

40. Kataev, S., Sidorov, V., & Hordeev, S. (2011). Almaz-karbidnyi kompozitsionnyi material «Skeleton» dlia teplootvodov v izdeliakh elektronnoi tekhniki [Diamond-carbide composite material «Skeleton» for heat sinks in electronic products]. *Elektronika: Nauka, Tekhnologiya, Biznes – Electronics: Science, Technology, Business*, 3, 60–64 [in Russian].
41. Ekimov, E.A., Suetin, N.V., Popovich, A.F., et al. (2008). Vliianie mikrostruktury I razmera almaznykh zeren na teploprovodnost almaznykh kompozitov, poluchennykh pri vysokikh davleniakh [Influence of the microstructure and size of diamond grains on the thermal conductivity of diamond composites obtained at high pressures]. *Nerhanicheskie materialy – Inorganic materials*, Vol. 44, 3. 275–281.
42. Ghosh, S., Bao, W., Nika, DL, et al. (2010). Dimensional crossover of thermal transport in few-layer graphene materials. *Nature Materials*, Vol. 9, 7, 555–558.
43. Shul'zhenko A. A., Jaworska L., Sokolov A. N., et al. (2017). Phase transformations of n-layer graphenes into diamond at high pressures and temperatures/ *Journal of Superhard Materials*, Vol. 39, 2, 75–82.

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COMPOSITION, STRUCTURE, PROPERTIES (MECHANICAL, OXIDATION RESISTANCE, ELECTRICAL RESISTANCE) AND PERFORMANCE OF WHISKER-REINFORCED CBN-BASED MATERIALS WITH NBN BINDER

Three types of cBN-based composites (without whiskers, reinforced with Si₃N₄ whiskers (Si₃N_{4w}) and reinforced with SiC whiskers (SiC_w)) obtained by High Pressure-High Temperature (HPHT) sintering. Density, Young's modulus, Bulk modulus, Poisson ratio, hardness and fracture toughness, oxidative resistance and electrical resistivity have been measured. Whisker-reinforcement using all above-mentioned whisker's types (SiC_w, Si₃N_{4w}) led to the improvement of mechanical properties (hardness, fracture toughness), oxidative resistance and electrical conductivity. Despite this, only SiC_w-reinforcement was effective wear resistance improvement due to the higher chemical resistance of SiC_w compared to Si₃N_{4w}.

Key words: cBN, whiskers, oxidation, electrical resistivity, wear, mechanical properties

Introduction

Impact cutting is a difficult complex process. The processed material is simultaneously exposed to the chemical, mechanical and oxidative wear at the same time during this process [1]. In [2–4] it is shown that thermoelectric phenomena in the process of cutting enhance the diffusion of the components of the tool material into the processed material, affect the oxidation processes and adhesion of materials. Electric current during cutting has a complex effect on the processes occurring in the cutting zone and on the contact surfaces of the cutting tool. At the same time, there are also

data showing that the electric current flowing along the «machine tool – product – machine» circuit during cutting leads to an intensification of oxidative, adhesive and diffusion wear of the cutting tool [4]. Thus, there is a need for a detailed study of not only the mechanical characteristics, but also the oxidation resistance, as well as the electrical resistance of cBN-based composites. Therefore, this work presents the results of studying the effect of the content of the chemical nature of fibers on the microstructure, elastic and mechanical properties, resistance to oxidation, thermoelectric resistance of samples based on cBN. The composition of the studied samples is shown in Table 1.

Table 1. The composition of sintered samples

1	60 vol. % cBN – 5 vol. % Al – 35 vol. % NbN
2	60 vol. % cBN – 5 vol. % Al – 25 vol. % NbN – 10 vol. % SiCw
3	60 vol. % cBN – 5 vol.% Al – 25 vol. % NbN – 10 vol. % Si ₃ N ₄ w

Experimental

The powders of cBN ($d=2-6 \mu\text{m}$), Al ($d=1 \mu\text{m}$), NbN ($d=2-3 \mu\text{m}$) and different whiskers (Si₃N₄w and SiCw) were used as a starting materials. Mixing of powders was carried out using «drunk barrel» mixer type over 5 hours in isopropyl alcohol. The mixture without whiskers were obtained this way. For production of powder mixtures with 10 vol. % whiskers ultrasound mixing of start mix

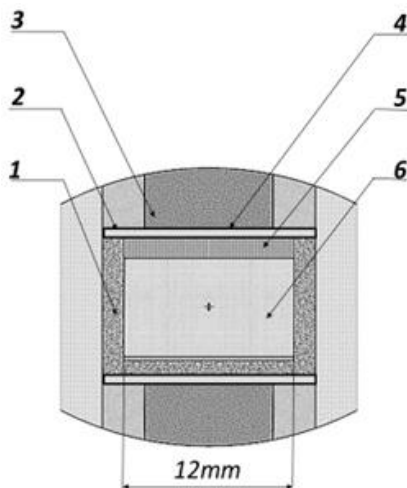


Fig. 1. Central part of the high-pressure cell (1 – fine-grained graphite cup-heater; 2 – pyrophyllite pressed ring; 3 – axial heaters; 4 – titanium disks; 5 – pressed disks; 6 – sample)

with whiskers in isopropyl alcohol was done. The green compacts creation and density measurements of green compacts was done after mixing. After this step, all samples were placed in graphite crucibles for vacuum annealing. After composing of high-pressure cell assembly (Fig. 1) all samples were sintered in toroid-type high-pressure apparatus (HPA) at 7,7 GPa at 2000 °C. After HPHT sintering, the samples were ground to a round plate 9,2 mm in diameter and 3,18 mm in height. The sintered samples density was measured both by the standard (definition the density as a mass to volume ratio) method and by hydrostatic weighing. Young's modulus was measured using non-destructive ultrasonic method (ASTM 1875-00 Standard Test Method for Dynamic Young's Modulus [5-6]. Microstructural investigations and element

distribution were carried using SEM Hittachi SU8010 Cold Field Emission with high resolution. The cutting performance of the samples was tested by interrupted turning of hardened (HRC 62) alloy tool steel 107WCr5. Besides this, thermodynamic modeling of chemical interaction in the systems under study was done with the use of ThermoCalc software.

Investigation of samples oxidation using synchronous thermal analysis (STA) were performed. STA method combines the simultaneous conduct of thermogravimetric (TG) and differential scanning calorimetry (DSC). Investigations were performed on the STA 449F1 device (company NETZSCH) in an oxidizing atmosphere (air). The heating and cooling rate of the test sample was 20 deg./min.

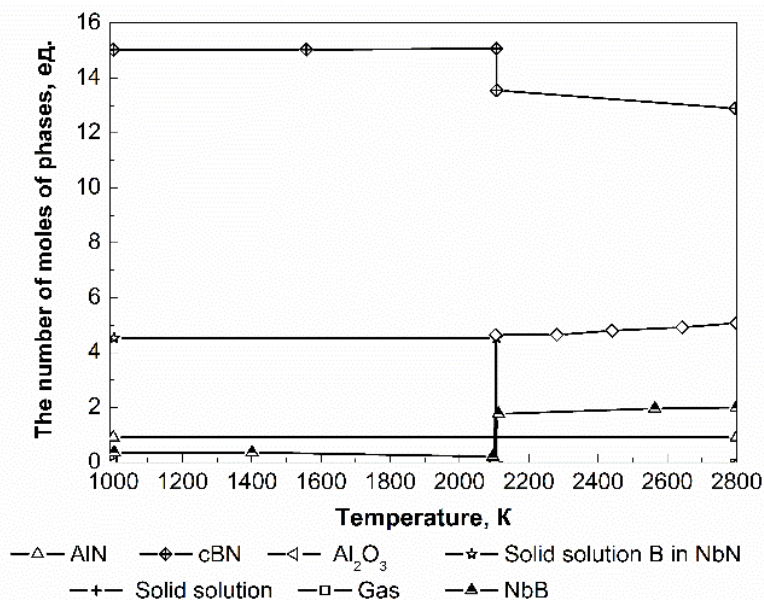
To determine the samples electrical resistance, a stand was used for the electrical conductivity measuring of composites in a wide range of temperatures and stresses. The electric scheme of the stand is mounted on the basis of Agilent 4339B and B7E-42 electrometers and gives the chance to work both in the mode of current stabilization, and in the mode of voltage stabilization. The magnitude of the voltage drop across the sample was measured using a nanovoltmeter NV724. The samples resistance was determined on the ohmic section of the I – V characteristics. The resistivity of polycrystals was calculated taking into account the geometric dimensions of the contacts by the formula:

$$\rho = \frac{U}{I} \frac{\pi d^2}{4h},$$

where U – voltage drop across the sample, V; I – current through the sample, A; h – thickness of the sample, mm; and d – diameter of the electrodes, mm

