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The Influence of the Phase Composition of the B-N-C System Composite Material on Its Physical-mechanical and Tribological Characteristics

V.M. Volkogon[1], S.K. Avramchuk[1], A.V. Kravchuk[1], T.V. Pavlychuk[1], V.S. Antonyuk[2], K.I. Avramchuk[2]

[1] *Frantsevich Institute for Problems in Materials Science, National Academy of Sciences of Ukraine, 3, Krzhizhanovsky St., 03142 Kyiv, Ukraine*
[2] *National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", 37, Peremogy Ave., 03056 Kyiv, Ukraine*

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The results of investigations of physical-mechanical and tribotechnical characteristics of composite materials based on wurtzite boron nitride of different phase composition, which contain a diamond component in the form of elements of the microstructure of the composite and solid solution of diamond in boron nitride, are presented. It is defined that the maximum hardness of the composites is formed in the temperature range T = 160-700 °C, and further increase of the sintering temperature is accompanied by a decrease in the hardness caused by the material recrystallization and the weakening of the intergranular boundaries. Composites obtained at a temperature T = 1700 ºC have the maximum index of the physical and mechanical characteristics. The influence of the phase composition of the composite material on its tribotechnical properties at dry friction on a steel counter in the conditions of a steady change in the speed of sliding in the range V = 6-14 m/s at a load of 20 N is determined. The obtained results can be used to develop practical recommendations for the effective use of composites of WN_B-diamond systems in metalworking processes, as well as in heavy-duty friction pairs under conditions of limited lubrication.

Keywords: Boron nitride, Wurtzite, Sphalerite, Diamond, Composite, Solid solution, Hardness, Coefficient of friction, Wear resistance.

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1. INTRODUCTION

Polycrystalline superhard composite materials (PSCM) based on dense modifications of boron nitride are mainly used as a cutting tool in the machining of hardened steels [1-3], and can also be effectively used in elements of heavy friction pairs [4, 5]. PSCM on the wurtzite boron nitride basis, depending on the barothermal conditions of formation, are characterized by a certain ratio of dense phases (BNw – BNsf). An increase in the content of the sphalerite component in the material contributes to the increase of thermal conductivity of the composite and the temperature threshold of oxidation [6]. It should be noted that the thermal stability of composites is determined by the process of oxidation of wurtzite and sphalerite boron nitride with oxygen and reverse phase transformation of them into graphite-like modification. In metalworking processes, the efficiency of the application of such PSCM is estimated by the temperature in the contact zone with the material being processed, which limits the processing efficiency and affects its structure and phase composition of the surface layer [1].

Therefore, when developing the optimum technology for machining hard-machined steels with a tool based on dense boron nitride modifications, it is necessary to take into account the thermal intensity of the cutting process, which is highly dependent on the heat treatment and associated with its tribotechnical characteristics. The main component of the composite PSCM system "wurtzite boron nitride – carbon" (BNW-C) is dense modifications of boron nitride, which according to structural studies [7], are in interphase with diamond and the microstructure of such compounds and the phase composition of the matrix component (BN) changes according to the change of thermobaric sintering conditions. The high hardness and strength of the composite are not sufficient conditions to ensure its effectiveness both in the cutting tool, which must have a sufficient level of wear resistance (which depends largely on the temperature on its working surfaces), and in the friction contact of the friction pairs. The operational characteristics of composite materials are closely related to their phase composition and structure state.

The purpose of the study is to investigate the physical-mechanical and tribotechnical characteristics of composite materials based on wurtzite boron nitride containing a diamond component depending on the phase state of the matrix component.

2. METHODS OF SAMPLE PREPARATION AND RESEARCH

Samples of composite materials based on wurtzitic boron nitride of different phase composition containing the diamond component were obtained by sintering at high static pressures (p = 7.7 GPa) in the temperature range T = 1500-1700 °C for τ = 60-120 s. The initial mixture consisted of wurtzite boron nitride powders with a dispersion of 0.1-5.0 μm and diamond powders of static synthesis with a grain size of 0.1/0 μm in a ratio of 90:10 by weight. The sample after sintering was subjected to mechanical grinding of all surfaces, after which its phase composition, uniformity of the grinding field and microhardness were determined.

