the basic criterion with selection of lubricant components. However soon it was revealed, that not structure in itself, and nature of connections is important. The materials with hexagonal «layered» by structure appeared effective, if the connection between layers were weak, and within the limits of a layer - rather strong. The materials of a type borazon, having strong interlayer of connection, are not effective as firm lubricant materials. So, Holinski and Gansheimer and other authors connect lubricant action MoS₂ to strong polarization of atom of sulfur giving an opportunity to generate layered structure. The graphite has not weak, border, if its layers are not covered with a lubrication moisture. The early researches PTFE connected its low friction to the minimal force of molecular interaction caused by shielding by a large ion of fluorine a charge on atoms of carbon. Thus,
the mechanism of lubricant action PTFE, in essence, same, as well as at MoS₂, behind that exception, that PTFE consists of the poorly connected among themselves circuits, instead of layers. There is, a formation on the initial stage of the transferred layer PTFE on counterspecimen rather, it is essential for efficiency of lubrication. Then actually there is a sliding PTFE on PTFE. With sliding PTFE (volumetric) on PTFE two modes of friction are observed: high friction with characteristic intensive carry and low friction with guided films of shift in interphone of area. Further will be shown, that MoS₂ and other firm lubricant materials (for example, Ag/Fe) behave similarly.

The approach based on representation weak interlayer of connection, was deeply advanced Jamison, come to a conclusion, that the efficiency of firm lubrication is caused by this weak connection. However MoS₂ has unique structure among layered lubricant materials, that makes it especially effective. In essence, the lubricant ability depends on distance between the basic crystal planes being function of electronic structure of metal. In MoS₂ the atoms of molybdenum settle down above and below «holes» in the nearest layer, but not above or under other atoms of molybdenum. Such specific structure connect with spin coupled electrons, that at the end causes absence residual interlayer of connections. Further is shown, that such type of a structure can be received by implantation of atoms copper and silver in layered structures with rather strong interlayer by connections of a type NbS₂ and NbSe₂. In such cases factor of friction decreases with 0.30 up to 0.10. The implantation in graphite chlorides and metals also raises it wear resistance and loading ability.

The researches in a little bit other direction have shown, that of a film MoS₂ received dispersion, have not by lubricant ability, if are used in amorphous a condition (418 K). Besides it is revealed, that of a lubricant film are effective with thickness 200 nm, that makes approximately 300 layers MoS₂. However if the dispersion was carried out with higher temperature (423 K), wear resistance was reduced even with constant factor of friction. This result connect to presence of a porous irregular film with the low contents of sulfur.

Fleischauer has carried out detailed research films, received by dispersion, and has found out, that they can have two versions: crystalline grains with base planes parallel a surface or perpendicular to it. The serviceability such films is various, and this distinction is caused by different chemical potentials of crystal planes and their edges. The weak connections and low chemical activity are characteristic of base planes, while the edges of planes form strong connections and actively oxidize. Thus, the lubricant ability is essentially connected to orientation of crystals.

3. The study of the structure of the modified lead-tin-base bronze

Bowden and Tabor for the first time have developed the theory of lubricant action thin films, being based on experiences with films India, lead and copper on substrates from steel, nickel, copper and lead [2]. Were used of a film of different thickness, and counter-specimen served steel indenters of different radius. They have found out, that the force of friction in all cases depends on width of a path of friction (contact platform). It, certainly, serves confirmation that, that

\[ F = AS_f, \]

where \( F \) - force of friction; \( A \) - area of contact; \( S_f \) - durability on shift of a material of a film. Varying such parameters, as thickness of a film, geometry of a sample, loading and hardness of a substrate, they achieved change of the area of contact and accordingly force of friction. Their concept of lubricant action thin films was retied that

\[ f = \frac{S}{P} = \frac{S_f}{P/H_s}, \]

where \( f \) - factor of friction; \( P \) - pressure; \( H_s \) - hardness of a substrate. In other words, the area of contact depends on hardness of a substrate, while the durability of a film on shift determines specific
force of friction $S$. Friction of a metal film was much lower, than volumetric sample, as for last

$$f = \frac{S_f}{H_f},$$

(3)

where $H_f$ - hardness of a material of a film.

