Chevrel phase-based solid lubrication coating for wear resistant electrocontact friction pairs in vacuum

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Abstract. The work comparatively studies the wear kinetics of copper friction pairs with Chevrel phase-based coating (Cu-Mo-S) and without it in vacuum of 1.5x10\(^{-3}\) Pa. The coating is deposited on test pads by the ion-plasma method. The tribological investigations scheme were used the “disk – coated pad”. The detected falling of the wear rate of the friction pair with the coating is explained by the change of the adhesive wear mechanism to fatigue one.

The solution of the problem concerning the low life of rotating contact devices in space vehicles operated in open space requires electroconductive tribological materials capable of working in vacuum. Known solid lubrication materials based on dichalcogenides of transition metals MC\(_2\) (where M is a transition metal, C is a chalcogen), widely used in friction pairs operated in vacuum, cannot be used because they lack sufficiently high electric conductivity. However, such materials have expressed quasi-two-dimensional crystal lattice, which is due to the presence of so-called van der Waals gap between tree-layer structural blocks, where atoms of other elements can be intercalated into [1, 2]. The physical properties of the compounds produced by intercalation considerably differ from those of the initial constituents of MC\(_2\). For instance, molybdenum dichalcogenides after intercalation by copper may possess superconducting properties, while preserving quite high tribological characteristics [3]. Therefore, one of the approaches to the solution of the aforementioned problem [4–6] proposes similar solid lubricants. They can be applied by the ion-plasma method on the components of friction pairs from pure copper or silver as thin films based on a Cu-Mo-S or Ag-Mo-S systems (Chevrel phases) [7–10]. We have studied such coatings in terms of operation of friction pairs in an inert gas [11]. However, their operation in vacuum still remains understudied.

The present work studies the effect of such coatings on the tribological characteristics of a pair “copper pad-counter body represented by a disk from pure copper (M1 as per GOST 859-2014(Ru))” subjected to wear in vacuum. The method and regimes of deposition of tribological films, the dimensions and shape of the specimens, parameters of mechanical testing of the specimens are described in [6, 11]. The tribotester was placed in the vacuum chamber that at high pressures was evacuated by a dry scroll pump, and at low pressures by a cryogenic pump. These procedures ensured dry vacuum in the chamber which is critical for tribological testing. The residual air pressure in the vacuum chamber during the wear testing of the experimental specimens was no more than 1.5x10\(^{-3}\) Pa. The temperature of the specimens and the testing machine was maintained below 50 °C using a cooling circuit with running water.
Figure 1 depicts the plots of copper friction pair wear without the coating on the test pad (1) and with the Cu-Mo-S-based coating (2). The decrease of the friction pair mass $\Delta m$, was calculated as the sum of the changes in the mass of the test pad $\Delta m_s$ and the mass of the counterbody $\Delta m_c$. Each point $\Delta m$ on the curves is an average of no less than three values of $\Delta m_i (i \geq 3)$. The approximation of the experimental plots $\Delta m = f(\Delta t)$ is linear. The average friction pair wear rate in vacuum can be estimated by the slope of the trend line:

$$\frac{\Delta m_1}{\Delta t} \approx 6.71 \times 10^{-4} \text{ mg/s},$$

$$\frac{\Delta m_2}{\Delta t} \approx 2.56 \times 10^{-6} \text{ mg/s},$$

where $\Delta m_1$ and $\Delta m_2$ are the values of average mass decrease for the friction pairs without the coating (1) and with the Cu-Mo-S-based coating (2), correspondingly, during wearing over time $\Delta t$. Evidently, in vacuum, the average wear rate of the friction pair “uncoated copper pad-copper counterbody” is ~260 times lower than that of uncoated friction pairs.

![Graph 1](image1.png)

![Graph 2](image2.png)

**Figure 1.** Wear curve of the copper friction pairs in vacuum of $1 \times 10^{-3}$ Pa without coating on the pad (1) and with Cu$_x$Mo$_y$S$_z$ coating (2).

The wear of the friction pairs under study manufactured from technically pure M1 copper in oil-free vacuum proceeds according to the adhesive wear mechanism (figure 2a and 2b). The process is nonuniform. After some time after the process begins, small sparse spikes occur on the kinetic curve of the friction momentum. Then, with increased wear time, their number and amplitude increases, which testifies to the formation and destruction of the welding links on the contacting surfaces of the specimen and counterbody. After the deforming stress reaches the yield value, the welding links break and form microparticles of copper with a size of less than ~0.2 mm that detach from the contacting surface layers and abundantly amass under the friction pair.