Discussion of thermodynamic modeling and microscopy investigations results

Thermodynamic modeling was performed in the ThermoCalc [7] program in order to understand the processes occurring during HPHT sintering, as well as to study the oxidation processes of the synthesized material. The main advantage of using this program compared to manual calculations is the availability of a large database of substances and the necessary data to calculate the Gibbs energy (enthalpy, entropy, molar volume, temperature and pressure intervals of polymorphic modifications of substances, etc.), which allows taking into account most possible options for reactions. The results of thermodynamic calculations of the reactions at high pressure showed that at high pressure (7,7 GPa) were predict the formation of solid solutions of boron and nitrogen in NbN was predicted, as well as the formation of NbB, (Fig. 2), which indicates the interaction of matrix material (cBN) and binder material (NbN).



a

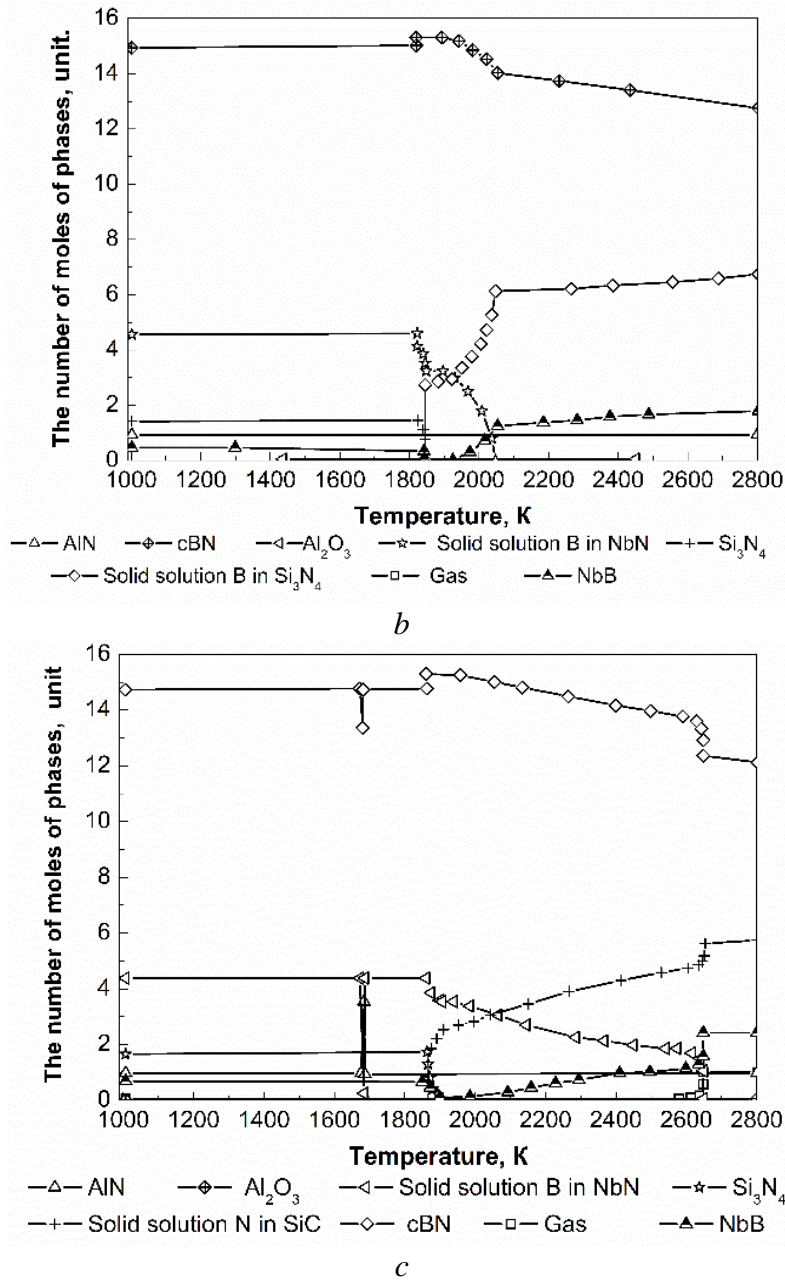


Fig. 2. Results of thermodynamic modeling of different system's behavior (cBN-NbN-Al (a), cBN-NbN-Al-Si₃N₄ (b), cBN-NbN-Al-SiC (c)) under pressure $P = 7,7 \text{ GPa}$

The simulation showed the presence of a chemical interaction between aluminum, nitrogen and oxygen with the subsequent formation of aluminum oxide and nitride. The formation of solid solutions of boron and nitrogen and the diffusion of boron and nitrogen atoms into whiskers of silicon carbide and silicon nitride was predicted too, which was also confirmed elements on the surface of the samples using SEM (Fig. 3).