X-ray studies of the phase composition was carried out using a DRON-3 diffractometer in copper radiation with a monochromator in automatic mode with a stepwise movement of 0.050 and an exposure duration at each point of 4 s.

The microhardness of the composites was measured by the microhardness mod. MHU-2000 with the help of the Vickers pyramid at 2H load in automatic mode with exposure under load $\tau = 15$ s.

Studies of friction properties were carried out on the installation of MT-62M in friction by friction and linear contact (cylinder by cylinder), in the air without the supply of coolant in the friction zone. The tests were carried out at a constant load of 20 N and the sliding speed $V = 6$-14 m/s, which varied stepwise (after 2 m/s). The composite specimens were in contact with a rotating 100 mm diameter steel ball having a diameter of 7 mm with a length of 4 mm. Counterpart material HRC steel (HRC 58-62).

During the experiment, the friction force and the total linear wear of the contact pair were determined simultaneously and independently, which determined the friction coefficient and the wear rate of the sample (μm/km). Samples of Composite-10, which consisted entirely of sphalerite boron nitride, were specially made from the same batch of wurtzite boron nitride powder that was used to obtain the "wurtzite boron nitride – diamond" composites.

3. EXPERIMENTAL PART AND DISCUSSION OF RESULTS

The results of studies of the phase composition of composite materials based on wurtzite boron nitride obtained at different temperatures showed that the content of sphalerite boron nitride is determined only by the sintering temperature, regardless of the composition of the original charge (Table 1).

According to structural studies, the diamond component of the composition after sintering is almost completely stored in a sintered matrix material based on boron nitride, both in the state of the component structure of the composite and in the form of a solid BNC solution. The character of the composite hardness formation depending on the sintering temperature shown in Fig. 1 indicates that its maximum value is reached at a temperature $T = 1600$-1700 °C, and further increase in temperature is accompanied by a decrease in the hardness due to, apparently, the process of gathering recrystallization of the material and the weakening of the intergranular boundaries.

The duration of the sintering process [8, 9] has a decisive influence on the formation of the physico-mechanical characteristics of the composite materials of the “wurtzite boron nitride – diamond” system.

Table 1 – The phase composition of the composite materials of the system "wurtzite boron nitride – diamond" depending on the composition of the initial mixture and sintering temperature

№ of sample	Material	BN_w	Phase composition, % vol.			
			BN_w	BN_{sf}	Diamond	Solid solution
1	$BN_w + C_a$ 0.1/0 μm	1500	17	73	9	1
2	$BN_w + C_a$ 0.1/0 μm	1600	6	84	9	1
3	BN_{sf} (composite-10)	1700	–	100	–	–

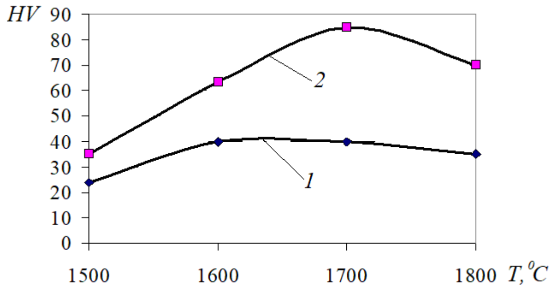


Fig. 1 – The nature of the hardness of composites depending on the temperature and the duration of sintering: 1 – $\tau = 60$ s; 2 – $\tau = 120$ s

The duration of the sintering process [8, 9] has a decisive influence on the formation of the physico-mechanical characteristics of the composite materials of the “wurtzite boron nitride – diamond” system.

Fig. 2 shows the nature of the physico-mechanical characteristics formation of composite materials of this system, depending on the duration of the sintering process.

The microstructure of the composite is unevenly distributed across the field of samples in the area of solid BNC solution (Fig. 3), which is probably due to the heterogeneity of the initial mixture to obtain the composite before sintering, resulting in the hardness of the composition fluctuates within 55.0-83.0 GPa.

