Anomalously low friction of an electron bombarded surface of molybdenum disulfide

E. A. Dukovskoĭ, A. N. Ponomarev, A. A. Silin, and V. L. Tal'roze

Institute of Chemical Physics, USSR Academy of Sciences

(Submitted April 27, 1974; resubmitted July 15, 1974)
Zh ETF Pis. Red. **20**, 268–272 (August 20, 1974)

We present experimental data on the production of anomalously low friction by electron bombardment of a molybdenum-disulfide surface. It is indicated that the effect and its mechanism are identical when the molybdenum disulfide is bombarded by electrons and by accelerated helium atoms.

The authors have previously observed that when surfaces of polyethylene, molybdenum disulfide, and graphite are bombarded by a beam of helium atoms of energy 2 keV their friction becomes anomalously low.[1,2] We have attempted to realize this phenomenon by bombarding an MoS_2 surface in vacuum by a 2-keV electron beam. The experimental setup is shown in Fig. 1. It consists of a steel vacuum chamber in which is placed a friction unit consisting of an immobile spherical indentor of ShKh-15 steel and a disk of the tested material, which rotates in a metallic frame. The load and the friction force were measured with strain gauges by a standard scheme.[3] The disk was rotated in vacuum by a magnetic clutch. The experiments were performed at a friction-unit temperature 20 °C, at a load ranging from 50 to 150 g on an indentor of 0.5 cm diam, and at a slip speed 20 cm/sec. The investigated disks were prepared of M-801 material produced by the following technology: an annular disk of metallic molybdenum, 5 mm thick with outside diameter 55 mm and inside diameter 50 mm, was exposed to sulfur vapor at 600 °C, as a result of which a molybdenum-disulfide layer up to 10 μ thick was produced on the surface of the metal. We chose this technology for the purpose of obtaining sufficiently pure molybdenum disulfide on the surface.

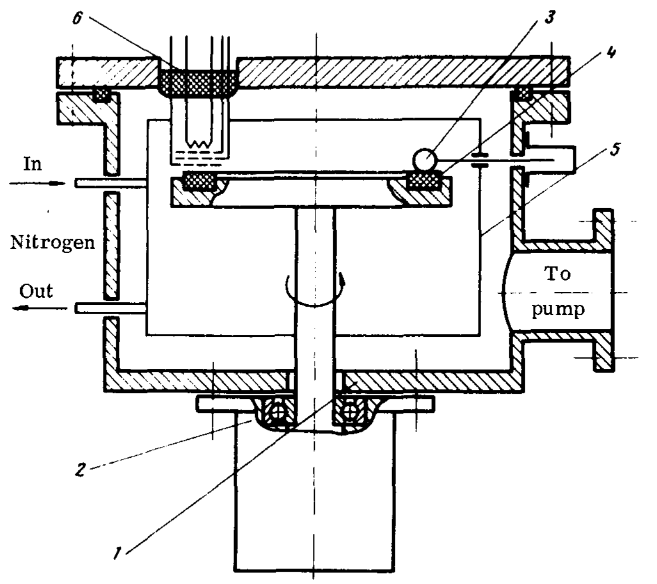

FIG. 1. Experimental setup: 1 – vacuum chamber, 2 – magnetic clutch, 3 – indentor with measuring apparatus, 4 – tested specimen, 5 – nitrogen screen, 6 – electron gun.

The friction unit was surrounded by a copper screen cooled with liquid nitrogen.

An electron gun consisting of a heated cathode, a drawing grid, an accelerating grid, and a secondary-electron collector produced a beam of 10 mm diameter, 2 keV energy, and current up to 1 mA. The beam was applied to a disk-surface section positioned 180° away from the indentor along the friction track. The depth of penetration of the electrons into the material was estimated from the formula[4]

$$h = 250\,(M/\rho)\,(E/Z^{1/2})^n, \qquad (1)$$

where M is the molecular weight of the bombarded material, ρ is the density, E is the electron energy in keV, Z is the atomic number of the element, and

$$n = \frac{1.2}{1 - 0.29\lg Z} \qquad (2)$$

For compounds, particularly MoS_2, Z and M in formula (1) are replaced respectively by the sums of the atomic numbers and atomic weights of the individual elements.