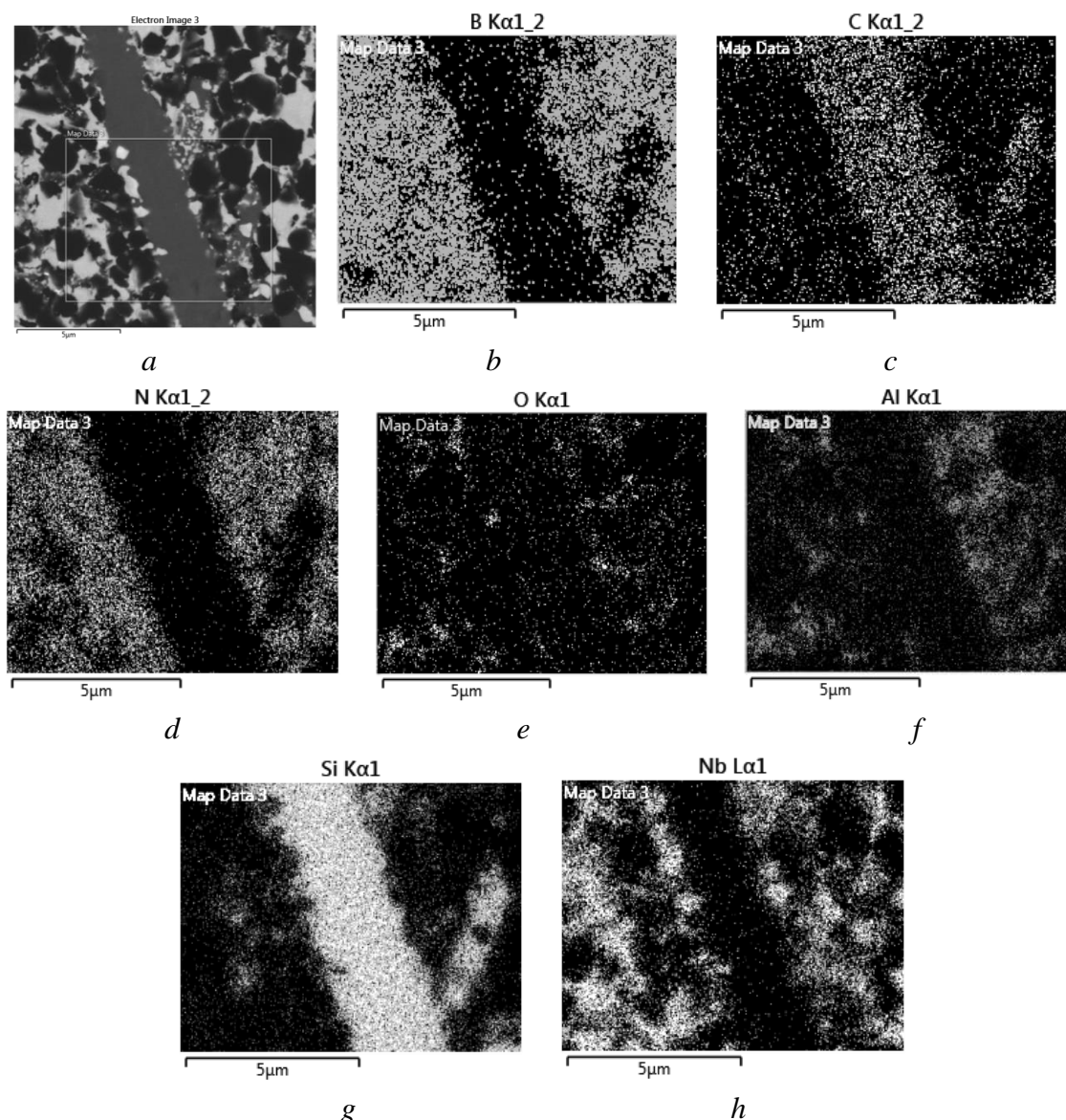


Fig. 3. SEM (a) and EDX (b, c, d, e, h) pictures of new cBN–NbN–Al–SiCw sample

Influence of whiskers on microstructure, chemical composition and mechanical properties of sintered composites

The high microstructure homogeneity degree of all the sintered samples (regardless of cBN content) (Fig. 4, c-e) and high density (Table 2) at the same time shows the correctness of mixing parameters choosing (Fig. 4) [8]. The absence of aluminum compounds peaks for non-reinforced sample (Fig. 4, f) and reinforced by silicon nitride whiskers (Fig. 4, h) is most likely due to the overlap of the peaks of aluminum-containing phases with peaks of other phases due to their low content and low intensity as a result [9].

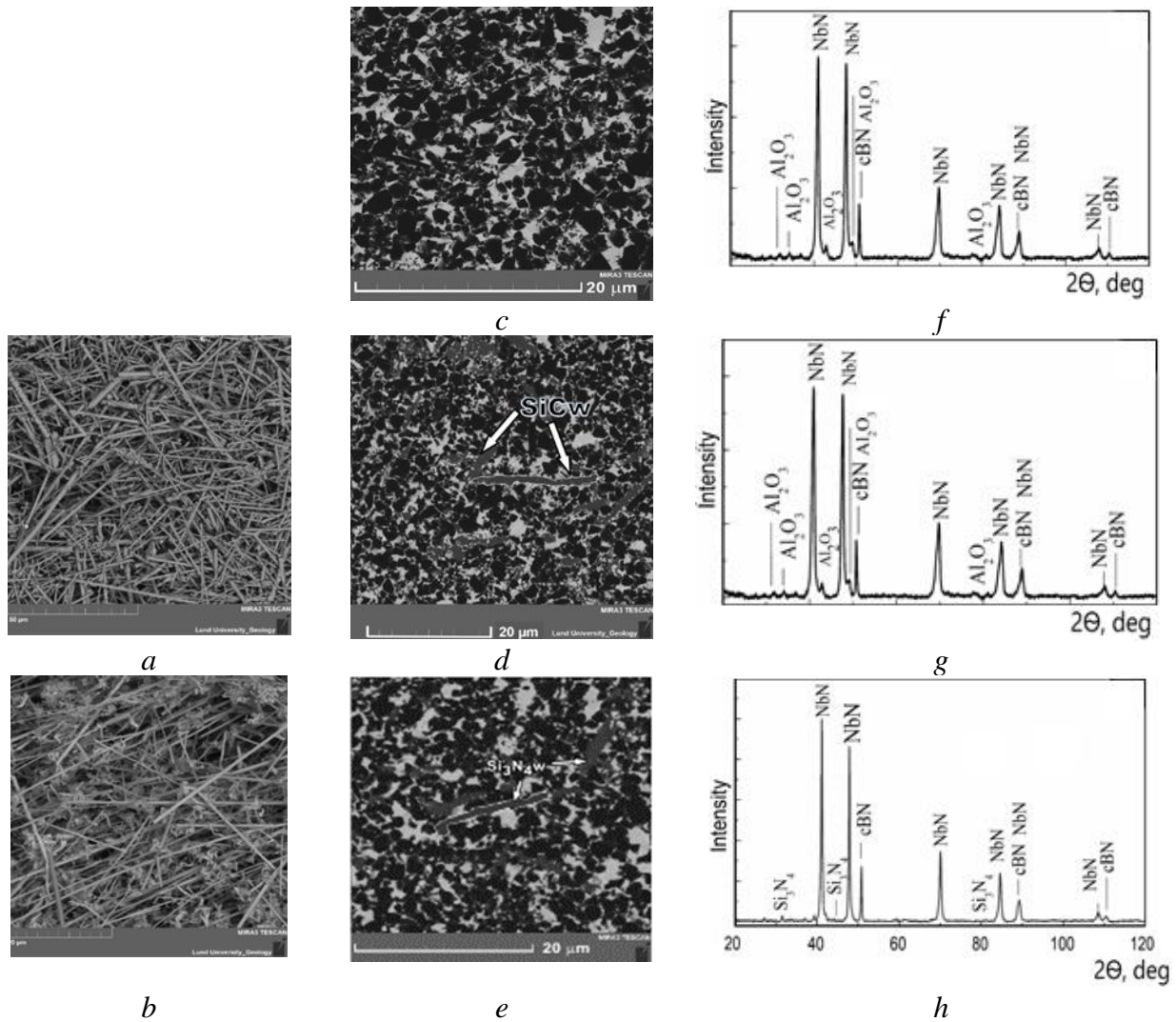


Fig. 4. Morphology of SiCw (a) and Si₃N₄w (b); microstructure and XRD results for 60 vol. % cBN – 5 vol. % Al – 25 vol. % NbN (c and f respectively), 60 vol. % cBN – 5 vol. % Al – 25 vol. % NbN – 10 vol. % SiCw (d and g respectively), 60 vol. % cBN – 5 vol. % Al – 25 vol. % NbN – 10 vol. % Si₃N₄w (e and h respectively)

The study of the microstructure showed that whiskers length after mixing and sintering is 15–20 μm, the absence of recrystallization processes and insignificant formation of solid solutions around grain boundaries. In addition, there was a simultaneous increase in hardness and fracture toughness when adding whiskers, associated with the implementation of strengthening mechanisms [10] and indicating the correctly selected mixing and sintering parameters [11].

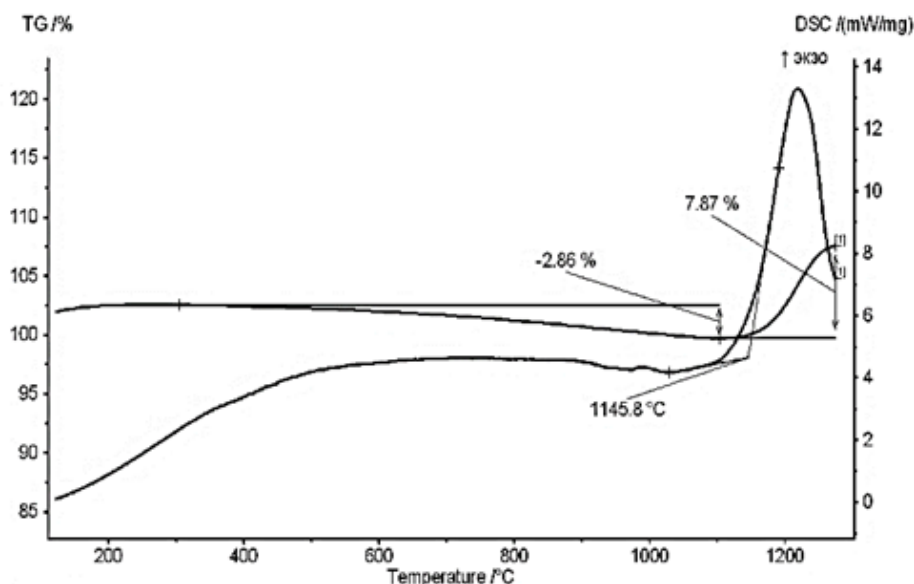
The addition of whiskers led to some decrease in elastic characteristics (E, G, B) and increase in relative density(γ) (Table 2). But usually, according to the theory of sintering [12], the addition of whiskers leads to a deterioration of the compaction of the material. Hence, it may be associated with the formation of low-modulus phases with high density (most likely, solid solutions, provided by thermodynamic calculations and registered in microstructural studies – Fig. 4), or with insufficient quality of mixing of start mix without whiskers in drunk barrel.