For example [2], with friction of spheres ($r = 8$ and $3$ mm) on leaden films (thickness 1... 12 microns) on a steel substrate the area of contact first of all are defined by elastic deformation of steel. Thus,

$$f = \frac{S_f}{P} = \frac{\alpha S_f}{L} = \pi \left( \frac{3LR}{4E} \right)^{2/3} \frac{S_f}{L},$$

(4)

where $\alpha$ - area; $L$ - loading; $R$ - radius of a sphere; $E$ - module of elasticity. The plastic deformation of a film begins to influence the area of contact, when radius of contact is less, than five-multiple thickness of a film. Thus, the area of contact can depend both from elastic, and on plastic deformations.

The experiences of Bridgeman and other researchers have shown, that the durability grows by shift with increase of pressure. Therefore equation (4) should be modified, by replacing $S_f$, on $S_p$.

$$S_p = S_f + \alpha P,$$

(5)

Where $S_p$ - durability on shift of a material of a film with the given pressure $P$; $\alpha$ - constant. The equation (4) will look like

$$f = \frac{\pi \left( \frac{3LR}{4E} \right)^{2/3} S_p}{L} = \pi \left( \frac{3LR}{4E} \right)^{2/3} \frac{S_p + \alpha P}{L},$$

(6)

With plastic deformation of a film

$$f = \frac{L}{H_f} \cdot \frac{S_p}{L} = \frac{S_f}{H_f} + \alpha,$$

(7)

here $P$ is equal to hardness of a film.

However usually deal with surfaces, flat initially or generated during wear process of curvilinear indenter, thus the area of real contact can be defined by a film [see equation (7)] or geometrical area of contact. Then factor of friction becomes function of loading (or pressure) (figure 2), and, as shown numerous researches, frictional the behavior is best described by the equation

$$f = \frac{S_p}{P} + \alpha,$$

(8)
Figure 2. Dependence of factor of friction $f$ of firm lubricant materials on pressure $p$: I - zone of sliding; II - zone of shear.

From the equation (8) follows, that factor of friction decreases with growth of pressure, $S$ and $\alpha$ remain constant. If the material is used as a film, in accounts are accepted its durability on shift and parameter $a$. In quality $S$ the durability on shift of a film $S_f$ or interphase of area $S_i$ can be accepted, if in the latter case has a place sliding. The pressure $P$ also accepts different meanings: with low loadings $P$ the equation (7) can be equalled of hardness of a film $S_f$. In this case surface of contact ($A_r$) is discrete and is limited to tops of roughnesses. Thus, the friction should be same, as well as with sliding the friend on the friend of volumetric samples of a lubricant material. With very thin films elastic or plastic deformation of a substrate the influence on the area of contact up to limiting meaning $P = H_s$ can render. In this case friction should be much lower, as shown in a figure 3.

With growth of loading the area of contact is increased, and the friction remains constant up to some critical pressure $P = P^*$. Above than this pressure $A_r = A_a$ (nominal area of contact) and $P = L/A_a$. Then the friction is reduced, while (with rather high pressure) will not reach size $f = a$. Thus, for flat surfaces it is possible to use three equations:

$$f = \frac{S_f}{H_L} + \alpha_f \text{ at } P < P^* \text{ and } A_r \approx L,$$

(9a)

where $H_L$ - hardness of a lubricant material.

$$f = \frac{S_f}{H_L} + \alpha_f \text{ at } P < P^* \text{ and } A_r \approx L,$$

(9b)

(for thin films) and

$$f = \frac{S_f}{P} + \alpha_f \text{ at } P > P^* \text{ and } A_r = A_a,$$

(9c)

($A_a$ - constant determined by geometry of system).

4. Conclusion
So, it is possible to assume, that there are two modes of friction of firm lubricant materials; a mode of sliding with low pressure and shift mode with high. In the latter case, the mechanism of viscous or plastic current is realized. Factor of friction is directly proportional to the area of contact. This area is defined by the nominal area for flat samples or elastic deformation for curvilinear of contact. In a mode of sliding the area of contact is defined or hardness of a lubricant film, or (for very thin films)
hardness of a substrate. The mechanisms of sliding are described by models 3, 4 or 5 (see tab. 1). And as durability on shift $S_f$ it is necessary to use adhesional durability $S_i$. If the above mentioned reasons are applied to real materials, for silver, MoS$_2$, lead and model viscous material (200 N/m$^2$ s) it is possible to receive curves shown in a figure 3. The appropriate data on hardness and durability on shift are taken from several sources. The meanings of parameter and are received from work of Bridgeman.

