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Effects of sintering temperature and addition of Fe and B_4C on hardness and wear resistance of diamond reinforced metal matrix composites

The effects of sintering temperature and addition of Fe instead of Co into the matrix composition on the mechanical properties of diamond-reinforced MMC's have been studied. Diamond-reinforced MMC's based on Fe–Co compositions with and without boron carbide (B_4C) have been processed. Three different matrix composites (with different Fe/Co ratios) have been produced with and without B_4C at a pressure of 25 MPa and sintered in N_2 at various temperatures (800, 900, and 1000 °C). After sintering, mechanical properties of the resultant composites have been studied and the results discussed. Addition of B_4C has been found to improve the hardness and wear resistance of the composites. Optical microscopy, SEM and EDS have been used to examine the microstructure and surface of the synthesized composites.

Keywords: *diamond, powder metallurgy, Fe-based metal matrix composites, hardness, wear.*

INTRODUCTION

Powder metallurgy (PM) method is the only viable method for manufacturing diamond tools among the other methods such as brazing and infiltration [1, 2] due to the graphitization problem [3]. During the sintering process, the solid state prevents excessive chemical interaction between the metal phase and the diamond. Therefore, sintering parameters (T, p and environment) must be carefully controlled in order to avoid the graphitization.

The parameters for the production of diamond tools using PM technique depend on (1) matrix constituents, (2) abrasive powders (metal carbides and diamond). Oliveira et al. [4] stated that the mechanical properties (such as hardness and wear rate) of diamond tools mainly depend on the selection of matrix constituents. The matrix constituents determine the bonding strength between the diamond grain and the matrix, and the wear rates of the diamond and the matrix. It is underlined that the properly selected matrix composition results in optimum wear rate of diamond tools (matrix and abrasive media). Some metal (Cu, Sn) and alloys (brass and bronze) with a low chemical affinity for carbon are used as filler metals to fill the pores formed during sintering [3]. Some metals (Co, Ni, Ti, and W) with higher chemical affinity for carbon are commonly used as binders due to their good wettability and chemical compatibility that holds the diamonds together and forms chip flow grooves via rapid wear during cutting. When diamond-reinforced MMCs are heated, the metals attack the diamond surface and bonds are formed between the diamond surface and metal powder. Cobalt is currently used as a matrix metal in the production of diamond-reinforced MMC's However, Co is an expensive, hazardous and strategic metal; therefore, over the last fifteen years, researchers have focused on methods to develop alloy powders that could serve as an alternative to cobalt or reduce the content of cobalt in diamond tools. Fe metal can be used for bonding purposes instead of Co as Fe is easy to apply, inexpensive and not a hazardous material [5–8]. Several titanium alloys as matrix metals for diamond tools were studied by Spriano et al. [9]. In reviewing the literature, although there are many researches on matrix composition of diamond-reinforced MMC's, one can see that matrix composition is still one of the most important parameter in the production of diamond reinforced MMC's.

Abrasive medium (i.e., diamond and metal carbides) is another important parameter. Diamond has been used as abrasive powder due to its extreme hardness [10–12]. Diamond concentration and quality (e.g., grain size, shape, and strength) affect mechanical properties of diamond tools [13–15]. Beside of diamond, some metal carbide has been used as a metal matrix wear rate controller in diamond tools. Oliveira et al. [4] worked on Fe–(5, 10, 15–20) wt% Cu alloys, with and without 1 % SiC addition and concluded that among the produced composite materials the best mechanical properties (yield strength, hardness, and wear resistance) were obtained in the composite material comprising Fe–20 wt% Cu and 1 wt% SiC. Khalid et al. [16] worked on the formation of TiC particles and epitaxial layer structure at the interface between diamond grit and Cu-based active brazing alloy during processing. Wang et al. [11] coated diamond with Ti by the vacuum slow vapor deposition method. Continuous and compact TiC shielding layer was investigated.

The aim of this study was to investigate the effects of sintering temperature and addition of Fe into matrix on hardness and wear resistance of diamond-reinforced MMCs; to improve the mechanical properties (hardness and especially wear resistance) by adding B_4C, and to compare the mechanical properties of the resultant composites with those of the commercial product.