Table 2. Density (ρ) та relative(γ) density; Young's (E), Bulk (B) and Shear (G) modulus; Poisson ratio (μ); Vickers Hardness (HV_{98}) and Fracture Toughness (K_{Ic}) of cBN-based sintered samples

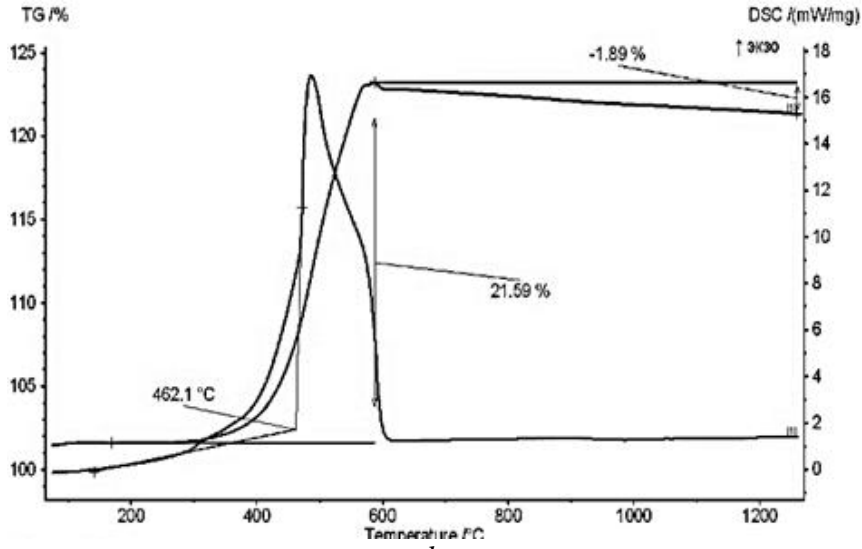
Sample	60 % cBN–35 % NbN– 5 % Al	60 % cBN–25 % NbN– 5 % Al–10 % SiCw	60 % cBN–25 % NbN– 5 % Al–10 % Si ₃ N ₄ w
ρ , г/см ³	4,74	4,51	4,53
γ , %	93,45±0,2	97,98±2	98,84±1,2
E , GPa	669	639	590
G , GPa	285	272	250
B , GPa	345	379	308
μ	0,176	0,176	0,181
HV_{98} , GPa	27,12	28,00	30,20
K_{Ic} , МПа·м ^{-1/2}	6,71	7,01	7,05

Influence of whiskers on oxidation resistance of sintered composites

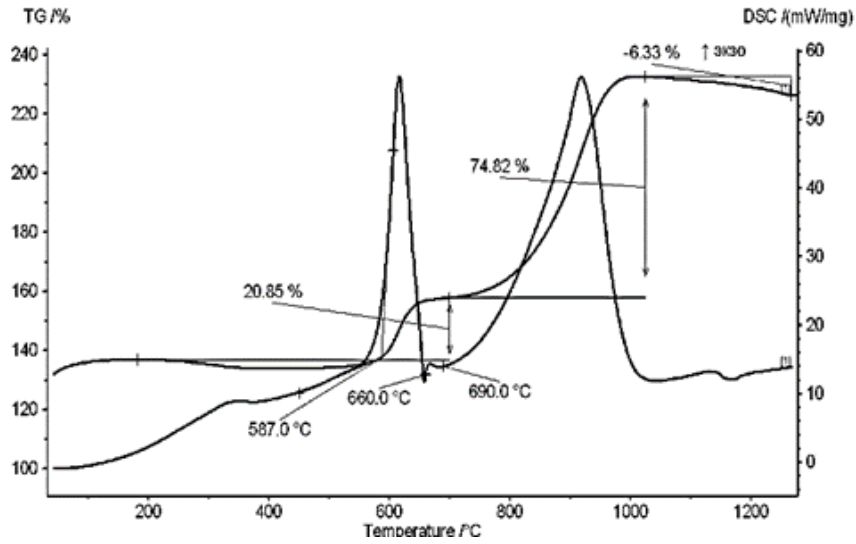
The results of oxidation resistance investigations (Fig. 5) for start powders showed that the most intensively oxidized aluminum powder (oxidation processes begin at 587 °C, and at a temperature of 1000 °C the powder burns), and the cBN powder are most resistant to oxidation. High resistance to oxidation of cBN powder (the beginning of oxidation occurs at a temperature of 1145,8 °C) indicates the absence of impurities and structural perfection of the original powder [13]. In addition, NbN powder also was unstable to oxidation, which confirmed the data [14]. In work [14] it was found that NbN oxidation occurs at the temperature range 290–645°C with a peak at 580°C with a significant thermal effect 1200 ± 200 kJ/mol with the formation of the highest niobium oxide Nb₂O₅.