These curves are based on simple reasons and do not apply for severity. However they illustrate the tendency in behavior of firm film lubricant materials. Let's notice, that with small loading the friction should be very high, if has a place pure shift or current

![Figure 3](image-url). Dependence of factor of friction $f$ on pressure $p$: 1 - Ag; 2 - MoS$_2$; 3 - Pb; 4 - model material by viscosity 2000 poise (200 Pa×s).

Obviously, in this case will occur grip or transition to other type of sliding. Usually has a place transition to slipping or essential reduction of the area of contact caused by decrease of normal pressure owing to deformation of a material.

Numerous literary given for films MoS$_2$ (experiments in conditions of a dry atmosphere) it is enough precisely approximate by the equations (9a) and (9b). Factor of friction makes 0.04 down to pressure $\sim$ 560 MN/m$^2$. Then it begins to decrease. It is interesting to note, that for guided films MoS$_2$ the hardness makes 600 MN/m$^2$, so for MoS$_2$ $P^* = H_f$ (hardness of a film). Both Barry and Binkelman, and Reed and Shaw it is revealed, that with small pressure the friction, does not depend on hardness of a substrate. Thus, the equation (9b) is not applied. All experiments with small pressure are carried out for the different nominal areas, so the friction does not depend and on the nominal area of contact. It serves confirmation that, that the hardness of a film determines the actual area of contact. Last circumstance predetermines subsequent tribological behavior.

The film MoS$_2$ is not ideally smooth. With small loading of roughness of a film perceive this loading and, being deformed, form the actual area of contact. The effort of shear individual spot also makes measurable force of friction. With growth of loading the actual area of contact is proportionally increased. Thus, factor of friction remains constant. At the end, when the pressure becomes equal to hardness films MoS$_2$, the contact is entered by the whole area of a contact. Then the friction begins to decrease, as now and $A_r$ and $S_f$ constant:

$$f = \frac{A_r S_f}{L} + \alpha$$

where $\frac{A}{L} \approx \frac{1}{H}$ and $A_r = A_o$ at $P^* = H$. 


If the pressure exceeds $P^*$, the friction decreases up to size equal $a$, owing to $ArSfL^{-1} \to 0$. When the durability on shift is not increased with growth of pressure, and should be equalled to zero and factor of friction will aspire to zero. Thus, low factor of friction MoS$_2$ is caused by high hardness of a guided film.

For very soft backs the friction can grow, as shown in a figure 4 (on the data Barry and Binkelman). If the hardness of a substrate is less, than the hardness MoS$_2$, friction grows, probably, because of deformation of a substrate. The thicker film, the effect will be less significant.

![Figure 4](image_url)

**Figure 4.** Influence of hardness of a substrate on factor of friction MoS$_2$ ("+" — Spherical particles MoS$_2$) 1 - lead; 2 - babbit; 3 - silver; 4 - copper; 5 - silver plate; 6 - brass; 7 - aluminium; 8 - bronze; 9 - steel 1020; 10 - molybdenum; 11 - titanium; 12 - TZM; 13 - tungsten; 14 - rigid steel.

![Figure 5](image_url)

**Figure 5.** Friction MoS$_2$ in a wide range of pressure: 1 - film; 2 - film; 3 - film; 4 - balls; 5 - film; 6 - film; 7 - film; 8 - balls; 9 - balls; 10 - film; 11 - Film; 12 - balls; 13 - balls.

From the data submitted in a figure 5, follows, that factor of spherical particles MoS$_2$ sliding on metal. Such behavior is clear in light of the data of a figure 4. The volumetric hardness of particles MoS$_2$ makes, as show measurements, 180 MN/m$^2$. If to accept this size as hardness of a substrate, the meaning of factor of friction 0.08 is possible to consider quite acceptable.

