AN ANALYSIS OF THE FUNCTIONAL PROPERTIES OF SUPER HARD COATINGS ON BORON CARBIDE SYNTHESIZED BY SHORT-PULSE LASER PROCESSING

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ABSTRACT

Modern engineering pays great attention to ways to improve the durability and reliability of friction surfaces. This is especially true in those areas of engineering, where components and assemblies experience high dynamic and thermal loads. One of the most effective ways to ensure the necessary physical and mechanical properties of the contacting surfaces is the creation of thin functional coatings based on highly solid materials. However, obtaining superhard thin coatings is associated with a number of difficulties, based on the lack of in-depth theoretical studies in the field of features of the synthesis of coatings. This paper presents the results of studies of some properties of superhard coatings synthesized by short-pulse laser treatment from a powder composition based on boron carbide. The features of phase changes in the surface layer of contacting bodies from the surface temperature are analyzed. The optimal combination of structures at which the minimum coefficient of friction is achieved is determined. The results of laboratory studies provide clear evidence of the performance of coatings in the bearing units of sliding in comparison with standard friction pairs.

KEYWORDS: Superhard Material, Friction Coefficient, Boron Carbide, Laser Processing, Wear Resistance & Sliding Bearing

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INTRODUCTION

In modern conditions, with the policy of import substitution and other changes, it is necessary to take new steps to optimize and improve the mechanisms and materials (wear resistance) involved in all sectors of the national economy (Kislitsky et al., 2018; OstaeV et al., 2018; OstaeV et al., 2018).

The wear resistance of the thin surface layer of the rubbing parts determines the durability of friction surfaces subject to sliding relative to each other. The wear resistance of the friction surface depends on the whole complex of processes occurring in the contact zone, caused by dynamic and thermal effects. It was believed until recently that the interaction of two surfaces is a constant physical quantity independent of the dynamic and kinematic characteristics of the friction unit. As a result, for many years, researchers tried to find a relationship between the antifriction characteristics and the structure of the material, which led to incorrect design of friction units. Today it is known that the anti-wear properties of friction surfaces depend on the energy state of the surface,

chemical activity and structural features that determine the complex nature of the interaction in the friction process.

THEORETICAL BASIS

Friction surfaces is characterized by the release of a large amount of energy, which changes the thermodynamic processes in the contact zones, leading to an increase in surface free energy with the formation of various polymorphic structures in thin surface layers, chemical compounds with environmental components that change the antifriction properties of the material. Therefore, there are certain ranges of loads and friction rates for all antifriction materials, at which the normal (mechano-molecular) wear mechanism is realized.

In the process of friction, depending on the thermodynamic potential of the friction surface, the formation of primary structures (solid solutions) and secondary structures (chemical compounds) is possible (Figure 1). Primary structures are formed as a result of minimal thermal effects on the surfaces of the contacting bodies (low A_1). Primary structures are relatively plastic, homogeneous in structure, and have low wettability.

Figure 1: Scheme of Changing the Type of Secondary Structures Depending on the Specific Work of Friction

Secondary structures arise due to the great work of friction (A_2 and A_3); they are characterized by a significant thermal background of formation and have high hardness, brittleness, heterogeneity, good wettability.

The lubrication conditions, kinetic parameters, and dynamic loading of the friction unit determine the influence of the formed structures on the antifriction properties. The low coefficient of friction can provide both the structure of the primary kind, and the structure of the secondary kind. To obtain a stable and low friction coefficient value, a certain combination of primary and secondary structures is necessary. Numerous experiments have shown (Bowden, 1980) that the minimum stable level of friction coefficient is observed if one surface is covered with structures of the 1st kind, and the other with structures of the 2nd kind (Figure 2).

