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The Assessment of Wear Resistance of Thin-Layer Carbide Coatings under Vacuum Arc Deposition

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***Abstract*— The presented research considers the tribological properties of titanium carbide coatings TiC and their areas of application.**

It is noted that titanium carbide TiC is one of the most effective materials used as a wear resistant coating. TiC to the greatest extent satisfies the requirements for coatings: good adhesion to the surface of the material - the base; corrosion resistance, low tendency to seizure and cold bonding. Arc plating vacuum deposition (cathodic arc ion plating) - Arc-PVD is widely used to apply high-quality titanium-based coatings.

The article considers the issues of wear resistance of carbide-titanium coatings obtained by the Arc-PVD method with respect to friction at high pressures with lubrication. The Arc-PVD method makes it possible to widely vary the structure of the emerging coatings due to the change in pressure in the working chamber and the potential applied to the sublayer. The article shows the results of comparative tests of samples on a friction machine according to the scheme of two rotating rollers. It is shown that at different loading levels (50 and 500 H) the wear resistance of coated samples significantly exceeds the wear resistance of hardened steel samples. On the basis of experimental studies, the technological modes of Arc-PVD are proposed for the formation of coatings with optimal durability.

Keywords— titanium carbide coatings, Arc-PVD method, wear-resistance

I. INTRODUCTION

In order to increase the wear resistance of machine parts, due attention is paid to various branches of engineering. One of the leading directions in this area is the improvement of technological methods, including the development of modern wear-resistant thin-layer coatings [1-8].

Titanium compounds are widely used in various industries. Nowadays, titanium carbide is receiving much attention. It is due to the fact that it has a number of unique properties, such as super hardness, high heat resistance, high modulus of elasticity, resistance to acids and alkalis, good electrical conductivity.

High hardness and heat resistance make it possible to successfully use titanium carbide in the preparation of alloys from which is used in the production of gas turbine blades, parts of aircraft engines, and special protective coatings of jet nozzles and other parts of rockets. The usage of this substance significantly increases the strength and durability of stainless and heat-resistant steel alloys, significantly increases their bondability. Titanium carbide and tungsten alloy are used in order to make various kinds of equipment parts for pumping sodium melts, which withstand elevated pressure values (more than 8 atm.) and temperatures.

In addition, this material is widely used in the manufacture of abrasive pastes for the processing of semiconductors, metals and dielectrics, in grinding and in the development of cutting tools for viscous compounds. The equipment made of titanium carbide allows accelerating in several times the processing of various kinds of steel and increasing of labor productivity in the mining, ore and metalworking industries. In addition, such a tool can easily work with viscous materials that "classic" cutters cannot cope with [9–13].

Fig. 1. The examples of the use of titanium carbide in mechanical engineering

Titanium carbide coatings are widely used in various fields: aerospace, nuclear power, automotive industry (Fig. 1). The use of coatings can increase several times the service life of products, save expensive and scarce materials. TiC is one of the most effective materials used as wear resistant coatings. This is due to the fact that TiC to the greatest extent meets the requirements for coatings: good adhesion to the surface of the material - the base; scale resistance, low tendency to seizure and cold bonding.

TiC titanium carbide is a wear- and corrosion-resistant, hard, chemically inert material that is in demand in various areas for the production of hard alloys, metal-ceramic tools, heat-resistant products, protective coatings for metals. New prospects for the use of titanium carbide open up when it is used in the nanostate (modification of alloys of different composition and purpose). The properties of titanium carbide coatings and methods for their preparation are described in the research works [14 -17].

Arc-PVD method (cathode arc deposition) is a widely used for the application of coatings (thin films) in vacuum, by condensing to the sublayer (product, part) material from plasma flows generated at the cathode, for the application of high-quality titanium-based coatings - targets in the cathode spot of a vacuum arc of a high-current low-voltage discharge, which develops exclusively in pairs of electrode material.

The method is also known by the names: cathode arc deposition (Arc-PVD), the method of cathode-ion bombardment.

The method of Arc-PVD makes it possible to widely vary the structure of the emerging coatings due to the change in pressure in the working chamber and the potential applied to the sublayer. The change of technological regimes leads to changes in the density of coatings, as well as in the ratio between titanium carbide and individual elements. It is obvious that such structural transformations should influence the wear resistance of the resulting coatings.

The purpose of this work is to optimize the technological regimes during the deposition of carbide-titanium coatings obtained by the Arc-PVD method for wear resistance as applied to friction at high pressures with lubrication.

