Evaluation of the effectiveness of using solid lubricants to reduce the wear of the brushes of electric AC machines

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Abstract. The article aims to study the influence of the major solid lubricant powder materials on the wear of electric brushes of universal LNA grinders in the process of rotaprint lubrication of the brush sliding path. The lubricating effect of substances was evaluated by the loss of mass and height of the brush products. Based on the results, the authors have defined the two most effective powder lubricants - epimol and molybdenum disulfide. The authors have studied how these lubricants influence the switching quality. They have come the conclusion that a lubricating film of the two most effective lubricants does not cause to a deterioration in the performance of the electrical machines. The use of rotaprint deposition of epimol and molybdenum disulfide on the slip track reduces the wear effect of the G-33MI brushes by more than 3 times.

1. Introduction
Numerous negative phenomena can occur during the operation of electric machines, often caused by environmental conditions. It leads to a change in the friction conditions in the brush – collector contact pair (brush – collector ring) and the character of the current distribution over the brushes operating in parallel can also change. Also, a frequent negative process in the practice of operating brushing machines is the mechanical-electrical erosion of the metal of the collector ring, which leads to their rejection due to excess wear on their surfaces compared to permissible deviations [1,2,3].

The presence of improper lubrication conditions on the contact path of an electric machine can lead to increased wear of the brushes, which is especially noticeable during the operation of high-power electric machines, where the replacement and prevention of brush pairs is time and cost-consuming. Improving the friction conditions in the slip collector assembly due to liquid lubricants is ineffective due to their strong dielectric barrier and viscosity increase due to solvent evaporation [4,5]. The use of powder lubrication by dusting is also often unacceptable due to their possible blowing.

2. Statement of the problem
The solution to the problem of reducing the wear rate and the implementation of trouble-free operation of critical friction units is possible on the basis of self-lubricating solid materials. Obviously, under these conditions, changes in the friction conditions during contact interaction are possible on the basis of rotational lubrication, which allows to create an ever-renewing layer of solid lubricant.

Thus, the principle of operation of solid lubricating particles in dry friction is to ensure the continuous formation of a lubricating film on the surface of the counterbody, which prevents the
brush-metal from adhering adhesively and thereby reduces the wear rate of the tribocontact participants.

The use of solid lubricants does not require frequent periodic introduction of lubricant and occurs due to the constant replenishment of the lubricant due to the adjustable clamping force.

At the same time, one of the problems in ensuring the efficient operation of the brush-collector assembly (sliding current collector assembly) is the passage of electric current in the contact, since the nature and thickness of the lubricating layer formed on the sliding surface will have a significant influence on the current flow. In the case of using solid lubricants, a film of complex phase composition will be formed on the slip track, which, in addition to the traditional polythene film, will have inclusions of solid lubricant fragments. In this case, due to the temperature factor from switching processes and mechanical friction, various solid-state reactions can occur in the conjugation zone, the products of which can be either solid or gaseous substances.

2.1. Theory

There is a large number of substances that can be used as solid lubricants [6,7,8]. However, there are still no clear and justified ideas about the nature of their influence on sliding friction. The crystalline structure of lubricants does not entirely determine their lubricity. In this case, an important characteristic of a lubricant is its ability to increase adhesion on a metal surface, which allows it to remain and hold on the interface for a relatively long time.

There is a wide variety of substances with a pronounced lubricity, which allows to have a relatively low coefficient of friction slip in the friction zone. So, there is a group of substances of a layered type, they have mostly a lattice of a hexagonal structural type. These are molybdenum and tungsten disulfides, tungsten and molybdenum selenides. Here layers of molybdenum or tungsten atoms are located between two layers of sulfur and selenium. They are compounds in which the relative bond strength between atoms is sharply different in different directions [9].

In general, for lubricants there is a dependence of their sliding friction coefficient on temperature, and a change in its value can occur due to decomposition or chemical transformation of their substances into oxides [10]. So, molybdenum disulfide is gradually converted into oxide if the contact temperature is above 350 °C, and the friction coefficient can increase by more than 20 times [11,12].

In the hexagonal lattice, boron nitride crystallizes in the lubricant, and this lattice is similar to the graphite lattice, in which one atom is replaced by boron and the other by nitrogen. Hexagonal boron nitride has a high temperature oxidative stability, reaching 7000°C, and enhanced oxidation begins only at 10000°C.

Calcium and barium difluorides are also solid lubricants. Their positive effect on the structure of the metal during its cutting by milling cutters allows to significantly reduce the heating temperature of interacting metals. These substances have high temperature resistance exceeding the heat resistance of layered greases by 200-3000°C.