The wear of the friction pair with the specimen coated by Cu-Mo-S-based coating (Chevrel phase) is different. It proceeds as per the fatigue wear mechanism with boundary lubrication, i.e. fluently and without spikes. Over the first several hours of wear during grinding (figure 2c and 2d), a thin layer of the coating is transferred to the counterbody’s surface as longitudinal bands of the solid lubricant. Then, the established wear stage proceeds. During this process, the working surface of the counterbody’s surface suffers the formation of local zones with alternating chemical composition (figure 2d) composed of pure copper and heavily fragmented nanoparticles fibers of Cu-Mo-S-coating material [11]. The film formed on the surface of the counterbody is not visually visible, since it is very thin. This was confirmed by a study of the concentration profiles of elements by the method of mass spectroscopy of the second ions in the surface layer of the counterbody after it wears out together with
the coated sample. The thickness of solid lubricating films formed in different places on the surface of the counterbody with different wear times ranges from 3 nm to 10 nm (figures 3a and 3b). The concentration of elements in the surface layer was measured with an MS-7201M instrument (OOO SELMI, Ukraine) by layer-by-layer etching with an argon ion beam with a cross-sectional diameter of ~ 3 mm.

This stage is characterized by low wear rate and is controlled by structure, composition and properties of the boundary solid lubrication layer. The development of this process leads to the accumulation of fatigue stresses in the boundary layer of the specimen and counterbody as a result of plastic deformation and dynamic mixing of the dispersed Chevrel phase based on Cu-Mo-S system [9] and pure copper.

Figure 2. Photographs of working surfaces of the specimen without coating (a) and counterbody (b) having worked in one friction pair over 2 hours, and specimen with Cu-Mo-S coating (c) and counterbody (d) having worked in one pair over 110 hours in vacuum.

Figure 3. Concentration profiles of Cu, Mo, S elements over the thickness of a copper counterbody, paired with a sample with a coating based on Cu-Mo-S after wear for 25 hours (a) and 72 hours (b) in vacuum.
This heterogeneous layer, on the one hand, is a good solid lubricant that prevents adhesive seizure of the contacting surfaces of the specimen and counterbody, and on the other hand, localizes a part of the shear deformation during wear. Another part of shear deformation, due to interaction of micro-bumps on the contact surface, generates cracks and defects in the crystal lattice in the surface layers of the counterbody and specimen under the solid lubrication coating. As a result of multiple formation and merger of structural defects, the solidity of the material becomes compromised accompanied with liberation and evacuation of its isolated microparticles. Together with the separating copper particles, small portions of solid lubrication coating material are gradually evacuated from the contact zone of the friction surfaces. In this connection, after depletion of the boundary layer of the solid lubrication material, the fatigue wear mechanism will shift to adhesive wear mechanism, which should increase the wear rate [6, 11].

Thus, ion-plasma deposition of a thin Chevrel phase-based coating on the surface of a copper pad operating in vacuum of 1.5x10⁻³ Pa with a counterbody represented by a copper disk more than 260 times reduces the average wear rate of such a pair. High reduction of the wear rate of the copper friction pair in vacuum is due to the shift of the adhesive wear mechanism to fatigue one. The reason for the change in the controlling mechanism is the formation of the boundary film of solid lubricant as a nanocomposite including the mixture of copper nanocrystallites and nanoparticles of deformed fibers of Chevrel phase based on Cu-Mo-S system [9]. The thickness of solid lubricating films formed in different places on the surface of the counterbody with different wear times ranges from 3 nm to 10 nm. After depletion of the boundary layer of the solid lubrication material, the fatigue wear mechanism will shift to adhesive wear mechanism, which should increase the wear rate.

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References
[1] Hibma T 1982 Intercalation Chemistry. Structural Aspects of Monovalent Cation Intercalates of Layered Dichalcogenides / T Hibma; eds. M S Wittingham and A J Jacobsen (London: Acad. Press) 313
[2] Balaž P, Balaž M, Achimovicová M et al. 2017 J. Mater. Sci. 52 11851–90
[3] Foner S et al. (eds.) 1981 Superconductor Materials Science: Metallurgy, Fabrication, and Applications (New York: Plenum Press) 431
[4] Hudec Tomáš, Mikula Marián, Satrapskýy Leonid et al. 2019 Appl. Surf. Sci. 486 1–14
[5] Ming Cao, Lan Zhao, Libin Wu et al. 2018 Coatings 8 134–41
[6] Sergeev V P, Zharkov S Yu, Kalashnikov M P et al. 2015 AIP Conf. Proc. 1683 020203-1-4
[7] Fischer O et al. 1978 J. Appl. Phys. 16 1–28
[8] Peña O 2015 Physica C. 514 95–112
[9] Lemée N, Guilloux-Viry M, Perrin A et al. 1998 Eur. Phys. J. – Appl. Phys. 1 197–201
[10] Seong-Ju Hwang, Valeri Petkov, K Kasthuri Rangan et al. 2002 J. Phys. Chem. B 106 12453-8
[11] Zharkov S Y, Sergeev V P, Kalashnikov M P et al. 2019 J. Phys. Conf. Ser. 1281 012096-1-5