For very firm backs (more than 8 GN/m$^2$) was not observed of essential reduction of friction, though a brass and bronze give lower, and titanium the higher debate, than predicts dependence submitted in a figure 4. With pressure exceeding 560 MN/m$^2$, continuous film MoS$_2$ shearing. Factor of friction is directly proportional to the area of contact with the given loading. The contact is defined by the nominal area of a sample or elastic deformation of the concentrated contact. For softer backs there can also be their plastic deformation, which increases factor of friction a little. However, when $f$ comes nearer to $\alpha = 0.02$, the influence of pressure becomes insignificant.
The small meaning of factor of friction (0.02) with high pressure (2.8 GN/m²) is fixed Peterson and Johnsoiri for very thin films, roughnesses, generated at tops, of a substrate. In this case pressure is equal to hardness of a substrate and the actual area of contact is small. For continuous films other meanings turn out. Thus, in a mode of shear of adhesional connections the friction first of all is defined by pressure; for the given pressure it remains constant.

The data for films of tin are submitted in a figure 6. There is a satisfactory conformity between the equations (9a) and (9b) and experimental results. With small pressure factor of friction equal turns out 0.40. This size is close to received Rabinowich with friction of a volumetric sample of tin on steel (0.29...0.51).

The data for lead are submitted in a figure 7. Though as a whole the described above tendency is appreciable, but there are some distinctions, especially with small pressure. Factor of friction lays in a range 0.40...0.70, instead of is equal, as was predicted, 0.20. However it nevertheless is lower, than meaning 1.30, received in experiences Tsus with sliding lead on steel. This fact becomes clear if to proceed from of the adhesional theory of friction. The strong coupling of lead with steel results in increase of the area of contact for the account of tangential effort. The same behavior observed Kato, working with thick films. Also has noticed, that of a thicker film give higher factor of friction close to friction of a volumetric sample of lead.
As the growth of adhesional connections is not characteristic of tin and MoS₂, they frictional behavior can be predicted. It, probably, is caused low adhesion (Sn/Fe and MoS₂/MoS₂) or that the deformation of these materials does not conduct to growth of friction. Some researchers have fixed high friction (0.30) with sliding MoS₂ on films MoS₂ in a damp atmosphere [5]. Thus the carry of large fragments was observed, that connect to increase adhesion MoS₂/MoS₂. Other examples of such influence adhesion are known also. The silver behaves similarly to tin or MoS₂, when is used as a film for lubrication steel or nickel, but with friction on an aluminium surface its behavior is similar to behavior of lead. For the same reason inefficient lubricant materials are of an aluminium film.

5. Acknowledgments
The analysis of dependences of friction from pressure for solid lubricant films allows better to understand them frictional behavior. The assembled data enable to offer the simple theory agreed to the numerous literary data. According to this theory friction and deterioration solid lubricant films are simple adaptation of their behavior in the volumetric form. Such adaptation is limited to growth of connections, which can take place for thin films.

Certainly, this concept is speculative and is based on the limited data received under different conditions. These results should be reproduced on one equipment in a wide range of loadings with the control and measurement of the actual area of contact. The measurement of micro hardness of surfaces is necessary for carrying out after sliding for definition of hardness thin films. The concept of growth of connections is not suitable for a number deforming of processes, for example, with reference to contact of materials with hexagonal and cubic structures.

It is offered five different models solid lubricant films. The extensive review of the literature with the purpose is carried out to determine, what from models will be coordinated with the basic knowledge about tribological behavior of firm lubricant materials. The behavior films with the account adhesion of a substrate, features of formation films, their deterioration and destruction, crystal structure, influence of the atmospheric factors and of frictional the characteristics is discussed. On the basis of the limited data the conclusion about applicability standard of the adhesional theory of friction to thin films is made. It is offered to distinguish two modes of friction: of sliding with small loadings and shear with large. The transition from one mode to other occurs, when the pressure becomes approximately equal to hardness of a film. In a mode of sliding the actual area of contact is caused nominal, which depends on elastic deformation of a material of a substrate. Exhalation and oxides of a surface change frictional behavior solid lubricant films.

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