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CONTRIBUTION OF GRAPHITE-LIKE BORON NITRIDE TO THE FORMATION OF RESIDUAL STRESSES, STRENGTH, AND PERFORMANCE OF MATERIALS BASED ON WURTZITIC BORON NITRIDE

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The paper deals with the mechanism of the formation of physico-mechanical properties of polycrystalline superhard materials based on wurtzitic boron nitride – Hexanite-A. We have studied the influence of graphite-like BN modification, which is present in Hexanite-A, on the residual stress level upon sintering, and analyzed the relationship between these stresses and the strength and performance of the polycrystalline superhard materials. The results of investigation of wBN-based material confirm the presence of residual stresses due to graphite-like boron nitride.

Polycrystalline superhard materials (PSHM) based on wurtzitic boron nitride are usually a three-phase system (wBN + cBN + gBN). Depending on the PSHM production conditions, the phase composition varies over a wide range, thus affecting the physico-mechanical and performance characteristics of the material.

We have found [1] that graphite-like boron nitride (gBN) forms during the PSHM sintering and is present in the material in two forms: compressed along the *c* axis (gBN_{comp}) and in the initial state (gBN_{init}), thus generating residual stresses in this material. The gBN_{init} component is located mainly at the grain boundaries and deteriorates the material strength thus leading to cracking and fracture of PSHM in heating, while gBN_{comp} is formed in micropores, and since it has a considerable elastic energy stored, it induces residual stresses.

The objective of the present work was to estimate the contribution of gBN, which is present in PSHM, to the formation of residual stresses, and to clarify their relationship with strength and performance of PSHM.

For the investigation we used the polycrystalline wurtzitic boron nitride (Hexanite-A) powder sintered at p = 6.0 GPa. The value of residual stresses in the heterophase powder of Hexanite-A due to a significant difference in linear thermal expansion of crystal lattice between gBN and (cBN, wBN) in sintering can be represented as $\sigma^{res}_{\text{Hex-A}} = P - (\sigma^{T}_{\text{gBN}} + \sigma^{p}_{\text{gBN}})$, where σ^{T}_{gBN} are the stresses induced due to the difference in thermal expansion coefficient between dense and laminar modifications of PSHM; σ^{p}_{gBN} are the stresses due to external pressure; p is the external pressure in PSHM sintering.

From J. Eshelby's formula we find

$$\sigma^{p}_{\text{gBN}} = \frac{4\mu_{\text{wBN}} + 3\chi_{\text{wBN}}}{4\mu_{\text{wBN}} + 3\chi_{\text{gBN}}} \cdot \frac{E_{\text{gBN}}}{E_{\text{wBN}}} \cdot p,$$

where μ is the shear modulus, χ is the bulk modulus, E is the modulus of normal elasticity.

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Assuming that in the case of a small amount of gBN in PSHM the elastic modulus $E_{gBN} << E_{wBN}$, we represent the σ^T_{gBN} component as

$$\sigma^T_{gBN} = b(T_{sint} - T_{room}),$$

where T_{sint} and T_{room} are the sintering and room temperatures, respectively, and determine the b factor from the formula

$$b = \frac{\alpha_{gBN} - \alpha_{wBN}}{(1+\nu_{wBN})/2E_{wBN} + (1-\nu_{gBN})/E_{gBN}},$$

where α_{gBN} and α_{wBN} are the linear thermal expansion coefficients of a solid, ν is the Poisson ratio.

Using the equation of the gBN + cBN equilibrium line in the boron nitride phase diagram [2], we obtain

$$P = \frac{3\times10^{-3}(\text{GPa})\cdot T(\text{K})}{\Delta T(\text{deg})} - 1.03(\text{GPa}).$$

Let us assume that the local pressure for the sintering conditions used in this work is approximately equal to p_0. Then, using the known values of the modulus of normal elasticity and the linear thermal expansion coefficient, in view of considerable anisotropy of gBN, and taking $E_{gBN} = \chi_{gBN}$ and $\nu_{gBN} = 0$, we find $\sigma^T_{gBN} = 0.46$ GPa; $b = 1.4 \times 10^{-3}$ GPa/deg.