II. MATERIALS AND EXPERIMENT PROCEDURE

In order to create high contact pressures, a particular scheme was used to contact two cylindrical samples, one of which was fixed motionless, and the second was driven into rotation at a constant speed. At the same time, at the initial moment of time, the contacting of samples is carried out along the line. The methodology for conducting such studies is described in the research [18] as applied to the wear resistance of thin-layer coatings.

Experimental studies were performed on a standard friction machine. The stationary sample with a titanium carbide coating was investigated — the roller was made of steel 20 and had a diameter of 46 mm. The rotating roller with a diameter of 46 mm did not have a coating and was made of steel 45, followed by quenching (42 ... 45 HRC).

The formation of the coating was carried out at two pressure levels of C_6H_6 - 0.17 Pa and 0.27 Pa and four potential levels on the sublayer — 50, 100, 150, and 200 V. The coating thickness was 6 ... 10 mcm.

An oil bath with a volume of 200 sm3 was used to lubricate the friction unit, in which the rotating roller was partially (2 mm) immersed. Industrial oil I-40A was used as a lubricating medium.

To assess the comparative wear resistance of coatings at high pressures, the samples of steel 40X without quenching (28 ... 32 HRC) and quenched (42 ... 45 HRC) were also tested.

The study of wear resistance was carried out at two loading levels: 50 and 500 H. The calculations showed that Hertz contact pressure for these loads is ~ 85 and ~ 300 MPa, respectively, i.e. differ by 3.5 times. Therefore, as it will be shown below, the friction under low and heavy loads is associated with various wear mechanisms. The time of the experiment was limited to complete wear of the coating and ranged from 1 minute to 7 hours. A separate experimental point was determined from three to four experiments, while the mean-square error of the results did not exceed ± 15%.

With this pattern of friction in the process of wear on the stationary sample, a wear slot is formed. The width of the slot in the sliding direction is a, the length in the perpendicular direction is b, and the height in the center of the slot is h.

Under condition $h \ll D$ we obtain:

$$h = \frac{a^2}{2D} \tag{1}$$

and the volume wear (in the case of a rectangular spot in shape) is equal to:

$$V = \frac{a^3 b}{3D} \tag{2}$$

However, in the study of thin coatings, the misalignment of the rollers of just a few hundredths of a degree leads to the fact that the shape of the wear spot may differ significantly from the rectangular one. In the general case, it may be close to a trapezoid, and in the limiting case, it may have a triangular shape. Then the calculation by the formula (2) becomes impossible. However, if we break the spot length b into n equal sections and find the average size within each section, then the formula (2) is converted to:

$$V = \frac{b}{3D} \sum_{i=1}^{n} \frac{(\bar{a}_i)^3}{n}. \tag{3}$$

The use of the formula (3) is associated with time-consuming measurements, and the convention of splitting the spot length introduces an error in the calculation.

Thus, it becomes necessary to obtain specific calculation formulas for wear spots resulting from non-axial contact.

The worn-out volume at the contact of two cylinders of the same diameter can be divided into two equal parts, each of which has the shape of a circular segment in cross section and is formed by the intersection of the planes with the surface of the second order. The volume formed by surfaces not higher than the second order can be calculated by the following formula:

$$V = \frac{b}{6}(S_b + 4\bar{S} + S_t). \quad (4)$$

The areas included in expression (4) can be determined by the approximate formula for the area of a segment, which is obtained from expression (2) by dividing it *by 2b:*

$$S = \frac{a^3}{6D} = \frac{2}{3}ah. \quad (5)$$

Substituting relations (4) and (5), we obtain the formula for the calculation of the volumetric wear of a cylindrical sample across the width of the wear slot

$$V = \frac{b}{36D}(a_m^3 + 4\bar{a}^3 + a_s^3). \quad (6)$$

However, taking into account the relation expressed by formula (1), it is not necessary to carry out additional measurements of the width of the slot in the middle part. Combining the expressions (1) and (5), the cross-sectional area in the middle part of the volume can be expressed in terms of the width of the slot at the base and in the upper part.

Omitting further simple transformations, we obtain the most general formula for the calculation of volumetric wear when cylindrical samples contact according to the extreme dimensions of the wear slot.

$$V = \frac{(a_m^3 + a_s^3)b}{18D} + \frac{(a_m^2 + a_s^2)^{\frac{3}{2}}}{9\sqrt{2D}}. \quad (7)$$

Substituting into the formula (7)$a = a_m = a_s$, after simple transformations, we obtain the formula (2), as a special case. Another special case of the expression (7) is the calculated ratio for the calculation of the volume of a triangular spot. Substituting it in the expression (6), we get:

$$V = \frac{2a_m^3 b}{15D}. \quad (8)$$

Thus, the formulas (2), (3) and (6), (7) make it possible to easily find the volume wear from the measured values of *a* and *b* for any form of a wear spot.