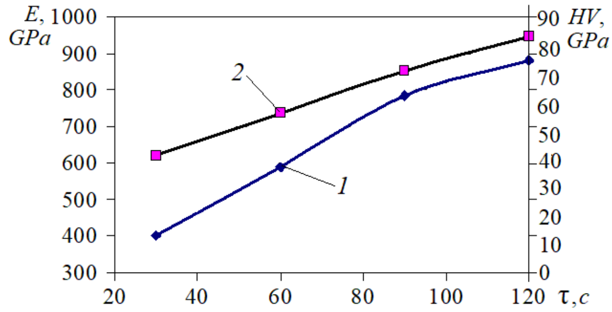


Fig. 2 – The influence of the sintering duration of the composite material of the "wurtzite boron nitride – diamond" system at a temperature $T = 1700$ °C on its physical and mechanical characteristics: 1 – Young's modulus, E; 2 – hardness, HV

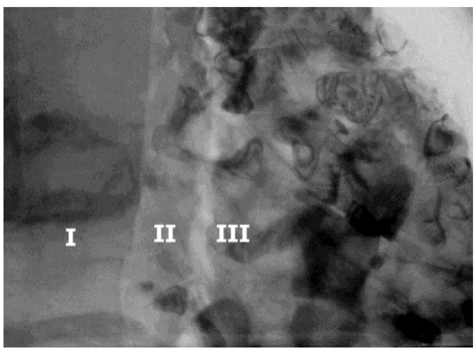


Fig. 3 – Microstructure of the composite with a fragment of the "wurtzite boron nitride – diamond" BNC solid solution: I – diamond; II – layer of BNC solid solution; III – BN matrix

Studies of tribotechnical characteristics of the composite material of the BN_w-C system found that in the initial period of testing the increase in the velocity of sliding of the friction pair is accompanied by a gradual decrease in the coefficient of friction and wear in the process of working, and when the critical velocities are formed and stabilize, has no significant changes as the sliding speed increases.

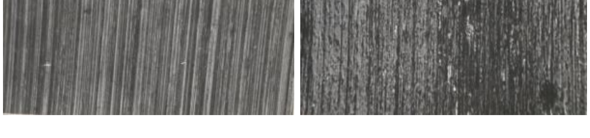
Such a change in the friction properties of the friction pair under study can be explained as follows. It is known [3] that for materials characterized by a large value of the elasticity modulus in the elastic contact region in the zone of low sliding velocities and low temperatures, a sufficient protective film on the connected surfaces is not able to form and deformation of the surface is transformed into a micro-cutting process ($V = 6$ m/s). Further increase in the sliding speed, which is accompanied by an increase in temperature in the contact zone, contributes to the formation of a protective film of sufficient thickness at $V = 8$ m/s.

By its composition, this film may include B_2O_3 boron oxide [6] and graphite, which helps to reduce the friction coefficient and the wear rate of the samples. A further increase in the sliding speed changes the nature of the film itself and the quality of the friction process.

The high temperature in the pair contact zone can contribute to the partial phase transformation of diamond microvolumes and dense modifications of boron nitride into graphite modification [6, 10], which initiates the appearance of a screen film with a high level of antifriction characteristics. Some influence on the formation of these indices has the presence in the material of high-strength wear-resistant sections of BNC solid solution, which appear during the formation of the structure of the composite under conditions of high pressures and temperatures.

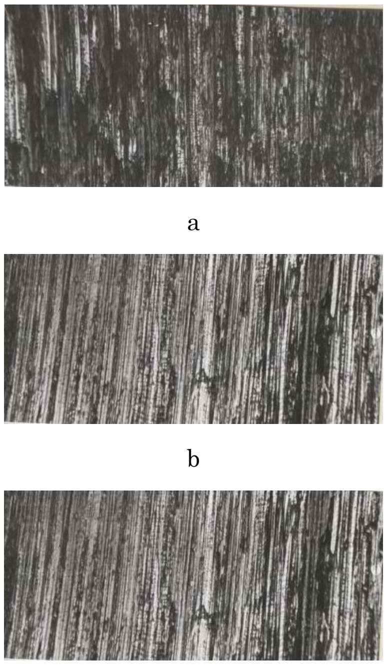
Given that the real transformation of $BN_w \rightarrow BN_g$ and $C_d \rightarrow C_g$ begins at the surface of the samples along the grain boundaries in the polycrystal, the origin of graphite and BN_g depends essentially on the dispersion of the crystalline superhard phases. It should be noted that during the test of friction steam, there is a smoothing of the contact surface of the counter and it has a polished appearance (Fig. 4b). Decrease of roughness from machining, which is clearly manifested on the counter prior to its testing, indicates the presence of a period of working pair in the initial stages of testing (Fig. 4a).

