

# Influence of the Addition of Vanadium Nitride on the Structure and Specifications of a Diamond–(Fe–Cu–Ni–Sn) Composite System

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**Abstract**—This article discusses the influence of the addition of vanadium nitride on the mechanical and operational properties of diamond composite material based on metallic bond comprised of iron, copper, nickel, and tin obtained by sintering in a mold at 800°C for 1 h with subsequent hot repressing. It has been established that the addition of vanadium nitride in the amount of 2 wt % to diamond–(51Fe–32Cu–9Ni–8Sn) increases the ultimate compressive strength from 846 to 1640 MPa and bending strength from 680 to 1120 MPa, as well as decreases the wear intensity of the composite material from 0.0069 to 0.0033 g/km. The mechanism of improving the tribological properties has been revealed.

**Keywords:** diamond, iron, copper, nickel, tin, vanadium nitride, composite, pressure, temperature, structure, mechanical properties, coefficient of friction, wear resistance

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## INTRODUCTION

At present, diamond composite materials (DCM) on the basis of metallic bonds comprised of iron, copper, nickel, and tin [1, 2], as well as other metals and alloys, are widely applied for the fabrication of tools for the stone working and mining industry. On a commercial scale, diamond–(Fe–Cu–Ni–Sn) composite materials are fabricated by powder metallurgy, in particular by sintering in molds with subsequent hot repressing [2]. In addition, these composite materials can be fabricated by spark plasma sintering (SPS), high-frequency induction heated sintering (HFIHS), pulse plasma sintering (PPS), and intensive electric sintering (IES). The final structure of this DCM depending on their fabrication process is formed at a temperature of 700–900°C and pressure of 20–200 MPa [3].

The physicomachanical properties of DCM are determined by the chemical composition, structure, and morphology, which in turn depend on their constituents, sintering procedures, and technological modes [2]. The results of an analysis of diamond–(51Fe–32Cu–9Ni–8Sn) composite material (here and below, the composition of composite material is given in wt % with regard to the metallic bond) indicate that samples obtained by sintering of pressed briquettes in furnace at 800°C in 1 h with hot repressing

under 200 MPa are characterized by superior mechanical and tribological properties than those obtained under lower pressure [4]. Herewith, Fe<sub>3</sub>C nanoparticles are formed in the transient zone instead of graphitic carbon particles, which improves DCM properties.

Another promising method of targeted influence on DCM properties is a modification of their structure. This is aided by the addition of carbides, borides, and nitrides of transient metals to DCM, these substances activate sintering and bind graphitic carbon with a metallic bond of the composite material.

In particular, it was demonstrated in [5] that the addition of tungsten carbide (WC) nanopowder to diamond–(Fe–Cu–Co–Sn) composite material in a minor amount compared with major components decreases graphitization of surface layers of diamond grains upon sintering and, thus, increases its wear resistance. It was demonstrated in [6] that as a consequence of addition of chromium diboride (CrB<sub>2</sub>) in amount of 2% to diamond–(51Fe–32Cu–9Ni–8Sn) composite material it became possible to completely bind graphitic carbon into carbides Cr<sub>3</sub>C<sub>2</sub>, Cr<sub>7</sub>C<sub>3</sub> and complex boride Cr<sub>1.65</sub>Fe<sub>0.35</sub>B<sub>0.95</sub>. As a consequence, the operational properties of composite material are significantly improved. One of the promising additives for increasing DCM wear resistance is vanadium nitride (VN), since upon heating, it dissolves in iron-

based solid solution and, upon cooling, it is deposited in the form of fine dispersed particles, thus strengthening the metallic bond [7] on one hand, and, on the other hand, in terms of dispersity and homogeneity of deposition the vanadium nitride particles are superior to other nitride phases (NbN, TiN) [8]. This method is economically efficient, since it is not required for expensive nanopowders of metals and nonmetals aimed at increasing the strength and wear resistance of DCM. Regularities of structure formation in the considered system in the presence of solid additions of vanadium nitride have not been studied in detail. Therefore, investigations of the influence of the addition of VN on the structure and properties of DCM on a metallic bond containing iron, copper, nickel, and tin are very urgent for both science and practice. At the first stage, it would be reasonable to add the same amount of VN to the diamond-(51Fe-32Cu-9Ni-8Sn) blend as to the similar blend of CrB<sub>2</sub> in [6], thus facilitating an estimate of its role upon development of DCM of increased wear resistance.