Figure 2: Dynamics of Change of the Friction Coefficient depending on the Load with different Combinations of Structures on the Friction Surfaces

The highest level of friction coefficient is observed during the formation of primary and secondary structures on friction surfaces, which corresponds to 1 and 5 sections. At the same time, the minimum value of the friction coefficient is consistently observed at 3 and 4 sites, when various types of structures are realized on the friction surfaces. Thus, the condition of high antifriction properties is the realization of primary and secondary structures on friction surfaces. This phenomenon does not contradict the most adequate model of molecular-mechanical friction.

According to the molecular - mechanical theory of friction, the coefficient of friction is determined by the following expression (Bowden, 1980; Garkunov, 1989).

$$f = \frac{\tau_0}{p_r} + \beta + k\sqrt{\frac{h}{r}}, \quad (1)$$

where

τ_0 – strength of adhesive bond to cut in the absence of compressive force;

p_r – actual pressure, N;

β - adhesion bonding coefficient;

k – coefficient of proportionality, depending on the geometric shape of the surfaces;

h – depth of implementation of single irregularities, microns;

r – radius of single irregularity, microns.

It follows from formula (1) that the surface is harder, i.e. the larger the p_r , the smaller the first and third components of the right side.

External friction will occur if

$$\frac{h}{r} \leq \frac{1}{2} \left(1 - \frac{2\tau}{\sigma_0} \right), \quad (2)$$

where τ - adhesion strength of adhesion bond of setting bridges, MPa;

σ_0 – yield strength of the deformable surface, MPa.

It follows from formula (2) that external friction will completely cease if the ratio $2\tau/\sigma_0 \geq 1$ and the best condition for friction is if $\tau \rightarrow 0$.

Therefore, in order to provide external friction with a minimum coefficient of friction, the hardness of surfaces must be different, for example, the use of a bronze-steel friction pair. With this combination of materials, the soft base of the copper alloy creates conditions for minimizing the values τ and σ_0 , which is characterized by the appearance of a thin quasi-liquefied copper film.

Based on the foregoing, it follows that the resource of the friction unit is largely determined by the preservation of various structures on the friction surfaces in the range of dynamic, kinematic loads, as well as temperatures that occur in the friction zone. Therefore, in modern engineering it is very important to develop modern materials with a stable state of the structure, minimal chemical activity at elevated temperatures and preservation of physical and mechanical properties in a large range of loading parameters. In this paper, we consider a friction pair based on a promising material based on superhard materials (SHM).

METHODOLOGY

The use of standard pairs of friction on the basis of steel and bronze has not met the modern requirements of mechanical engineering for a long time, in particular, it concerns the operation of interfaces in high temperature conditions and lubricant restriction. The most attractive materials for friction pairs are materials resistant to chemical processes and thermal structural changes, which include superhard materials (SHM) (Adamovsky et al., 2015). This class of materials has found primary use in tool making, where friction pairs work under conditions of high temperatures and lack of lubrication. As construction materials, SHM began to develop in the late 80s with the start of the implementation of PVD - and CDV - technologies. The use of these technologies in mass production is limited due to low productivity and efficiency.

In this paper, we propose to analyze the antifriction properties of thin antifriction coatings based on the powder composition $B_4C+BN+C$ (boron carbide, boron nitride, carbon) obtained by short-pulse laser melting (Ipatov et al., 2015; Ipatov and Kharanzhevsky, 2018; Harris et al., 2002; Kharanzhevskiy et al., 2015; Ipatov et al., 2011; Kharanzhevskiy and Ipatov, 2010; Ipatov et al., 2015). To analyze the tribological properties, wear tests were carried out in accordance with the methodology presented in (Ipatov et al., 2018; Ipatov and Kharanzhevsky, 2018), while monitoring the friction coefficient in the friction zone. Copper alloy Br010 was used as a counter body. The wear tests of the steel-bronze friction pair under those conditions produced for comparison of the obtained data.

The formed coatings were subjected to metallographic examination (macro- and microanalysis) in order to determine the porosity of the structure and the quality of adhesion to the surface of the steel substrate, using the metallographic microscope “Neophot-32”.