Due to the fact that polycrystalline samples of composite material based on dense modifications of boron nitride have different phase composition and different component based on diamond, the friction contact behavior of such materials is of the greatest interest. For samples No.1 and No.2, the critical sliding velocity that promotes film formation on the surface of the counter is $V = 8$-10 m/s. It should be noted that if for a single-phase sample based on BN_{sf}, the film on the counter only appears at a critical velocity $V = 12$ m/s (Fig. 5), then for samples No.1 and No.2 it is characteristic that at the surface of the counter in the velocity range 8-10 m/s there are dark areas, and at critical speed there is a complete covering of the working area with a film.



a b

Fig. 4 – Appearance of the surface of the HRC counter-hardened steam in the friction pair: before tests (a) and after tests at a velocity $V = 6$ m/s (b)



a

b

c

Fig. 5 – Appearance of the surface of a HRC steel ball counter after single-phase friction test: sliding velocity $V = 14$ m/s (a); $V = 12$ m/s (b); $V = 8$ m/s (c)

This pattern is explained by the fact that the increase in the content of wurtzite component in the composite facilitates the flow of reverse phase transformation $BN_w \rightarrow BN_g$ [10], which can take place on the surface of the samples due to the heterogeneity of their structure and phase composition. Such circumstances lead to the fact that the transformation in the wurtzite boron nitride and the diamond component in the graphite modification decreases the temperature in the zone of the contact friction pair, as the loss of friction decreases, and for the transition of dense modifications of boron nitride and carbon (diamond) again in the contact area.

Such conditions are realized by increasing the sliding velocity, which causes the shift of its critical value towards growth with a lower content of wurtzite phase in the material. It should be noted that the coefficient of friction of samples No.1 and No.2 after the film appeares is within 0.70-0.72 (Fig. 6), which indicates the identity of the appearing films, that is, the phase composition of the material does not affect the properties of the film, but is only a sign of determining the critical velocity for its occurrence, which is a confirmation of the transition of dense modifications of boron nitride – the basis of the composite into the layered structure BN_g.

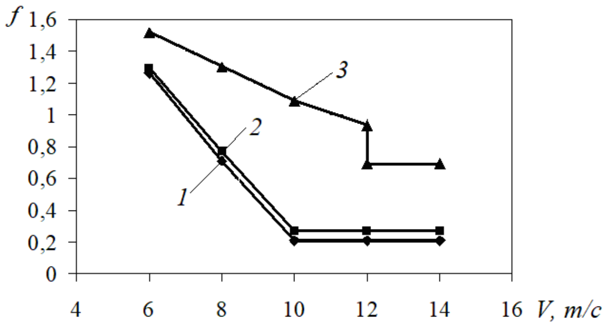


Fig. 6 – Dependence of the friction coefficient of the composites on the sliding velocity: 1 – sample No.1; 2 – sample No.2; and 3 – sample No.3

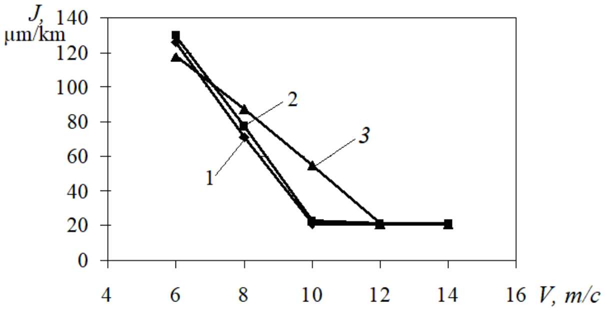


Fig. 7 – The dependence of the wear rate of the composites on the sliding velocity: 1 – sample No.1; 2 – sample No.2; 3 – sample No.3

The presence of the diamond component improves the frictional characteristics of the composite by changing the thermophysical properties and increasing the hardness due to the appearance of areas of BNC solid solution.