In general, it should be noted that the information on the temperature dependence of the friction coefficient of base solid lubricants (such as hexagonal boron nitride, calcium fluoride, barium fluoride, diselenide and tungsten disulfide) is rather abrupt and contradictory and are determined by attempts to solve specific tribological problems [13,14,15].

In addition, there is a relationship between the lubricity of powder lubricants and the average size of their grinding fineness. Obviously, the finer the grinding fineness is, the better the lubricity of the powder is. At the same time, too fine grinding fineness reduces the oxidative stability of the powder lubricant due to its increase in oxidative reactivity. Therefore, under conditions of the realization of high temperatures at the sliding boundary due to arcing and mechanical friction, too small particle size of the powder can play a negative role, since its chemical properties can rapidly change [16,17].

Also, the optimum particle size of the powder lubricant from the point of thermal stability will be determined by the nature of the substance. An important characteristic of the solid lubricant composite is the heat resistance of the binder. Temperatures above 400 °C lead to decomposition of the skeleton structure of organic polymer bonds, and subsequent influence on the tribological situation on the slip
track. It should be noted, however, that such a process may not occur under instantaneous short-term temperatures and is possible only under conditions of strong sparking between the participants in the contact of the slip collector assembly.

The effectiveness of powder lubricants is also associated with certain qualitative characteristics: fine grinding, brand, manufacturer. It is obvious that not all solid lubricants can withstand harsh operating conditions both in temperature and in spark formation. Therefore, the modernization of widely used powder solid lubricants by chemical treatment, for example, with halogens, can be of considerable scientific and practical interest. In particular, it is known that it is possible to improve the lubricity and temperature resistance of imported molybdenum disulfides based on their fluorination to obtain the marketed product “Epimol” [18].

Based on the foregoing, a number of known solid lubricants for the wear process of the G-33MI brushes in contact with an expensive copper collector of an alternating current electric machine were subjected to experimental evaluation in a full-scale experiment.

2.2. Research methodology

Solid lubricants based on powder reagents were obtained on the basis of the formation of a solid lubricating composite from the corresponding powders and with the same percentage of binder formed by the developed technology. The wear of the brushes was evaluated by a full-scale experiment on electric alternating current machines LNA2.2-230, by making an additional regular place for a lubricating brush (LB) in the machine body, followed by springing of the lubricating liner to the collector surface (Fig. 1). The stiffness of the spring made it possible to change the pressure force of the lubricating liner on the surface of the collector of the electric machine and to regulate the degree of lubricant supply. After preliminary rolling, the wear of regular brushes was evaluated without lubrication and using a solid lubricating brush. Depreciation was measured by weighing with an accuracy of 0.01 and with an electronic vernier caliper with an accuracy of 0.01 based on the total average value of the brush's rising and falling edges.

![Figure 1. Mutual arrangement of G-33MI electric brushes and a lubricating brush (LB) on the LNA collector](image)

1.-Collector; 2.- regular brushes; 3-LB.

2.3. The discussion of the results

According to Table 1, there is a satisfactory correspondence between the wear of regular G-33MI brushes in terms of their height and weight, depending on the type of lubricant. All solid lubricants reduce wear on regular brushes. However, the "Epimol" and molybdenum disulfide are the most effective lubricants. It should be noted that during the experimental assessment, no advantages in the lubricity of these substances were revealed. Imported molybdenum disulfide has some advantage. The latter may be due to a slightly larger fineness of disulfide grinding of 6 μm versus fineness of grinding of epimol having an average lubricant particle size of 3 microns. Thus, the factor of increasing the heat
resistance by fluoridation of molybdenum disulfide in the epimol product is comparable with molybdenum disulfide of a higher grinding fineness. Nevertheless, no additional benefits of the Epimol product with higher molybdenum molybdenum disulfide were found. Getting the "Epimol" is connected with additional labor costs for fluoridation, and the product itself has a higher cost. The effectiveness of the remaining test lubricants of Table 1 and Table 2 is lower, which is most likely due to their lower adhesion to the metal.