The range of 2-keV electrons in molybdenum disulfide, estimated from this formula, is approximately 2000 Å. The dose intensity averaged the thickness of the bombarded layer can be estimated from the equation

$$I = \frac{1000\,i\,E}{h\,\rho}\ \text{(W/g)}, \qquad (3)$$

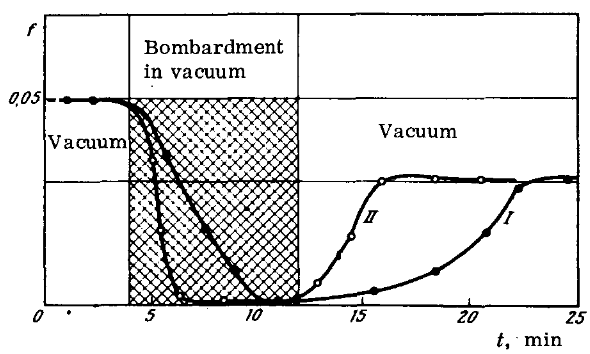

FIG. 2. Change of friction coefficient following bombardment of molybdenum disulfide friction surface by electrons (1) and by fast helium atoms (2).

where E is the energy of the electron beam in keV, I is the current density in A/cm^2, h is the depth of penetration in cm, and ρ is the density in g/cm^3.

Inasmuch as only a fraction of the surface of the rotating disk is bombarded during the rotation, the time-averaged dose intensity is $I' = I(d/\pi D)$, where d is the diameter of the electron beam and D is the diameter of the friction track.

In the friction experiments, we measured the temperature of the indentor by means of a thermocouple, one of the junctions of which was placed inside of the indentor 0.3 mm away from the friction surface. In ordinary friction we observed slight heating of the indentor, within 5 °C. When anomalously low friction set in, this heat rise disappeared completely. At an average electron-beam power on the order of 1 W/cm^2, at the typical thermal conductivity of the metallic disk, and at a very small thickness of the molybdenum disulfide layer (10^{-3} cm), the heat rise of the surface due to the bombardment was quite negligible even in the case of rather low thermal conductivity of the molybdenum disulfide ($\lambda \geq 3\times10^{-4}$ cal/cm-deg C[5]), and did not exceed 1 °C.

The experiment consisted of the following: The tested disks were wiped with alcohol and placed in the chamber, which was evacuated to 5×10^{-7} Torr. The copper screen was cooled with liquid nitrogen to approximately 80 °K. The motor was then turned on, a load was applied to the indentor, and the indentor was allowed to wear into the rotating disk until a stable friction coefficient was established. The electron gun was then turned on and the surface of the rotating disc was bombarded by the electron beam. The friction coefficient was then registered as a function of the current and of the bombardment time. The results of one of the typical experiments are shown in Fig. 2. At an indentor load 100 g, after the bearing surfaces have been "broken in", the stable friction coefficient in vacuum range from 0.04 to 0.05. When the electron then was turn on (gun current 500 μA, beam cross section diameter 1 cm, energy 2 keV, corresponding to a dose intensity 5×10^4 W/g or 5×10^9 rad/sec), the friction coefficient dropped to an anomalously low value, below the 0.002 sensitivity limit of the apparatus. When the electron beam was turned off, the friction coefficient increased slowly (within a time 10–15 min, and even more slowly in individual experiments), to a value 0.03. When atmospheric pressure was restored in the chamber after obtaining the anomalously low friction effect, the friction coefficient jumped almost instantaneously to values 0.05–0.06.

For comparison, Fig. 2 shows one of the plots of the friction coefficient against time, obtained earlier by bombarding the friction surface of molybdenum disulfide with a beam of helium atoms at approximately the same dose intensity as in the case of the electron beam.

The similarity in the character of the anomalously low friction following bombardment with electrons and with fast atoms indicates that the effect is universal.

The mechanism whereby the extremely low friction is produced is not quite fully understood (partly because the detailed microscopic mechanism of external friction is still not clear for real solids in general). However, our recent electron-diffraction investigations of the MoS_2 surface after the attainment of ultralow friction points to a strong orientation of the MoS_2 crystals, and mass-spectral observations of the partial pressure of water in the course of the described bombardment has shown that the latter leads to a removal of the hydroxyl-containing groups from the surface. On the whole, this is evidence that, at any rate, the adhesion component of the interaction, which causes the external friction, can become greatly weakened by a surface treatment that leads to ultralow friction.

[1] E. A. Dukhovskoĭ, V. S. Onishchenko, A. N. Ponomarev, A. A. Silin, and V. L. Tal'roze, Dokl. Akad. Nauk **189**, 1211 (1969) [Sov. Phys.-Dokl.-Dokl. **14**, 1218 (1970)].
[2] E. A. Dukhovskoĭ, A. N. Ponomarev, A. A. Silin, and V. L. Tal'roze, *ibid.* **200**, 75 (1971) [**16**, 757 (1971)].
[3] N. P. Paevskiĭ, Metody ėksperimental'nogo issledovaniya mekhanicheskikh parametrov mashin (Methods of Experimental Investigation of Mechanical Parameters of Machines), AN SSSR (1952).
[4] Ch. Feldman, Phys. Rev. **117**, 455 (1960).
[5] V. E. Vaĭnshteĭn and G. I. Troyanovskaya, Sukhie smazki i samosmazyvayushchiesya materialy (Dry Lubricants and Self-Lubricating Materials), Mashinostroeniye (1968).