Study of frictional characteristics of polycrystalline superhard materials (PSCM) from boron nitride of different phase composition paired with heat-treated steel in air under dry friction under conditions of stepwise variable sliding velocity $V = 6\text{-}14$ m/s (magnitude of 2 m/s) at a load of 20 N showed that the single-phase material is characterized by a gradual decrease in the coefficient of friction and the intensity of wear, after which there is a jumble establishment of constant values of these parameters (Fig. 7), which compared with the initial $f = 1.25\text{-}1.68$ decrease to $f = 0.25\text{-}0.62$, and $I = 100\text{-}130$ mm/km to $I = 25$ m/km.

At high critical velocity, there is a qualitative change in the friction process due to the intense occurrence of the film on the surface of the counter, which leads to the stabilization of the friction characteristics and the establishment of their minimum values. It is worth noting that for single-phase PSCM, the critical velocity is $V = 12$ m/s, while for two-phase PSCM samples with a diamond component it is practically absent, and there is a friction pair with a gradual decrease in the wear rate and coefficient. This circumstance is in good agreement with the thermal stability of various modifications of boron nitride and diamond and their thermal conductivity, when the presence in the material of high content of wurtzite boron nitride with low thermal conductivity and heat resistance than sphalerite boron nitride, at lower friction velocities, they are reversed by the phase transformation $BN_w \rightarrow BN_g$ in the contact zone and observed, which contributes to the reduction of the friction coefficient, and the sections of the solid solution with high hardness values provide increased wear resistance.

4. CONCLUSIONS

The results of the complex of researches give grounds for the following conclusions.

1. The hardness of composites of the "wurtzite boron nitride – diamond" system is determined by the duration of sintering at high pressures. The optimum sintering temperature of the composites is 1700 °C, which helps to obtain maximum index of physical and mechanical properties.

2. Tribotechnical characteristics of composites with a diamond component are of higher importance due to the change in thermophysical properties of the material, and the increase of the hardness due to the appearance of areas of BNS solid solution.

3. The presence in the composite of the diamond component and BNC solution with high physical and mechanical properties causes the formation of high tribological characteristics of the material, which can be effectively used in heavily loaded pairs operating in conditions of friction contact.

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Вплив фазового складу композиційного матеріалу системи B-N-C на його фізико-механічні та трибологічні характеристики

В.М. Волкогон[1], С.К. Аврамчук[1], А.В. Кравчук[1], Т.В. Павличук[1], В.С. Антонюк[2], К.І. Аврамчук[2]

[1] *Інститут проблем матеріалознавства імені І.М. Францевича Національної академії наук України, вул. Кржижанівського, 3, 03142 Київ, Україна*

[2] *Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», просп. Поремоги, 37, 03056 Київ, Україна*

Наведено результати досліджень фізико-механічних та триботехнічних характеристик композиційних матеріалів на основі вюртцитного нітриду бору різного фазового складу, які вміщують алмазну складову у вигляді елементів мікроструктури композиту та твердого розчину алмазу в нітриді бору. Встановлено, що максимальна твердість композитів формується в діапазоні температур T = 1600-1700 °С, а подальше підвищення температури спікання супроводжується зниженням твердості, обумовленого збиральною рекристалізацією матеріалу та послабленням міжзеренних границь. Максимальні показники фізико-механічних характеристик мають композити, отримані при температурі T = 1700 °С. Визначено вплив фазового складу композиційного матеріалу на його триботехнічні властивості при сухому терті по стальному контртілу в умовах ступінчатої зміни швидкості ковзання в діапазоні V = 6-14 м/с при навантаженні 20 Н. Отримані результати можуть бути використані для розробки практичних рекомендацій щодо ефективного застосування композитів системи «$BN_в$-алмаз» в процесах металообробки, а також у важконавантажених парах тертя в умовах обмеженого змащення.

Ключові слова: Нітрид бору, Вюртцит, Сфалерит, Алмаз, Композит, Твердий розчин, Твердість, Коефіцієнт тертя, Зносостійкість.