In order to assess the wear resistance, we used the specific wear rate *K*, which in general terms was found from the expression:

$$K = \frac{\Delta V}{F\Delta L}. \quad (9)$$

In order to calculate *K* in experiments, the time dependences of volume wear on the friction path were determined.

III. TEST RESULTS AND THEIR DISCUSSION

As the processing of experimental data has shown, under a load of 50 H (the initial hertz pressure is ~ 85 MPa), the *K* value does not depend on the friction path, and therefore, the volume wear can be used to calculate it directly from the beginning of the experiment.

For a load of 500 H (initial hertz pressure ~ 300 MPa), as it was shown below, the value of *K* depends on the friction path. At the first stage (within 1 ... 3 minutes), the intensive wear is observed, which then gradually decreases. In this case, the wear coefficient has different values in the first and second stages. To calculate *K* by the formula (9), at the first stage, the values of *V* and *L* are taken from the beginning of the experiment to the bending point. In the second stage, the following values ΔV и ΔL are determined for which the bending point is the starting point.

Fig. 2 shows data on the wear resistance of chromium steel and titanium carbide coatings deposited at pressures of C_6H_6 - 0.17 Pa (TiC 1) and 0.27 Pa (TiC 2) at voltages in the sublayer of 200 V. It is clear that such coatings well protect the surface from wear at relatively high contact pressures. In addition, it can be concluded that the wear resistance of titanium carbide coatings strongly depends on the pressure in the chamber during coating. The coating applied at a higher pressure also has a significantly higher wear resistance. In this regard, for subsequent tests on the influence of the electrode potential, the samples were made at a pressure in the chamber of 0.27 Pa description of the methods and materials used in this article.

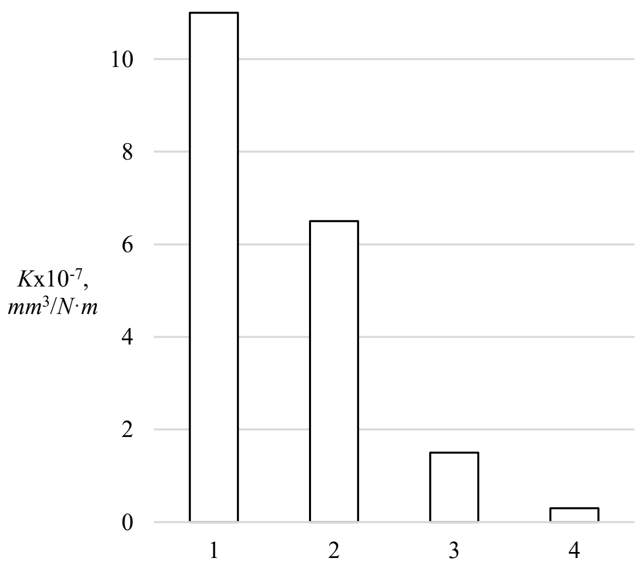

Fig. 2. Comparative wear resistance of materials and coatings:1 – steel 40X, 2 – steel 40X after hardening, 3 – TiC 1, 4 – TiC 2

The studies of the dependence of the specific wear rate of titanium carbide coatings on the potential on a sublayer at a load of 50 H (Fig. 3, curve 2) show that K has a minimum at a voltage of 150 V. This is apparently determined by the density of the coating and its adhesion strength.

