Increasing wear resistance of steel 18Cr2Ni4WA with magnetron sputtering Cu-based thin-layer coating

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Abstract. The paper studies the effect of parameters of a thin-layer copper-based coating applied by magnetron sputtering on the wear resistance of samples made of steel 18Cr2Ni4WA when working in a friction pair "18Cr2Ni4WA – cast iron GG 15". The rational values for the thickness of the applied copper coating are determined, at which the lowest friction torque during the burn-in period and the minimum burn-in time are achieved. Jeol JCM-5700 Scanning Electron Microscope is used to study the friction track of samples and counter bodies. It is found that in the process of friction, the coating is selectively transferred from copper to the surface of the counter body, which significantly reduces the wear of the counter body.

Keywords: magnetron sputtering, wear resistance, thin-layer copper-based coating, friction torque, friction pair, phenomenon of selective transfer

1. Introduction
Method of magnetron sputter coating is progressively used to increase the wear resistance of parts in friction pairs. This method has several advantages, such as the creation of a dense micro (nano) crystalline structure of metal coatings, the ability to coat thermo-sensitive materials at low temperatures, the widest range of coatings for various purposes, high deposition rate, and high antifriction properties of metal coatings. And, despite a number of disadvantages, such as the relative complexity of the technical implementation and the relatively high cost of equipment, magnetron sputtering technologies are increasingly being used in the manufacture of friction pair parts [1].

One of the most commonly used magnetron sputter coatings is copper- based coatings. This is due to the fact that copper coatings have a number of positive properties, such as: low coefficient of friction and high thermal conductivity required for efficient heat removal from the friction zone [2], [3]; high sputtering coefficient which increases the deposition rate of coatings and reduces the cost of their application [4]; high anti-corrosive properties of copper coatings, specifically coatings obtained in a stationary magnetron discharge with accompanying ion assisted initial stage and then in a magnetron discharge with a molten cathode [5]; high adhesion and density of the coating, specifically when applied to polymer substrates [6].

According to [7], the copper film and lubricant contribute to improving the burn-in conditions and reducing the coefficient of friction and wear for the sliding surfaces of machine parts.
In some cases, a layered solid lubricant, such as graphite, is introduced to improve the anti-friction properties of the copper coating. However, the use of such coatings in a humid environment, at elevated temperatures, or under oxidation conditions does not result in improved tribotechnical characteristics [8]. Also, one of the ways to improve the anti-friction properties is to use the coating in the Cu-B system. As a result, the hardness of the coating increases by 6-20 times, the wear resistance of the coating increases by 2-7.5 times, and the friction coefficient decreases [9].

Magnetron sputtering application of thin films of the Al - Cu system finds its use, with a hardness and elastic modulus value being higher than films based on Al and Cu. It is due to a decrease in the grain size of the Al and Cu phases with the formation of nano-dispersed inter-metallic compounds, and features of their impurity elemental composition, as well as a nano-crystalline substructure [10].

Thus, obtaining copper-based thin-layer coatings by magnetron sputtering to increase the wear resistance for parts of friction pairs is a relevant task in the field of nanotechnology due to high practical significance of this method and materials in the production of thin-film coatings with high physical, chemical and operational characteristics [11 - 13].

The purpose of this work is to study the effect of parameters of a thin-layer copper coating applied to the cylindrical surface of steel sample 18Cr2Ni4WA by magnetron sputtering on wear resistance during the burn-in period in the friction pair "steel 18Cr2Ni4WA – cast iron GG 15" under dry friction conditions.

2. Experimental methods and materials

For experimental studies, five samples were prepared from 18Cr2Ni4WA steel. These are cylindrical rollers with an outer diameter of 40 mm and a width of 12 mm. Three samples were used for coating by magnetron sputtering, one sample was subjected to oil quenching and tempering, and one sample was after mechanical treatment without heat treatment and without coating. The working surface of the samples was ground to a roughness value of $R_a 0.63$. For the reliability of experimental results all the samples were made from a single heat of metal.

The choice of 18Cr2Ni4WA steel as a material for samples is due to the type of steel used for critical parts that require high strength, viscosity and wear resistance, as well as for parts that are subject to high vibration and dynamic loads.

Copper-based coating was applied to the samples using the ADVAVAC VSM-200 magnetron sputtering unit in high-frequency mode with a source power of 100 W, an argon pressure from 0.32 to 0.34 PA, and preliminary ion cleaning of the chamber for 10 minutes [14]. Before being placed in a vacuum chamber, the samples were degreased with organic solvents, washed with ethanol and dried.

Processing parameters are shown in Table 1. Three samples were coated with copper of different thicknesses for 30, 60 and 90 minutes at a power of 100 W and a temperature of 100 °C.

| Sample code | Coating time, min | Power, W | Pressure, mbar | Temperature, °C |
|-------------|------------------|----------|----------------|-----------------|
| 627-3976-3  | 30               |          |                |                 |
| 627-3976-2  | 60               | 100      | 3              | 100             |
| 627-3976-1  | 90               |          |                |                 |
| 627-3975 (after heat treatment) | -               | -        | -              | -               |
| 627-3976-5 (after mechanical treatment) | -               | -        | -              | -               |
After coating, wear resistance tests were performed on the friction machine ИИ – 5018. The tests were performed according to the "rotating disk – rotating disk" scheme. As a counter body for the wear test, rollers were made of material GG15 with an outer diameter of 40 mm and a width of 12 mm, with a roughness of the outer cylindrical surface $R_a = 0.63 \, \mu m$.