RESULTS

Metallographic studies were carried out to determine the quality of adhesion of the applied superhard material on the surface of the steel substrate, the presence of pores and poor penetration in the coating structure (Figure 3). The coating is characterized by a dense structure, without the presence of pores and incomplete penetration, uniform thickness and good adhesion.

It should be noted that there is a thin layer between the steel substrate and the coating, which indicates the formation of hardening phases due to the reaction of the components of the coating and the substrate. The coating thickness is about 30–40 μm and is determined by the amount of filler material fed into the laser remelting zone (Ipatov and Kharanzhevsky, 2018).

Figure 3: Appearance and Microstructure of the Coating (BN+B₄C+C) Deposited on a Steel Substrate

The primary task of testing was to determine the performance of the coating. To this end, the test coating was subjected to wear tests under conditions of liquid and dry sliding friction. At the same time, the moment of destruction (seizure) of the coating was recorded (Figure 4). Hard alloy VK 20 was used as a counter body.

Figure 4: Influence of Lubrication Conditions of Conjugation on the Friction Coefficient

Under conditions of dry friction, the value of the friction coefficient is about one, which corresponds to the static friction. With an increase in dynamic loading, a smooth but insignificant decrease in the coefficient of friction occurs, which indicates an increment of surfaces and an increase in the nominal contact area. A further increase in load increases

the friction coefficient in a jump wise manner, which corresponds to 400-500 N load. Analysis of the friction surfaces showed that micro-seizures occurred on the surface of the counter body, while the coating did not undergo destruction and deformation. At the same time, a thin film of a vitreous material with low adhesive strength with the base was formed on the friction surface in the contact zones. Most likely, this structure is boron oxide, which is confirmed by studies conducted by competent authors (Harris et al., 2002). Boron oxide is naturally layered, i.e. low value of adhesive bonds on the cut (low internal friction), which reduces the friction coefficient.

DISCUSSIONS

The most significant from a practical point of view are comparative tests of friction pairs. Studies have shown the performance of the analyzed friction pair in the conditions of boundary lubrication.

Figure 5: Comparative Tests of Pairs of Friction

In the initial test period, the friction coefficient of the Steel-Bronze friction pair is lower than the friction coefficient of the analyzed SHM-Bronze friction pair. The lower coefficient of friction is due to increased deformation of asperities in the contacting surfaces, which leads to intensive stabilization of the effective contact area with a decrease in the coefficient of friction and wear processes. On the other hand, with an increase in dynamic loading, the compared friction pair exhibits an abrupt increase in the coefficient, followed by a setting process (with a load of 480–500 N). The high ductility of both surfaces causes deformation with the formation of a deformation roller along the relative movement of the contacting surfaces. In the analyzed friction pair, the situation is reversed, characterized by an initial high friction coefficient, which gradually stabilizes and decreases with increasing load on the friction pair. The Coulomb theory of the interaction of the contacting surfaces, which implies the elastic contacting of asperities, with the absence of adhesive processes, can serve as an explanation. The elastic form of contact provides lower values of the friction coefficient, which is caused by a decrease in the roughness in the friction zone and a stable contact area.

CONCLUSIONS

The presented laws of the dependence of antifriction properties, in particular, the friction coefficient on the type of structures being formed, as well as the fundamentals of molecular mechanical friction make it possible to create friction pairs with high antifriction properties. One of the ways to ensure high antifriction properties is to use as one of the friction surfaces superhard materials with high elasticity of the structure, high structural integrity at high temperatures and low

oxidizing ability. The presented results of wear tests suggest that the proposed technology using boron carbonitride-based coatings obtained by short-pulse treatment has high wear resistance and has high antifriction properties.

Considering the advantages of antifriction properties based on superhard materials, they can be used in friction assemblies, which is operated at high specific loads, high sliding speeds and temperatures.

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