**Table 1.** Dependence of average wear of regular brushes G-33MI (EB1, EB2) when using solid lubrication of the collector of an electric machine LNA 2.2-230 (B)-H3. The test time is 18h.

| Substance                        | Wear, mm | Weight loss, g |
|----------------------------------|----------|----------------|
| No lubrication                   | EB1 1.51 | EB2 1.32       |
|                                  | B3 -     | EB1 0.3        |
|                                  |          | EB2 0.25       |
|                                  |          | B3 -           |
| Hexagonal boron nitride          | 0.9      | 0.85           |
| Epimol *                         | 0.45     | 0.41           |
|                                  | 0.3      | 0.09           |
|                                  |          | 0.08           |
|                                  |          | 0.15           |
| Molybdenum disulfide             | 0.4      | 0.38           |
|                                  | 0.25     | 0.07           |
|                                  |          | 0.06           |
|                                  |          | 0.13           |
| Calcium fluoride                 | 0.96     | 0.88           |
|                                  | 0.3      | 0.2            |
|                                  |          | 0.17           |
|                                  |          | 0.03           |
| Barium fluoride                  | 0.85     | 0.84           |
|                                  | 1.32     | 0.17           |
|                                  |          | 0.16           |
|                                  |          | 0.45           |
| Tungsten disulfide               | 0.75     | 0.74           |
|                                  | 0.97     | 0.15           |
|                                  |          | 0.14           |
|                                  |          | 0.36           |
| Tungsten Diselenide              | 0.73     | 0.72           |
|                                  | 2.1      | 0.14           |
|                                  |          | 0.13           |
|                                  |          | 0.66           |

* Obtained by fluorination of molybdenum disulfide (USA)

Epimol and molybdenum disulfide are substances with low electrical conductivity, therefore, their lubricating film can worsen the process of current flow in the brush-collector assembly.

**Table 2.** The effectiveness of the impact of solid lubrication of the sliding track on the average wear of the standard brushes of the electric machine LNA 2.2-230. The test time is 18 hours.

| Binder lubricant      | Reduced brush wear compared to standard, mm/mm | Reduced brush wear compared to regular, g/g |
|-----------------------|-----------------------------------------------|-------------------------------------------|
| Boron nitride         | 1.62                                          | 1.61                                      |
| Epimol                | 3.29                                          | 3.23                                      |
| Molybdenum disulfide  | 3.2                                           | 3.3                                       |
| Calcium fluoride      | 1.54                                          | 1.49                                      |
| Barium fluoride       | 2.1                                           | 2.2                                       |
| Tungsten disulfide    | 1.9                                           | 1.89                                      |
| Tungsten Diselenide   | 1.95                                          | 2.03                                      |

Epimol and molybdenum disulfide were evaluated by their effect on the quality of LNA switching. Electrical characteristics were obtained at the test bench [19,20].

Tables 3-5 show that the use of solid lubricants leads to a decrease in sparking machines especially at high frequency revolutions.
Table 3. Characteristics of LNA2.2-230 without lubricating brush

| M, kgf·cm | 0  | 10 | 20 | 30 | 40 |
|-----------|----|----|----|----|----|
| П, rpm   | 6140 | 5235 | 4660 | 4250 | 3890 |
| I, А     | 3,4 | 5,6 | 7,6 | 9,7 | 11,6 |
| P1, kw   | 720 | 1200 | 1600 | 2000 | 2340 |
| K, о.е.  | 2   | 2   | 2   | 2   | 2   |

Table 4. Characteristics of LNA2.2-230 with a lubricating brush based on molybdenum disulfide

| M, kgf·cm | 0  | 10 | 20 | 30 | 40 |
|-----------|----|----|----|----|----|
| П, rpm   | 5980 | 4920 | 4410 | 4050 | 3770 |
| I, А     | 3,51 | 5,8 | 7,9 | 10 | 12 |
| P1, kw   | 780 | 1200 | 1600 | 2000 | 2400 |
| K, о.е.  | 2   | 2   | 11/2-2 | 11/2-2 | 11/2-2 |

Table 5. Characteristics of LNA2.2-230 with an epimol-based lubricating brush.

| M, kgf·cm | 0  | 10 | 20 | 30 | 40 |
|-----------|----|----|----|----|----|
| П, rpm   | 6070 | 5120 | 4600 | 4180 | 3820 |
| I, А     | 3,3 | 5,5 | 7,6 | 9,6 | 11,6 |
| P1, kw   | 700 | 1160 | 1580 | 1960 | 2340 |
| K, о.е.  | 2   | 2   | 11/2-2 | 11/2-2 | 11/2-2 |

The effectiveness of lubricating brushes largely depends on the amount of lubricant supplied to the contact zone, and the minimum wear of conductive brushes corresponds to the optimal supply. Excess lubricant can lead to a violation of the topography of the surface of the friction track. The wear rate of the tribocontact participants was studied depending on the pressure of the lubricating brush on the collector (table 6).