Wear resistance tests were performed at the room temperature in dry friction under the following conditions. The load is 100 N, rotation speed is 100 rpm. The samples were tested for 30 minutes, and the friction torque was recorded every minute.

Using the DL-200 analytical balance, the mass of the samples was measured before and after the wear test. From these data, mass wear was calculated by the following formula:

$$i_g = \frac{\Delta Q}{\Delta N} \cdot \frac{1}{A_n \cdot L_1}$$  \hspace{1cm} (1)

where $\Delta Q$ is the change in the mass of the sample before and after the test, g; $\Delta N$ is the number of revolutions of the sample during the test; $A_n$ is the area of contact, mm$^2$; $L_1$ is the circumference of the sample, mm.

The surface of the samples after the wear resistance test was examined using the JEOL JCM-5700 Scanning Electron Microscope.

3. Results discussion

**Figure 1** represents the dependences of the friction torque change on the time of samples testing during the burn-in period under the above test conditions.

As is clear from the presented dependencies, coated samples have more stable values of the friction torque during the burn-in period and lower values of the friction torque after 30 minutes of testing than samples after machining and without coating. The most stable friction torque values from 1.85 N·m to
1.5 N·m after 30 minutes of testing were observed in the sample 627-3976-2 with coating time of 60 min, and in the sample 627-3976-3 it was from 1.75 N·m to 1.4 N·m after 30 minutes of testing with 30 min of coating time.

The friction torque of the sample after heat treatment and mechanical treatment was rather less stable and varied from 1.4 N·m to 3.5 N·m after 30 minutes of testing. The sample after mechanical treatment showed a change in the friction torque from 1 N·m to 3.3 N·m after 30 minutes of testing.

After 8 minutes of testing, the samples without coating showed a sharp increase in the friction torque, while indications of the friction torque changed slightly for samples with coatings of different thicknesses.

According to the results of the experiment, mass wear was calculated by the formula (1). The results of calculations for samples and counter bodies is shown in Figures 2 and 3.

![Figure 2. Mass wear of the samples](image1)

![Figure 3. Mass wear of the counter bodies](image2)
Of the copper-coated samples, the lowest value of weight wear being 861 g/m$^3$, was observed for the sample with a coating time of 30 minutes. The highest values of 1389 g/m$^3$ were in samples with a copper coating applied over 60 and 90 minutes. The highest value of weight wear exhibited in the sample after machining and without coating was 1638 g/m$^3$.

Calculation results for weight wear of counter bodies showed the highest value of 306 g/m$^3$ for the sample in the friction pair with the sample after mechanical processing and without coating. The lowest value of 56 g/m$^3$ was monitored for the sample in the friction pair with the sample 627-3976-1 for the coating time of 90 min, and for sample 627-3975 it was observed after the heat treatment and mechanical treatment.

The surface of the samples after the wear resistance test was examined using the JEOL JCM-5700 scanning electron microscope. Figure 4 shows the surface (a) and composition analysis of the surface area (b) for the copper-coated sample with coating time of 60 minutes after the wear test.

![Figure 4](image)

**Figure 4.** Surface of samples made of steel 18X2H4B with the coating time of 30 minutes after wear resistance test (a) and surface area composition analysis (b)

Figure 5 shows the spectrogram of the sample after the wear test.

![Figure 5](image)

**Figure 5.** Spectrogram of the copper-coated sample with the application time of 60 minutes after the wear test
After testing for wear resistance, there is a sharp decrease in the copper content and an increase in the iron content in the coating, and the integrity of the applied coating is broken as well. 

**Figure 6** (a) shows the surface of the counter body made of material GG 15, as well as the analysis of the friction track composition (**Figure 6** (b)). Both **Figure 6** and the spectrogram in **Figure 7** show that parts of the copper film were transferred to the counter body surface.

![Figure 6. Surface of samples made of cast iron GG 15 after wear resistance test (a) and analysis of the surface area composition (b)](image)

**Figure 6.** Surface of samples made of cast iron GG 15 after wear resistance test (a) and analysis of the surface area composition (b)

![Figure 7. Spectrogram of the counter body surface made of cast iron GG 15 after wear resistance test](image)

**Figure 7.** Spectrogram of the counter body surface made of cast iron GG 15 after wear resistance test

Analysis of the counter body friction track shows that on its surface coupled with the magnetron sputtered copper coated sample the transfer of the copper film is detected, which significantly reduces the wear of the counter body (**Figure 3**), i.e. there is a phenomenon of selective transfer. On the other hand, the counter body coupled with the sample after machining and without applying a thin anti-friction film, surface peeling and chipping are discovered.
4. Conclusion

Using the method of magnetron sputtering under conditions of ion bombardment of a target made of copper on samples of alloy steel 18Cr2Ni4WA, protective coatings are obtained that have increased wear resistance when testing friction pairs “steel 18Cr2Ni4WA – cast iron GG 15”.

The rational modes of coating by magnetron sputtering, which provide the best wear resistance of samples made of steel 18Cr2Ni4WA in the friction pair with sample GG 15 according to the scheme “rotating disk - rotating disk” are: the power of 100 W, temperature of 100 °C, and coating time of 60 min.

Jeol JCM-5700 Scanning Electron Microscope is used to study the friction track of samples and counter bodies. It is found that in the process of friction, the coating is selectively transferred from copper to the surface of the counter body, which significantly reduces the wear of the counter body.

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