EXPERIMENTAL

Sample preparation

Polycrystalline diamond grits of size 297–420 μm (LS4750+, LANDS), a B_4C (H. C. Starck) powder with the average particle size less than 10 μm, a carbonyl iron powder with the average particle size less than 75 μm (Baymet Metal Industry Inc.), a cobalt powder with an average particle size of 37 μm (Umicore), and a bronze (Cu–15 wt% Sn) powder with an average particle size of 44 μm (Pometon Powder Inc.) were selected as precursors for this study. The composition of the matrix and the concentration of diamond in the composite samples are given in Table 1.

Table 1. The composition of produced composite samples and the commercial product

Composites	Composition of matrix, wt%			Diamond concentration
	Fe	Co	Bronze	
A	75	15	10	20
B	55	35	10	20
C	35	55	10	20
D-commercial product	–	75	25	20

Composite samples having three different compositions (i.e., different Fe/Co ratios) with and without B_4C were produced. The concentration of diamond grits in these composite samples was kept constant and maintained at a concentration of 20 % (where a concentration of 100 % diamond grits was designated as 4.4 cts/cm^3) to compare the resultant composites with the commercial product. A commercial product was bought from Ekip Soket Inc., Ankara. The production conditions (powder mixing time, heating, and cooling rates, diamond concentration, hot pressing, and lubricant) of the commercial product are the same as that of the composite samples produced in the current study. The performance of the commercial product that was prepared by hot-pressing was analyzed in a similar manner.

The procedure below was used to synthesize composite specimens (A, B, and C) with and without B_4C. Fe, Co, bronze, and diamond powders with and without B_4C were blended for 45 min in a T2F Turbula mixer, and alcohol with 2 wt% glycerin was added before blending to obtain a uniform and homogenous mixture. For each composition, the mixture was placed in carbon molds with dimensions equal to the commercial product (24×10×10 mm). After setting the mold, the powder mixture was cold compacted, and the green product in the mold was placed in a sintering machine. The hot zone was evacuated to remove air from the chamber, and sintering then was conducted using the hot press machine (Dr. Fritsch DSP 510 Sinter Machine) under nitrogen. The glycerin was heated up to 500 °C and held for 100 s, and a brown product was produced and heated up to the sintering temperature.

After brown product was obtained at 500 °C, the composite samples were heated to the selected sintering temperature (800, 900 or 1000 °C) under a compression load of 25 MPa and cooled in the sintering machine. The total sintering time (heating and cooling) was held between 12 to 14.5 min depending on the sintering temperature for each composite sample. Twenty four samples per unique composition were produced. Figure 1 shows the sintering regime. The sample preparation was briefly explained in [17]. The sintering temperature must be maintained below 1150 °C to keep the diamond from graphitizing and the tool from losing its cutting capability [18].

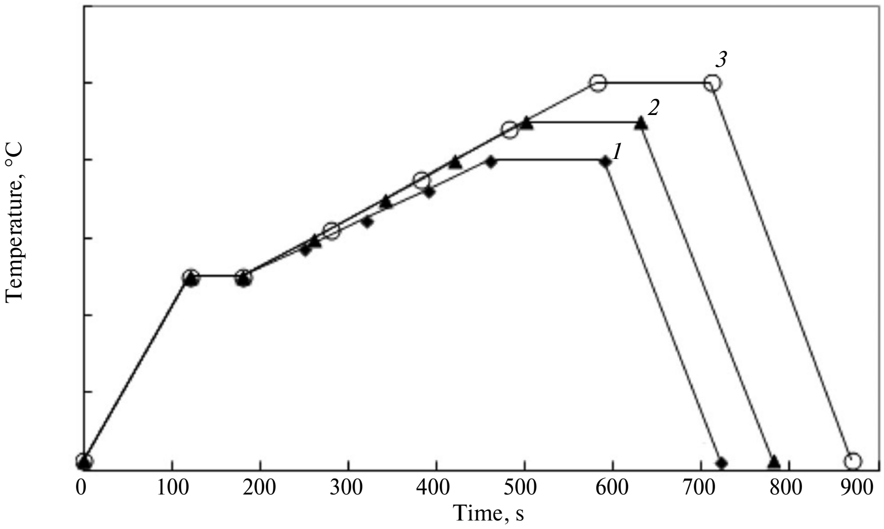


Fig. 1. Sintering procedure applied to the composite specimens. Sintering temperatures 800 (♦), 900 (▲), and 1000 (○) °C.

Density measurements

The theoretical densities of each composite specimen were calculated from powder mixtures. Then, the experimental density for each composite sample was measured with an Archimedes' balance (using the AD-1653 specific gravity measuring kit). The theoretical and experimental densities were compared.