**This work is aimed at** investigating the influence of the addition of 2% VN on the structural, mechanical, and operational properties of diamond-(51Fe-32Cu-9Ni-8Sn) composite material obtained by sintering in a mold at 800°C in 1 h with subsequent hot repressing, as well as detection of mechanism increasing its wear resistance.

## EXPERIMENTAL

Experimental studies were carried out with polished samples of metallic bond 51Fe-32Cu-9Ni-8Sn, 49.98Fe-31.36Cu-8.82Ni-7.84Sn-2VN, and diamond-(51Fe-32Cu-9Ni-8Sn), diamond-(49.98Fe-31.36Cu-8.82Ni-7.84Sn-2VN) composite materials with diameters of 10 mm and thicknesses of 8 mm. The considered DCM samples were prepared of powdered diamond AS160T with coarseness of 400/315 (Specifications TU 2-37-344-85), iron PZh1M2 (GOST standard 9849-74), copper PMS-1 (GOST standard 4960-75), nickels PNE (GOST standard 9722-79), tin PO-1 (GOST standard 9723-73), and vanadium nitride. Preparation of charging materials and technological sintering modes of DCM samples are described elsewhere [4]. Surface morphology of initial particles of diamond, iron, copper, nickel, tin, and vanadium nitride, as well as microstructure of the obtained DCM samples and their chemical composition were studied using a SELMI SEM-106M scanning electron microscope with the acceleration voltage of 20 kV. Quantitative calculations of chemical composition were performed using the ZAF correction method and Magelanes 3.1 software. For heavy elements, the measurement error was ~0.01 wt % and, for light elements, it was ~1 wt %.

The ultimate compressive and bending strengths were analyzed using standard procedure (error ≤5%). Tribological properties of DCM samples upon abra-

sive wear were studied using a multifunctional assembly for material testing by friction without lubrication according the following flowchart: disk (coupled element of electrocorundum with average hardness of SM-2 on ceramic bond 7K15 with the diameter of 60 and the width of 8 mm)—pin (DCM sample), based on an IMASh-20-75 serial machine [9]. The normal load of the sample on the disk was 500 g, the disk rotation frequency was 300 rpm, and the durations of the running-in and testing stages were 0.5 and 4.0 h, respectively, which corresponds to sliding distances ( $L$ ) of 1.7 and 13.6 km.

During testing, the coefficient of friction  $f$ ; bulk wear  $\Delta m$ , which is determined by the weight loss on a VLA-20g-M analytical balance (accuracy of ±4 mg); and wear intensity  $I_m$  ( $I_m = \Delta m/L$ ) were measured.

## RESULTS AND DISCUSSION

Figure 1 illustrates images of single particles of powdered diamond, iron, copper, nickel, tin, and VN in initial (loose) state obtained by scanning electron microscopy (SEM) used to sinter DCM samples.

The surfaces of the diamond grains (Fig. 1a) have no defects (cracks, cleavages, etc.), which evidences their high quality. Powdered iron particles with sizes of 5–20 μm are mainly of a globular shape with a dense structure, and they are prone to agglomeration due to intermolecular interactions (Fig. 1b). Powdered copper particles (Fig. 1c) with the sizes of 4–6 μm have finer, less dense dendrite structures with pronounced branches, which stipulates a decrease in the relative bulk density and prevents their compaction in a free state. Powdered nickel particles with average sizes of 6–8 μm do not form agglomerates and they have distinct nonsmoothed edges with dense structure, which, as in powdered iron, stipulates the high packing density in a loose state (Fig. 1d). Powdered tin particles have mainly spherical shapes (Fig. 1e). Their surfaces contain metal buildups, as well as finer particles (satellites). The spherical shape of powdered tin particles promotes their dense packing in a loose state. Powdered vanadium nitride in initial state is comprised of irregular particles with the average size in the range of 25–40 μm (Fig. 1f), though there are also both coarser and finer particles. It is characteristic that particles coarser than 40 μm have irregular shapes and reliefs with irregularities, the number of which increases with particle size. In particles finer than 20 μm, the irregularities are smoothed with decrease in sizes.

The particle shape and size of powdered iron, copper, nickel, tin, and vanadium nitride in the 49.98Fe-31.36Cu-8.82Ni-7.84Sn-2VN mixture (Fig. 2a) in comparison with single particles in initial state did not vary (see Fig. 1b–1f). Upon compaction, the powdered iron particles do not vary their shape and size (Fig. 2b), although in comparison with the initial state (see Fig. 1b), they are more compacted. The observed

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