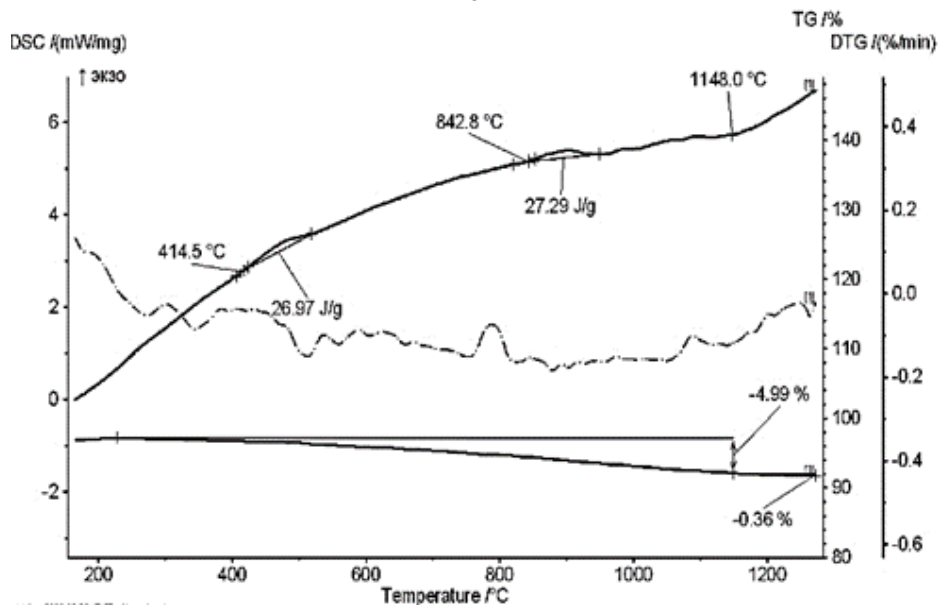
a



b



c



d

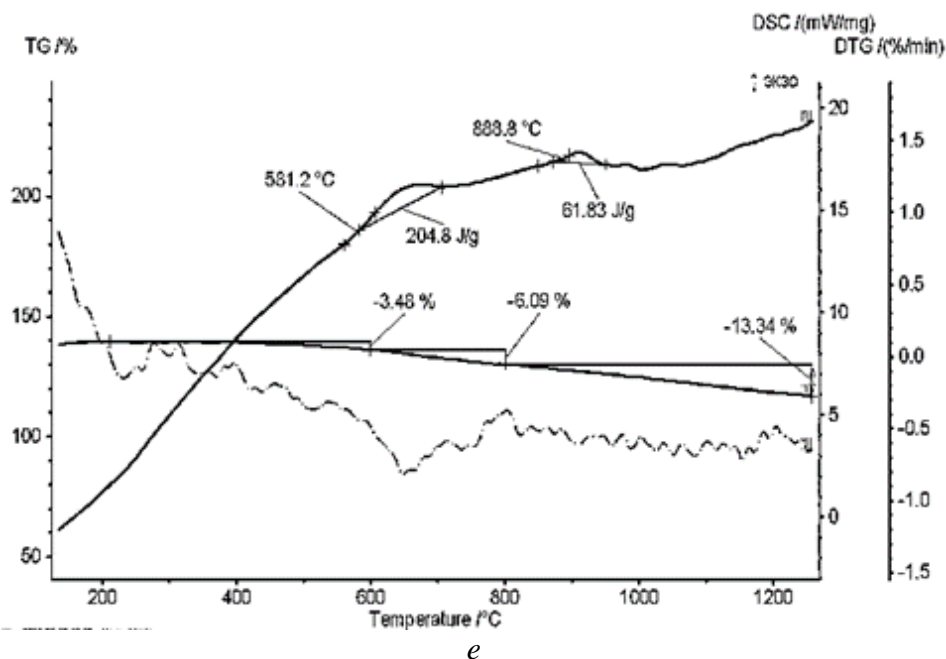
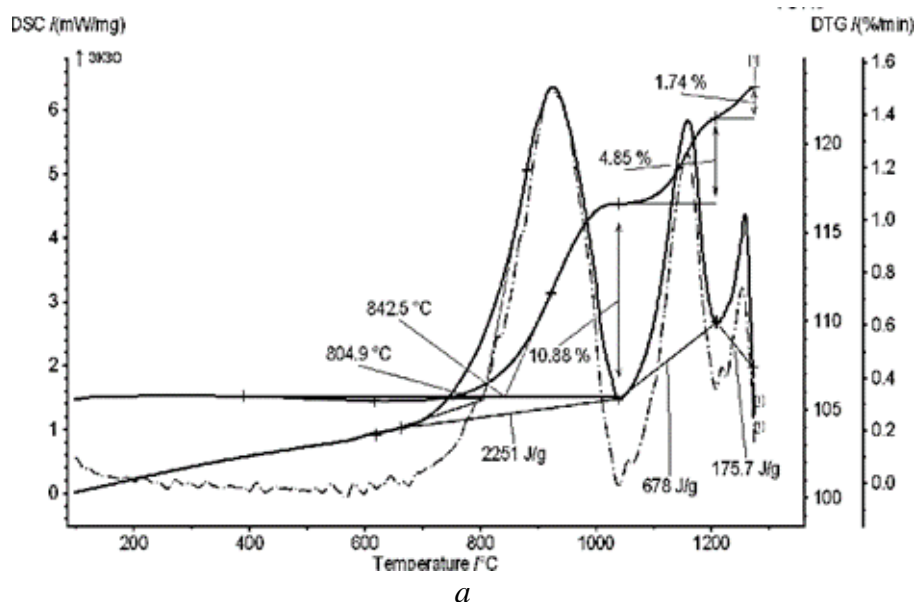


Fig. 5. STA results for start powders (*a* – *cBN*; *b* – *NbN*; *c* – *Al*; *d* – *SiCw*; *e* – *Si₃N_{4w}*)

The oxidation resistance of samples, which sintered from the above-mentioned powders, was studied (Fig. 6). Results of oxidation resistance investigations showed that the addition of whiskers to base material composition leads to the oxidation resistance. This fact can be associated with a decrease in the content of NbN (with low oxidative resistance) and a simultaneous increase in the content of oxidation-resistant whiskers (SiC and Si₃N₄), increasing the relative density (Table 2) [13] and the formation of solid solutions on “whiskers-matrix” boundary, which leads to the diffusion blocking of oxygen into the material [15].



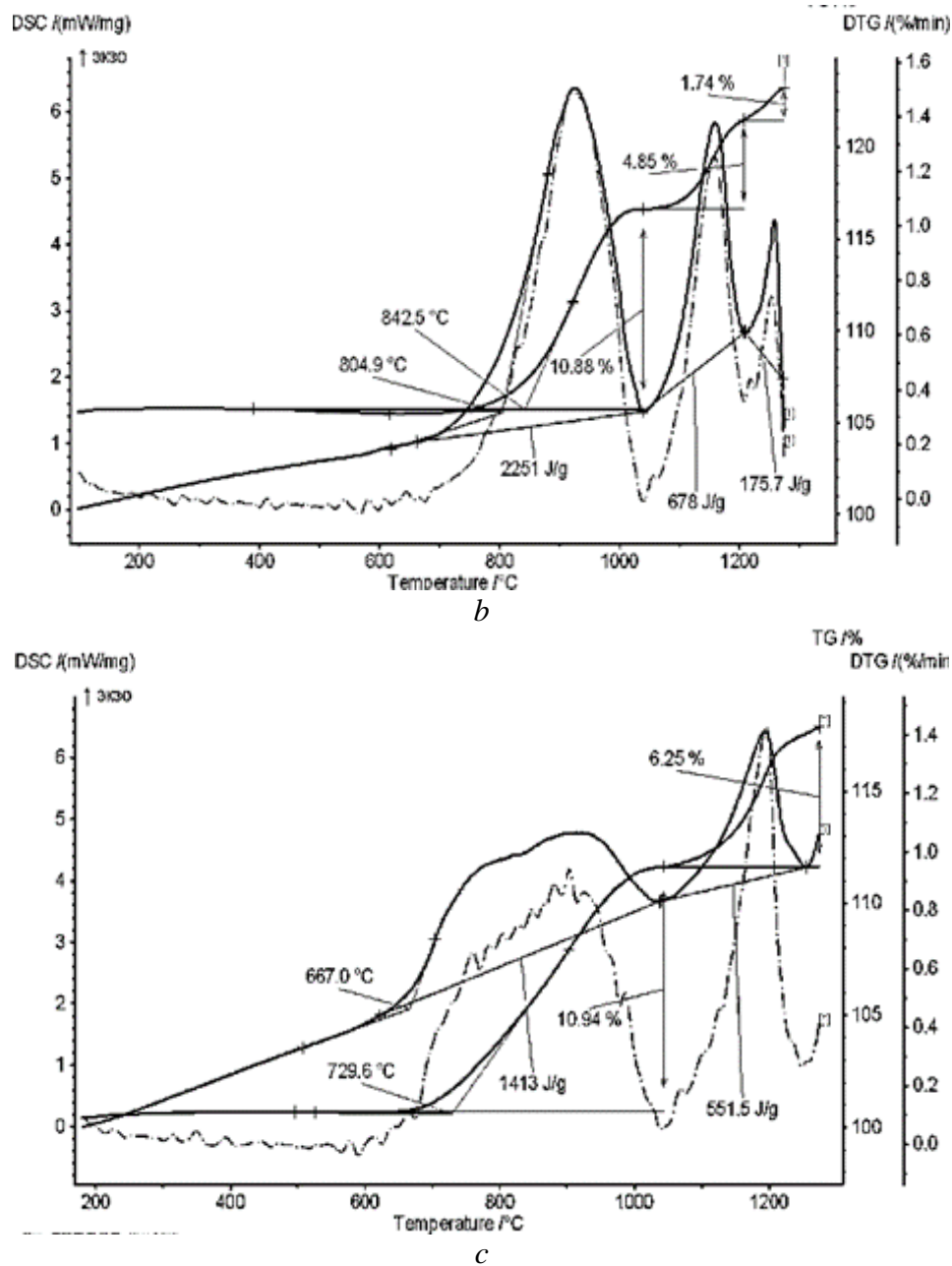


Fig. 6. STA results for sintered samples: 60 vol. % cBN – 35 vol. % NbN – 5 vol. % Al (a); 60 vol. % cBN – 25 vol. % NbN – 5 vol. % Al – 10% vol. SiCw(b); 60 vol. % cBN – 25 vol. % NbN – 5 vol. % Al – 10% vol. Si₃N₄w(c)

Influence of whiskers on electrical resistivity of sintered composites

The experimental investigations of the dependence of samples resistivity from the voltage applied to the sample before and after samples heating were carried out. The range of voltage during experiments was 100–700 mV. The results of these investigations showed that the resistivity of the samples both before and after heating the samples is almost independent of temperature (measurement error for samples with addition whiskers is 0,01 Ohm·cm). This fact indicates the homogeneity of the structure of the materials of the studied samples [16]. Some increase in the deviation of the measured values from the average for the non-reinforced sample (Fig. 7, a) may be caused by the inhomogeneity of the sample due to increased porosity (sample porosity is almost 7%, which is almost twice as high as whisker-reinforced samples – 2–3%).