Table 6. The influence of the pressure of the clamping spring of the lubricating brush on the wear of the conductive brushes G-33MI.

| Average wear of current-carrying brushes, mm | Brush wear with MoS2, mm | Reduction of wear of regular brushes, mm / mm | Pressure, g |
|---------------------------------------------|--------------------------|---------------------------------------------|-------------|
| 0,27                                        | 0,24                     |                                             | 0           |
| 0,14                                        | 0,04                     | 1,93                                        | 80          |
| 0,17                                        | 0,05                     | 1,59                                        | 200         |
| 0,20                                        | 0,06                     | 1,35                                        | 250         |
| 0,22                                        | 0,16                     | 1,22                                        | 300         |
The results obtained allow us to conclude that the optimal pressure of the lubricating brush are in the range of 80-200 g.

The inclusion of additional participants in the tribological interaction in the polythene film may affect the level of radio interference of the collector electric machine. The level of radio interference was evaluated by voltage according to GOST R51318.14.1-2006.

| Frequency, MHz | 0,16 | 0,24 | 0,55 | 1 | 1,4 | 2 |
|---------------|------|------|------|---|----|---|
| According to Gost | 75,5 | 72,1 | 69 | 69 | 69 | 69 |
| G-33MI | 48 | 48 | 43 | 36 | 35 | 38 |
| G-33MI with DM | 46 | 47 | 38 | 33 | 33 | 38 |

| Frequency, MHz | 3,5 | 6 | 10 | 22 | 30 |
|---------------|-----|---|----|----|---|
| According to Gost | 69 | 74 | 74 | 74 | 74 |
| G-33MI | 37 | 41 | 42 | 30 | 30 |
| G-33MI with DM | 32 | 32 | 36 | 27 | 26 |

Table 8. The effect of solid lubricant MoS2 (DM) on the level of LNA radio noise power.

| Frequency, MHz | 30 | 45 | 65 | 90 | 150 | 180 | 220 | 300 |
|---------------|----|----|----|----|-----|-----|-----|-----|
| According to Gost | 55 | 55,6 | 56,3 | 57,2 | 59,5 | 60,6 | 62 | 65 |
| G-33MI | 46,4 | 44,4 | 49,4 | 48,4 | 41,9 | 40,5 | 34,3 | 30,8 |
| G-33MI with DM | 43,4 | 41,4 | 47,4 | 45,4 | 41,9 | 30,5 | 27,3 | 22,8 |

An experimental check has shown that the reduction of sliding friction in the sliding current collection unit makes it possible to reduce the radio interference of the LNA 2.2-230 in the entire frequency range both in voltage and power due to the use of a lubricating brush.

3. Conclusion

Experimental studies of real objects (LNA electric collector AC machines) to assess the possibility of reducing the wear of regular electric brushes with various solid lubricants have shown that the best effect of reducing the wear of G-33MI carbon brushes has an imported manufacturer of molybdenum disulfide with a fineness of 6 microns and imported fluorinated disulfide "Epimol" with an average grinding fineness of 3 microns.

In addition, the use of lubrication of the slip track by molybdenum disulfide improves the switching quality of the LNA 2.2-230 machine, reduces the level of radio noise in the entire frequency range in terms of power and voltage.

At the same time, no additional positive wear effect was found when using the Epimol product in comparison with molybdenum disulfide with a higher fineness.

Nevertheless, the question of using fluorination of molybdenum disulfide powder with a fineness of 6 microns and higher is of undoubted scientific and practical interest for further improving the technology of rotaprint deposition of solid lubricant in the slip collector assembly of electric machines.

Non-layered greases — calcium and barium difluorides — also have demonstrated a positive effect on reducing wear on electric brushes. However, the effect of reducing wear in the presence of these
Grease is lower than that of layered ones. At the same time, the cost of these reagents is slightly lower than layered lubricants.

It was found out that tungsten dyselenide and disulfide also allow to reduce the wear of regular electric brushes. However, the cost of these powder lubricants is incommensurably high in comparison with the obtained effect and exceeds the cost of molybdenum disulfide by more than three times.

Russian-made hexagonal boron nitride of the Redkinsky plant at a very significant cost exceeding three times the cost of molybdenum disulfide also has not demonstrated a significant positive effect.

Thus, it should be noted that the final conclusion on the importance and possibility of using rotaprinting lubrication to reduce the brushes of electric machines can give an estimate of the effect on high-power electric machines (in rolling mill engines, turbine generators).

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