Mechanical tests

Hardness test. Hardness is the most widely used parameter to determine the quality of diamond-reinforced composites for stone cutting in industrial applications, and thus, hardness tests have been carried out on the composite specimens. The Brinell hardness test was performed on three samples for each unique composition, in which five measurements were conducted on each specimen. Thus, 15 measurements were obtained for each sample. Brinell hardness values were measured under a load of 100 kgf for each sample, and the average hardness values and standard deviation were calculated.

Wear test. For the wear test, a pin-on-disc type apparatus was employed to evaluate the wear characteristics of the composite as shown in Fig. 2. Wear tests were conducted according to ASTM G99-05–2010 standard. In this test, an AISI 5190 steel disc with a hardness of 65 *HRC*, a thickness of 12 mm, and a diameter of 160 mm was used to wear of the composite specimens. The pin specimens made from the composites were machined to be approximately 5 mm in length. To form a pin of the necessary length, each sample was bonded to a 50-mm long steel extension pin of the same cross-section using an epoxy adhesive. The pin was then mounted in a steel holder of the wear machine such that it was held firmly perpendicular to that of the flat surface of the rotating counter disc. The samples were loaded against the adhesive medium with the help of a cantilever mechanism. The wear test was performed under varying loads, such as 10, 20, and 40 N, and at a constant speed of 1 m/s with a constant sliding distance of 3600 m. The wear pin was cleaned in acetone prior to and after the wear testing; it was then dried and weighed on a microbalance with 0.1 mg sensitivity. Wear tests were carried out for three samples per one composition and the average weight loss and standard deviation were calculated.

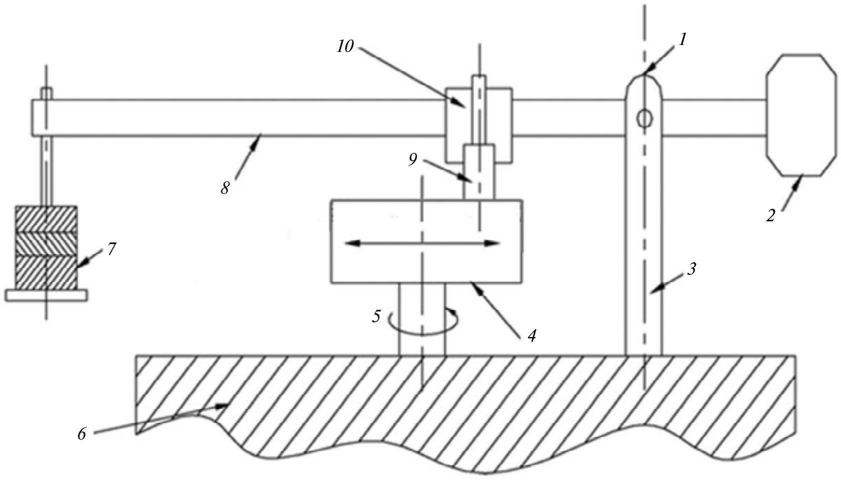


Fig. 2. Schematic representation of pin-on-disc type of wear machine: bearing (*1*), balance (*2*), supporting shaft (*3*), hardened steel (*4*), rotational speed (*5*), machine table (*6*), load (*7*), loading arm (*8*), pin sample (*9*), pin holder (*10*).

The surfaces of the composite samples were examined using optical microscopy and scanning electron microscopy (SEM) with attached energy dispersive spectrometry (EDS) capabilities.

RESULTS AND DISCUSSION

Density

Effects of sintering temperature. The experimental densities were measured according to Archimedes' principles. The theoretical and experimental densities of the composites were given in Table 2. It is noted that as the sintering temperature increases, the experimental density of the produced composites slightly increases. Strength of a composite produced by PM technique depends on the amount of porosity. The porosity decreases with increasing densification of powders.