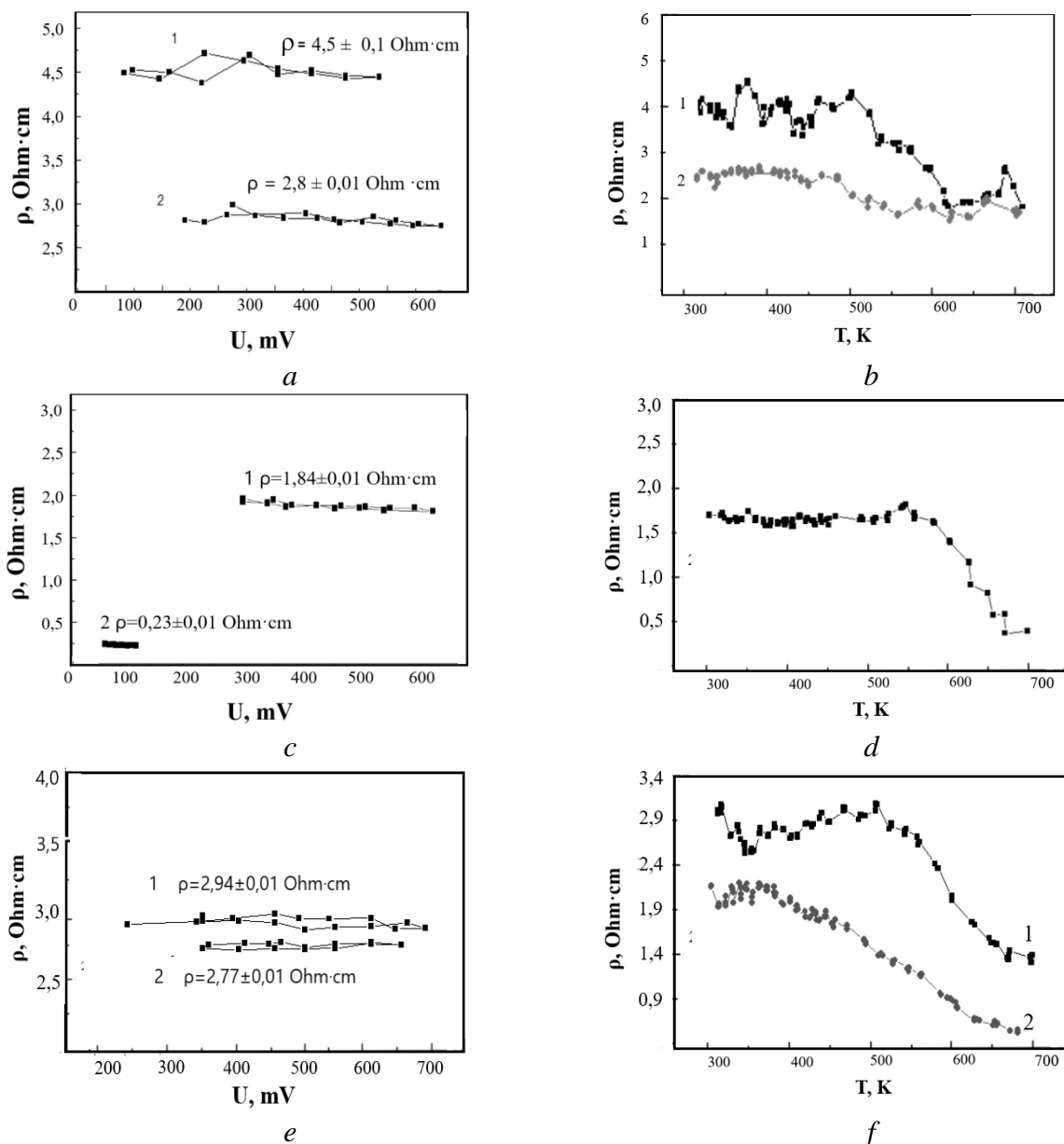


Fig. 7. Dependence of electrical resistivity from the applied voltage (a, c, e) and temperature (b, d, f) for 60 vol. % cBN – 35 vol. % NbN – 5 vol. % Al (a, b); 60 vol. % cBN – 25 vol. % NbN – 5 vol. % Al – 10% vol. SiCw (c, d); 60 vol. % cBN-25 vol. % NbN – 5 vol. % Al – 10% vol. Si₃N₄w (e, f) before (1) and after (2) heating up to 400 °C

The resistivity of the samples decreased both when adding whiskers and after heating the samples to 400 °C (Table 3). It is known that heating the samples leads to the removal of internal stresses in the material, which facilitates the flow of current through the sample, and hence to conductivity increase. Another possible explanation for this phenomenon is a sharp increase in the area of interfacial boundaries with whiskers addition, which also leads to the facilitation of electric current flow through the sample [16].

Table 3. Electrical resistivity before and after heating of sintered samples

Sample	60 vol.% cBN–35 vol.%NbN– 5 vol.%Al	60 vol.%cBN –25 vol.%NbN–5 vol.%Al –10%vol.SiCw	60 vol.%cBN –25 vol.%NbN–5 vol.%Al –10%vol.Si ₃ N ₄ w
electrical resistivity before heating, Ohm·cm	4,5±0,1	1,84±0,01	2,94±0,01
electrical resistivity after heating up to 400 °C, Ohm·cm	2,8±0,01	0,23±0,01	2,77±0,01

Influence of whiskers on wear resistance of sintered composites

Whisker-reinforced materials traditionally are used for interrupted machining due to their higher fracture toughness. Thus, we studied the wear resistance of the obtained (non-reinforced composite – 60 vol. % cBN – 35 vol. % NbN – 5 vol. % Al, SiC-whisker-reinforced – 60 vol. % cBN – 25 vol. % NbN – 5 vol. % Al – 10 vol. % SiCw and Si₃N₄-whisker-reinforced – 60 vol. % cBN – 25 vol. % NbN – 5 vol. % Al – 10 vol. % Si₃N₄w) and industrial (CBN170 and binderless cBN inserts) using interrupted (6 slots) longitudinal turning of 107WCr5 tool steel in hardened state (62 HRC). Machining tests were done with constant feed ($f=0,1$ mm/rev), depth-of-cut ($a_p=0,25$ mm) and machining time ($T=3,3$ min) but with variable cutting speed. The wear resistance of the materials was compared with the wear resistance of a CBN170 and commercial binderless cBN designed for interrupted machining [17]. Binderless cBN inserts manufactured at the Institute for Superhard Materials (Ukraine) are characterized by high hardness ($HV=54$ GPa) and low tool wear in interrupted machining applications due to their high cBN content (more than 95 vol. % cBN) and the heteromodularity of their microstructure[18]. Non-reinforced cBN-based material (60 vol. % cBN – 35 vol.