Finally, the value of the residual stresses in sintered wBN-based PSHM $\sigma^{res}_{Hex\text{-}A} = 1.6 \times 10^{-3}$ (GPa/deg) – 1.076 (GPa).

The gBN_{init} inclusions at the grain boundaries in PSHM induce shear-type residual stresses and are given by $\sigma^{res}_{gBN_{init}} = 0.75\sigma^{res}_{Hex\text{-}A}$. Such a PSHM, when heated, fails totally or partially and the graphite-like phase can be observed even visually. The measurements of compression strength of Hexanite-A grits of various compositions have demonstrated that an increase in the gBN content of this material leads to a noticeable deterioration of this characteristic [3]. The strength characteristics of the powders are given in Table 1 and Figs. 1 and 2.

Table 1

Composition and Properties of Hexanite-A

Batch No.	Phase composition, vol%			Mean fracture load, N, for powders of grit sizes			Hardness, GPa
	cBN	gBN		200/160	160/125	125/100	
		initial	compressed along the *c* axis				
1	98	1.5—2.0	—	16.3	13.2	13.2	45±2
2	75—80	6.0	2.0	20.3	17.8	15.8	27±5
3	60	4.0	2.0	21.6	18.0	17.1	34±2
4	60	3.0	2.0	26.2	19.2	19.2	40±2

Results of estimation of mechanical properties of Hexanite-A (see Figs. 1 and 2) show that for the three-phase system a decrease in the gBN content from 6 to 3 wt% in the initial state leads to strengthening by, on the average, 20—30% (on the second-order curve) irrespective of the powder grain size. Batch 1 of Hexanite-A, which does not have wurtzite-like phase, stands out. When the wBN → cBN transformation is almost completed and the gBN amount is less than

2 vol%, the strength of the abrasive decreases due to a shift of the temperature range of brittleness towards room temperature, while for the wurtzite-like material the temperature range of brittleness corresponds to 600—950 K [4].

Fig. 1

Fig. 2

Fig. 1. Compression strength σ_{comp} of Hexanite-A grits as a function of mean grit diameter d_g: *1—4* are batch numbers.

Fig. 2. Hardness H_μ (*1*) and compression strength σ_{comp} (*2*) of 125/100 Hexanite-A grits as a function of the content of gBN in the initial state.

Interestingly, the strength of the abrasive material $\sigma_{comp} \approx f(1/d_g^2)$ decreases hyperbolically with increasing grit size for all material batches (see Fig. 1).

The hardness of the material seems to depend on the gBN content of this material in the initial state (see Fig. 2), in this case it decreases linearly with increasing graphite-like phase content. The change in the ratio between cBN and wBN has almost no effect on the hardness of the abrasive material. Note that the lower values of the Hexanite-A hardness, which were obtained in this work, in comparison to those obtained by I. N. Frantsevich [3], can be attributed to higher indentor loads (2 to 10 N) during the hardness measurements as well as to the fact that the test surface was not subjected to any special treatment such as polishing and etching.

The tests have demonstrated that with increasing hardness of the abrasive (Fig. 3*a*) and decreasing gBN content in the initial state (Fig. 3*b*) the wear resistance of wheels of the three-phase material (cBN + wBN + gBN) grows (the abrasive consumption q goes down) almost linearly, i.e. exhibits a fairly reliable correlation with hardness. In this case, we revealed two different wear mechanisms: (i) abrasive wear (attrition) in batches 2, 3, and 4, and (ii) spalling and cracking in batch 1. These findings confirm the presence of temperature zones of embrittlement of polycrystals (various ranges for materials that differ in structure) under dynamic conditions of grinding, which was found earlier during heating under static loading conditions [4].

Fig. 3. Hexanite-A consumption q as a function of the hardness H_μ (*a*) and the content of gBN in the initial state (*b*): *1—4* are batch numbers.

The results of the present investigation of properties of the wBN-based material provide a fairly convincing explanation of residual stresses due to the presence of graphite-like boron nitride.

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