Table 2. The densities and porosities of the composites sintered at various temperatures

Composites	ρ_{theor}, g/cm^3	Sintering temperature, °C					
		800		900		1000	
		ρ_{exp}, g/cm^3	porosity	ρ_{exp}, g/cm^3	porosity	ρ_{exp}, g/cm^3	porosity
A	8.196	7.690	6.17	7.771	5.19	7.783	5.04
B	8.304	7.898	4.89	7.909	4.76	7.910	4.74
C	8.412	8.067	4.10	8.081	3.93	8.086	3.88
A-B_4C	8.175	7.203	11.89	7.649	6.43	7.7	5.81
B-B_4C	8.254	7.282	11.78	7.812	5.35	7.816	5.31
C-B_4C	8.385	7.461	11.02	7.925	5.49	7.994	4.66

The porosity of the composite materials was calculated by the equation:

$$\%\text{Porosity} = \frac{\rho_{\text{th}} - \rho_{\text{exp}}}{\rho_{\text{th}}} \times 100. \qquad (1)$$

The porosity percent values for each sintering temperature and each composite sample were given in Table 2. The minimum porosity (3.88 %) was obtained for the composite specimen C (35 % Fe) sintered at 1000 °C. The porosity decreases as the sintering temperature increases. As the sintering temperature increases from 800 to 1000 °C, the decrements in the porosity are 22.52 % for the composite specimen A, 3.05 % for the composite specimen B, and 5.83 % for the composite specimen C. There are some other methods to decrease the amount of porosity in composites. Another approach is a process of double sintering–double pressing to decrease the porosity (i.e., to increase the density). Thorat et al. [7] studied hot isostatic pressing (HIP) of Cu–Co–Fe–Diamond sintered specimens and it was demonstrated that the minimum porosity, 2.6 %, could be obtained by doubling the number of sintering processes at 900 and 950 °C. In that study, high-temperature pressureless sintering was followed by hot isostatic pressing, which suggested it might be possible to conduct presintering followed by HIP as an alternative fabrication route for prealloyed based diamond tools.

Effects of matrix composition. As the Fe content decreases from 75 (specimen A) to 35 (specimen C) wt% the density of the composite specimen increases (Table 2). In other words, as the amount of Fe in the composite specimen decreases, the porosity in the composite specimen decreases (Table 2). For the composite specimen A (75 % Fe) produced at 800 °C, the maximum porosity was obtained. The minimum porosity was obtained for the composite specimen C (35 % Fe) sintered at 1000 °C. When Fe content decreases from 75 wt% (specimen A) to 35 wt% (specimen C), the decrements in the porosity percent were obtained at 33.57, 24.12, and 23.09 % for the composite specimens sintered at 800, 900, and 1000 °C, respectively. It is concluded that addition of Fe powder increases the porosity of the composite. For these types of composite materials, densification can be increased by using a filler material (bronze, Cu, Sn) with a small particle size, because the filler metal melts and fills in the pores during sintering.

Hardness

Effects of sintering temperature. Hardness is a vital mechanical property that determines the quality of diamond-reinforced MMCs when cutting natural stones. The sintering temperature is important to production (i.e., consolidation of the powder) and the hardness of the diamond reinforced MMCs. The sintering temperatures were intentionally selected to be lower than 1100°C because diamond decomposes at higher temperatures. Figure 3 shows the change in the hardness values with changes in the sintering temperature. It was observed that the hardness of the composites increases with sintering temperature. As the sintering temperature increases from 800 to 1000 °C, the increment in hardness is 17.86 % for the composite specimen A, 11.11 % for the composite specimen B, and 6.25 % for the composite specimen C.

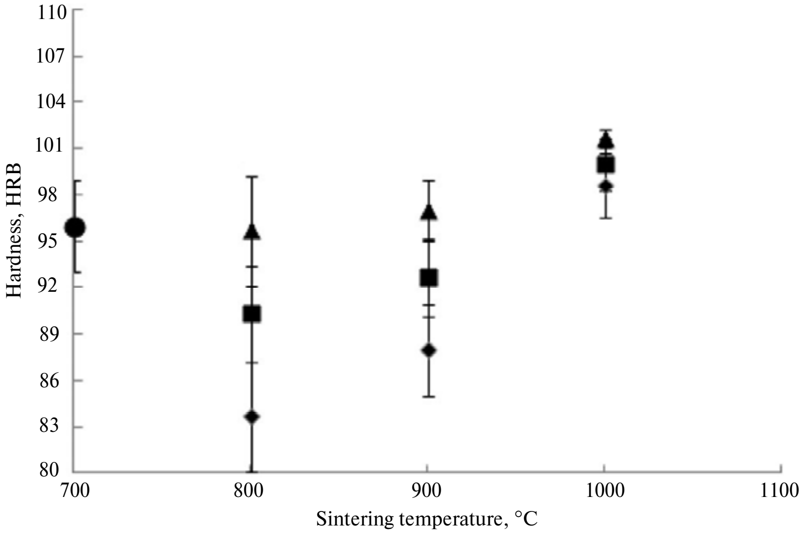


Fig. 3. Brinell hardness vs. sintering temperature for composite specimens: A (♦), B (■), C (▲), D-commercial product (●).