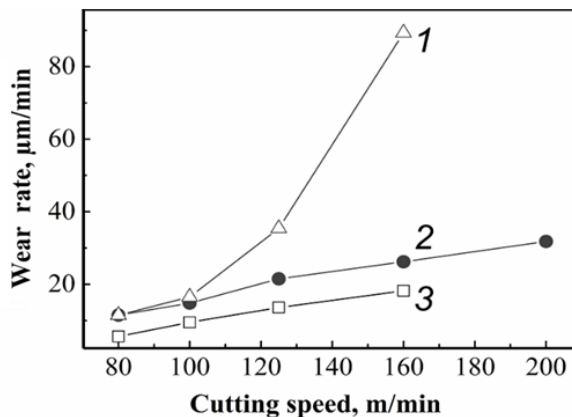


Fig. 8. The dependence of wear rate samples (e) on cutting speed for different of cBN-based samples (1 – binderless cBN; 2 – 60 vol.% cBN–25 vol.% NbN –5 vol.%Al–10% vol.SiCw; 3 – CBN170)

10 vol. % SiCw) at cutting speed up to 160 m/min was higher than wear resistance of binderless cBN inserts, but lower than wear resistance of CBN170. But at maximum cutting speed (200 m/min) microchipping of binderless cBN and CBN170 inserts occurred. This fact point to the inoperability of these tools at this cutting speed, while the new whisker-reinforced material still functions. New whisker-reinforced material (60 vol. % cBN – 25vol. % NbN – 5 vol. % Al – 10 vol. % SiCw) demonstrated almost linear slow increase in wear without microchipping. The value of wear rate at maximum cutting speed (200 m/min) was only 35 µm/min. Hence, new whisker-reinforced material

demonstrated high level of hardness and fracture toughness (due to the whisker reinforcement) and high enough level of oxidation resistance and chemical stability (due to the NbN binder), which provide high level resistance of new material during longitudinal turning of 107WCr5 tool steel. Thus, taking into account the similar effect of SiCw and Si₃N₄w on structure, mechanical (hardness, density, and fracture toughness) and elastic properties, as well as on oxidation resistance, it can be concluded that in this case the chemical interaction of whiskers with the processed material played a key role. Apparently, there was a chemical interaction of Si₃N₄w with iron, which is part of the steel, followed by recrystallization and softening of the whiskers, which is confirmed by the literature data [19-20].

Conclusions

The study of the properties of the obtained composites showed whisker-reinforcement leads to an increase in material's mechanical properties (hardness, fracture toughness and Young's modulus), which is consistent with published data [21-23], and to the improvement of oxidative resistance and electrical conductivity. Despite the similar set of properties of SiCw and Si₃N₄w-reinforced material, the material reinforced with 10 vol. % SiCw was characterized by the best wear resistance. The comparison of wear resistance non-reinforced (60 vol. % cBN – 35 vol. % NbN – 5 vol. % Al), whisker-reinforced materials (60 vol. % cBN – 25 vol. % NbN – 5 vol. % Al – 10 vol. % SiCw, 60 vol. % cBN – 25 vol. % NbN – 5 vol. % Al – 10 vol. % Si₃N₄w) and industrial materials (CBN170, binderless cBN) was done. New SiC whisker-reinforced material demonstrated high level of hardness and fracture toughness (due to the whisker reinforcement) and high enough level of oxidation resistance and chemical stability (due to the NbN binder and SiCw), which provide high level resistance of new material during longitudinal turning of 107WCr5 tool steel. Hence, it points to the prospectiveness of new cBN-NbN-Al-SiCw composites for cutting tool industry application, especially at the high cutting speed (more than 160 m/min), where industrial materials (CBN170, binderless cBN) don't work.

Acknowledgments

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СКЛАД, СТРУКТУРА, ВЛАСТИВОСТІ (МЕХАНІЧНІ ХАРАКТЕРИСТИКИ, СТІЙКІСТЬ ДО ОКИСНЕННЯ, ЕЛЕКТРИЧНИЙ ОПІР) І ХАРАКТЕРИСТИКИ АРМОВАНИХ МІКРОВОЛОКНАМИ МАТЕРІАЛІВ НА ОСНОВІ cBN ЗІ ЗВ'ЯЗКОЮ NbN

Методом високотемпературного синтезу за високих тисків (НРНТ синтез) було отримано три види композитів на основі cBN (без мікрОВОЛОКОН, армовані мікрОВОЛОКНАМИ Si₃N₄ (Si₃N₄w) і армовані мікрОВОЛОКНАМИ SiC (SiCw)). Було виміряно густину, модуль Юнга, об'ємний модуль, коефіцієнт Пуассона, твердість і тріщиностійкість, стійкість до окиснення та питомий електричний опір. Армвання обома видами мікрОВОЛОКОН (SiCw, Si₃N₄w) призвело до покращення механічних властивостей (твердості, тріщиностійкості), стійкості до окиснення та електропровідності. Незважаючи на це,

лише армування мікрОВОлокнами SiCw призвело до покращення зносостійкості, що пов'язано з більшою високою хімічною стійкістю SiCw в порівнянні Si₃N₄w).

Ключові слова: cBN, мікрОВОлокна, окиснення, питомий електроопір, знос, механічні властивості.

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СОСТАВ, СТРУКТУРА, СВОЙСТВА (МЕХАНИЧЕСКИЕ ХАРАКТЕРИСТИКИ, УСТОЙЧИВОСТЬ К ОКИСЛЕНИЮ, ЭЛЕКТРИЧЕСКОЕ УСТОЙЧИВОСТЬ) И ХАРАКТЕРИСТИКИ АРМИРОВАННЫХ МИКРОВОЛОКНАМИ МАТЕРИАЛОВ НА ОСНОВЕ cBN СО СВЯЗКОЙ NbN

Методом высокотемпературного синтеза при высоком давлении (НРПТ синтез) было получено три типа композитов на основе cBN (без микрОВОлокн, армированные микрОВОлокнами Si₃N₄ (Si₃N₄w) и армированные микрОВОлокнами SiC (SiCw)). Были измерены плотность, модуль Юнга, объемный модуль, коэффициент Пуассона, твердость и трещиностойкость, стойкость к окислению и удельное электрическое сопротивление. Армирование обоими видами микрОВОлокн (SiCw, Si₃N₄w) привело к улучшению механических свойств (твердости, трещиностойкости), стойкости к окислению и электропроводности. Несмотря на это, только армирование микрОВОлокнами SiCw привело к улучшению износостойкости, что связано с более высокой химической стойкостью SiCw по сравнению Si₃N₄w.

Ключевые слова: cBN, микрОВОлокна, окисление, удельное электросопротивление, износ, механические свойства.

Literature

1. Stephenson D. A., Agapiou J. S. Metal cutting theory and practice. Third edition. – CRC press, 2016. – 947 p.
2. Black J.T. Metals Handbook. Vol. 16: Machining (ASM HANDBOOK). 9th Edition. – ASM International, 1989. – 944 p.
3. Arriola I., Whinton E., Heigel J. & Arrazola P.J. Relationship between machinability index and in-process parameters during orthogonal cutting of steels // The International Academy for Production Engineering. – 2011. Vol. 60, N 1. – P. 93–96; doi: 10.1016/j.cirp.2011.03.082.
4. Rajshekhar L., Krishna P., Mohankumar G.C. An Experimental Investigation on Machinability Studies of Steels by Face Turning // Procedia Materials Science. – 2014. – Vol. 6. – P.1386–1395; doi: 10.1016/j.mspro.2014.07.118
5. Choi Y. C., Yoon D. B., Park J. H., Kwon H. S. An in-situ young's modulus measurement technique for nuclear power plants using time-frequency analysis // Nuclear engineering and technology. – 2009. – Vol. 41, N 3. – P. 327–334; doi: 10.5516/NET.2009.41.3.327.
6. Schwartz, M M. Composite materials. Volume 1: Properties, non-destructive testing, and repair. – United States: N. p., 1997. Web.
7. Thermo-Calc Software TCFE9 Steels/Fe-alloys database (accessed 23 March., 2019).
8. Rahaman, M.N. Sintering of ceramics. – Florida: CRC press, 2008. – 388 p.
9. Hummel, D. O. Atlas of plastics additives: analysis by spectrometric methods. –Berlin-Heidelberg: Springer-Verlag, 2012. – 539 p.