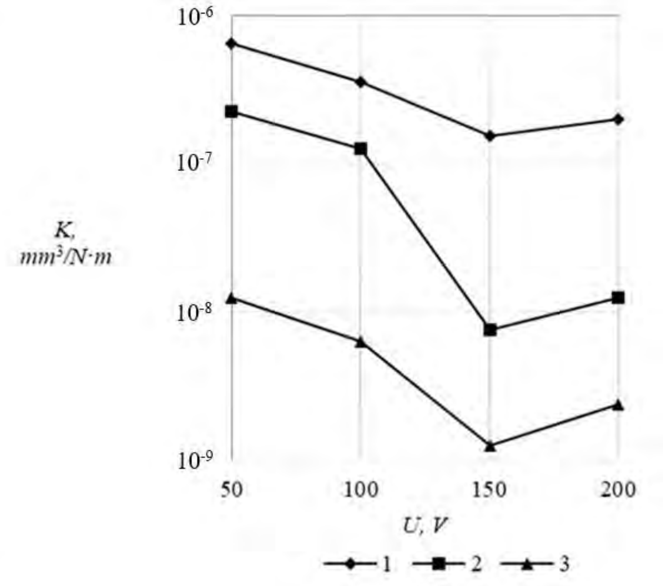

Fig. 3. The dependence of the specific wear rate of KT coatings on the potential on the sublayer under loads: 1, 3 – F = 500 H, 2 – F = 50 H

The tests under load of 500 H showed that there is a dependence of the specific wear rate of KT coatings on the time of testing (friction path). Curve 1, constructed from measurements of volumetric wear for a time equal to 1 ... 3 minutes from the start of testing, shows that at high loads at the initial moments of time there is an intensification of the wear process, expressed in an increase in K compared to data obtained at a load of 50 H.

Apparently, this is due to the existence at the initial moment of the metal contact of the counter body.

After the measurement of the volumetric wear for 1 ... 3 min, the tests were continued until linear wear was achieved close in its magnitude to the coating thickness. After that, the difference between volume wear was found and the corresponding K value was determined. The results obtained (Fig. 3, curve 3) show that after the initial intensive wear, a transition occurs to boundary friction, where the specific wear rate is noticeably lower than at a load of 50 H.

Thus, with a load of 500 H compared with a load of 50 H, an intensive run-in of the coating is observed. However, under those and other conditions, there is a significant difference in the wear resistance of coatings applied at voltages on the substrate of 50-100 and 150-200 V.

The transition from run-in to boundary friction occurs rather sharply. Therefore, it is possible to correlate the transition point with a specific critical pressure p_c. From figure 4, it can be seen that the critical pressure is noticeably higher for titanium carbide coatings formed at sublayer potentials of 150 and 200 V, and reaches values of the order of 110 MPa. As studies show, there is a significant dependence of p_c on the actual load.

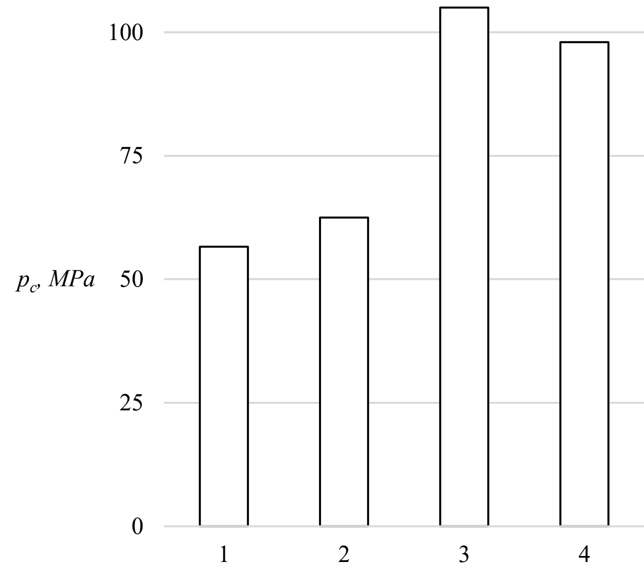

Fig. 4. The dependence of the critical pressure for KG coatings formed at different potentials:1 – U = 50 V, 2 – U = 100 V, 3 – U = 150 V, 4 – U = 200 V

IV. CONCLUSION

As a result of the research, new ratios for the calculation of volumetric wear in the presence of misalignment of cylindrical counter body with thin-layer coatings are presented; According to the results of the research we can draw the following conclusions:

1. Thin-layer coatings of titanium carbide are widely used in various fields of engineering. TiC titanium carbide is a wear- and corrosion-resistant, hard, chemically inert material that is in demand in various areas for the production of hard alloys, metal-ceramic tools, heat-resistant products, and protective coatings for metals.

2. The method of Arc plate-vacuum-deposition (Arc-PVD) is widely used to apply high-quality coatings based on titanium. The change in technological regimes leads to changes in the density of coatings, as well as in the ratio between titanium carbide and individual elements, which has a significant impact on the wear resistance of coatings.

3. The result of the conducted research is the establishment of the relation between the modes of Arc-PVD of titanium carbide coatings (chamber pressure and potential on the sublayer) with their wear resistance, which is especially noticeable at high contact pressures.

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