10. (2016). Microstructure-property correlations for hard, superhard, and ultrahard materials. Springer / Kanyanta, V. (Ed.). – Springer International Publishing, 2016. – 239 p.
11. Mehta, P. K., Monteiro, P. J. Concrete: Microstructure, Properties, and Materials. Fourth Edition. – McGraw-Hill Education, 2014. – 704 p.
12. Derlet, P. M. Sintering theory: Powder Technology course [Электронный ресурс] – Condensed Matter Theory. Paul Scherrer Institute, 2017. – 96 с. – Режим доступа: <https://www.epfl.ch/labs/lmc/wp-content/uploads/2018/06/PowderTech-11.pdf>.
13. Birks, N., Meier, G. H., Pettit, F. S. Introduction to the high temperature oxidation of metals. 2nd edition. – Cambridge University Press, 2006. – 338 p.
14. Чухломина Л.Т. Технология получения нитридов кремния и ниобия из ферросплавов методом самораспространяющегося высокотемпературного синтеза: дис. ... канд. техн. наук: 05.17.11. – Томск, 2006. – 181 с.
15. Zeng Y., Li Q., Bai K. Prediction of interstitial diffusion activation energies of nitrogen, oxygen, boron and carbon in bcc, fcc, and hcp metals using machine learning // Computational Materials Science. – 2018. – Vol. 144. P. 232–247; doi: 10.1016/j.commatsci.2017.12.030.
16. Rossiter, P. L. The electrical resistivity of metals and alloys. Vol. 6. – Melbourne: Cambridge University Press, 1991. – 434 p.
17. Bushlya V., Petrusha I., Gutnichenko O., et. al. Sintering of binderless cubic boron nitride and its modification by β -Si₃N₄ additive for hard machining applications // International Journal of Refractory Metals and Hard Materials. – 2020. – Vol. 86. – 105100; doi: 10.1016/j.ijrmhm.2019.105100.
18. Machining dynamics: fundamentals applications and practices / Cheng K. (Ed.). – London: Springer-Verlag, 2008. – 328 p.
19. High performance non-oxide ceramics II / Mingos D. M. P., Jansen M. (Eds.). – Berlin–Heidelberg: Springer-Verlag, 2002. – 172 p.
20. Shimoo T., Shibata D., Okamura, K. Interaction of Si₃N₄ with 18% Cr–8% Ni austenitic stainless steel // Journal of the Ceramic Society of Japan. – 1998. – Vol. 106, N 1234. – P. 545–550.
21. Devaraju A., Kumar A., Kumaraswamy A., et. al. Influence of reinforcements (SiC and Al₂O₃) and rotational speed on wear and mechanical properties of aluminum alloy 6061-T6 based surface hybrid composites produced via friction stir process // Materials & Design. – 2013). – Vol.51. – P. 331–341; doi: 10.1016/j.matdes.2013.04.029.
22. Xia K. Langdon T.G. The toughening and strengthening of ceramic materials through discontinuous reinforcement // Journal of Mater Science. – 1994. Vol. 29. – P. 5219–5231; doi: 10.1007/BF01171532.
23. Mallick, P. K. (2007), Fiber-reinforced composites: materials, manufacturing, and design. 3rd Edition. – London – New York: CRC Press, 2007. – 638 p.

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References

1. Stephenson D. A., & Agapiou J. S. (2016) *Metal cutting theory and practice*. CRC press.
2. Black J.T. (Eds.). (1989). *Volume 16. Machining*. (9th ed.) OH, USA: ASM International.
3. Arriola I., Whinton E., Heigel J. & Arrazola P.J. (2011). Relationship between machinability index and in-process parameters during orthogonal cutting of steels. *The International Academy for Production Engineering, Vol.60, 1*, 93–96; doi: 10.1016/j.cirp.2011.03.082.
4. Rajshekhar L., Krishna P., Mohankumar G.C. (2014). An Experimental Investigation on Machinability Studies of Steels by Face Turning. *Procedia Materials Science, 6*, 1386–1395; doi: 10.1016/j.mspro.2014.07.118.

5. Choi, Y. C., Yoon, D. B., Park, J. H., & Kwon, H. S. (2009). An in-situ young's modulus measurement technique for nuclear power plants using time-frequency analysis. *Nuclear engineering and technology*, Vol. 41, 3, 327–334; doi: 10.5516/NET.2009.41.3.327.
6. Schwartz, M.M. (1997). *Composite materials. Volume 1: Properties, non-destructive testing, and repair*. United States: s.n.
7. Thermo-Calc Software TCFE9 Steels/Fe-alloys database (accessed 23 March., 2019).
8. Rahaman, M.N. (2007). *Sintering of ceramics*. Florida: CRC press.
9. Hummel, D. O. (2012). *Atlas of plastics additives: analysis by spectrometric methods*. Berlin-Heidelberg: Springer-Verlag.
10. Kanyanta, V. (Eds.). (2016). *Microstructure-property correlations for hard, superhard, and ultrahard materials*. Springer International Publishing.
11. Mehta, P. K., & Monteiro, P. J. (2017). *Concrete microstructure, properties and materials*. McGraw-Hill Education.
12. Derlet, P. M. (2017). Sintering theory. Paul Scherrer Institute. *epfl.ch*. Retrieved from <https://www.epfl.ch/labs/lmc/wp-content/uploads/2018/06/PowderTech-11.pdf>.
13. Birks, N., Meier, G. H., & Pettit, F. S. (2006). *Introduction to the high temperature oxidation of metals*. Cambridge University Press.
14. Chuhlomina, L. N., (2006). Tekhnologiya polucheniya nitridov kremniya i niobiya iz ferrosplavov metodom samorasprostranyayushchegosya vysokotem-peraturnogo sinteza [Technology for producing nitrogen and niobium nitrides from ferroalloys by the self-propagation high-temperature synthesis]. *PhD Thesis* [in Russian].
15. Zeng, Y., Li, Q., & Bai, K. (2018). Prediction of interstitial diffusion activation energies of nitrogen, oxygen, boron and carbon in bcc, fcc, and hcp metals using machine learning. *Computational Materials Science*, 144, 232–247; doi: 10.1016/j.commatsci.2017.12.030.
16. Rossiter, P. L. (1991). *The electrical resistivity of metals and alloys* (Vol. 6). Cambridge university press.
17. Bushlya, V., Petrusha, I., Gutnichenko, O. et. al. (2020). Sintering of binderless cubic boron nitride and its modification by β - Si_3N_4 additive for hard machining applications. *International Journal of Refractory Metals and Hard Materials*, 86, 105100; doi: 10.1016/j.ijrmhm.2019.105100
18. Cheng, K. (Eds.). (2008). *Machining dynamics: fundamentals applications and practices*. London: Springer-Verlag.
19. Mingos, D. M. P., Jansen, M. (Eds). (2003). *High performance non-oxide ceramics II*. Berlin–Heidelberg: Springer-Verlag.
20. Shimoo, T., Shibata, D., & Okamura, K. (1998). Interaction of Si_3N_4 with 18% Cr-8% Ni austenitic stainless steel. *Journal of the Ceramic Society of Japan*, Vol. 106, 1234), 545–550.
21. Devaraju, A., Kumar, A., Kumaraswamy, A., et. al. (2013). Influence of reinforcements (SiC and Al_2O_3) and rotational speed on wear and mechanical properties of aluminum alloy 6061-T6 based surface hybrid composites produced via friction stir proces. *Materials & Design*, Vol. 51, 331–341; doi: 10.1016/j.matdes.2013.04.029.
22. Xia, K. & Langdon, T.G. (1994) The toughening and strengthening of ceramic materials through discontinuous reinforcement. *Journal od Mater Science*, Vol. 29, 5219–5231; doi: 10.1007/BF01171532
23. Mallick, P. K. (2007). *Fiber-reinforced composites: materials, manufacturing, and design*. London – New York: CRC Press.