Although the commercial product (specimen D) has a 96 HBN value when prepared at a temperature of 700 °C, the composite specimens A and B produced at 800 and 900 °C have lower hardness values than the commercial product. The composite specimen C (35 % Fe) sintered at 800 °C has the same hardness as specimen D. However, the average hardness values of the composite specimens A (75 % Fe), B (55 % Fe), and C (35 % Fe) sintered at 1000 °C are higher than that of commercial product by 3.13, 4.17, and 6.25 %, respectively.

Effects of matrix composition. The matrix composition of the composite also exerts an important influence on mechanical properties of the diamond-reinforced MMCs. As is seen in Fig. 4, addition of Co causes increase in the hardness of the composite samples. The maximum hardness value, 102 HBN, was measured from the composite specimen C (55 % Co) sintered at 1000 °C. Basically, the Co and Fe metals determine the hardness of the produced composite samples. The hardness of the composite material is affected by solid solutions of matrix composition (Co and Fe), and this solid solution strengthens the material. As it is seen in the binary phase diagram of Fe–Co, there occurs extensive solid solution formation in almost all compositions [19] since atomic diameters of Fe and Co are 1.24 and 1.25 Å and the numbers of valence electrons are +2 and +2, respectively [20]. Sintering temperature is more effective than the composition since the amount of the Fe–Co solid solution increases with increasing sintering temperature.

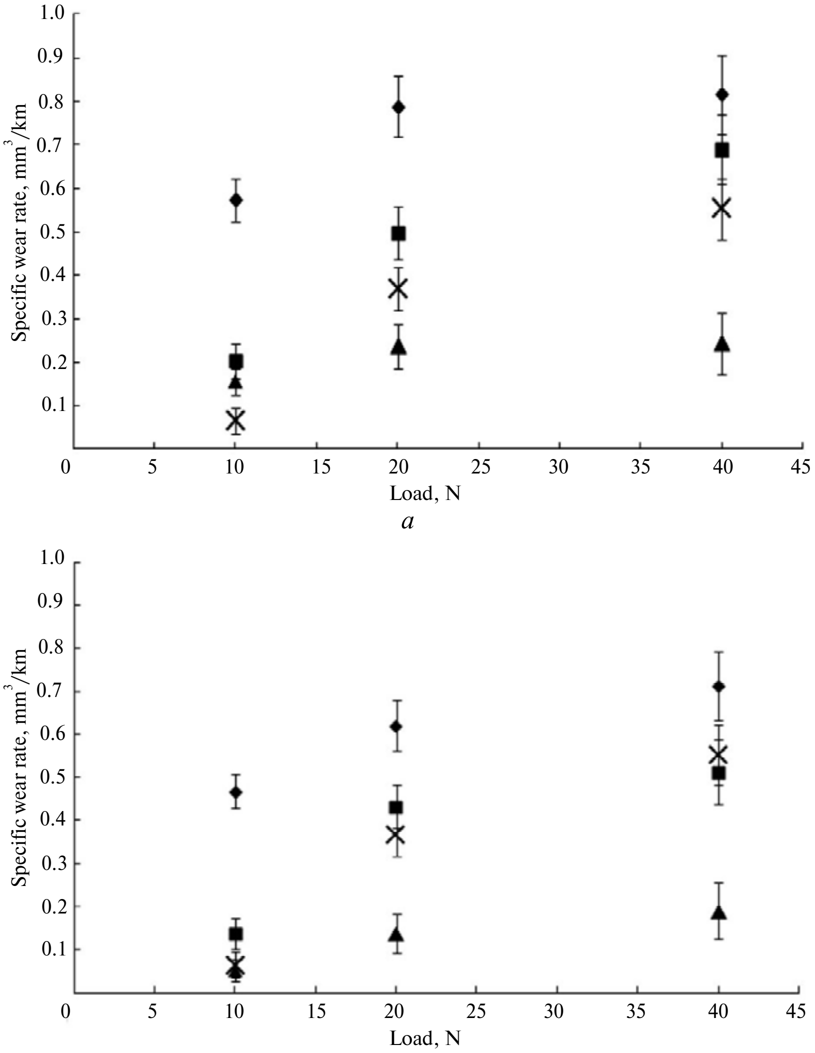
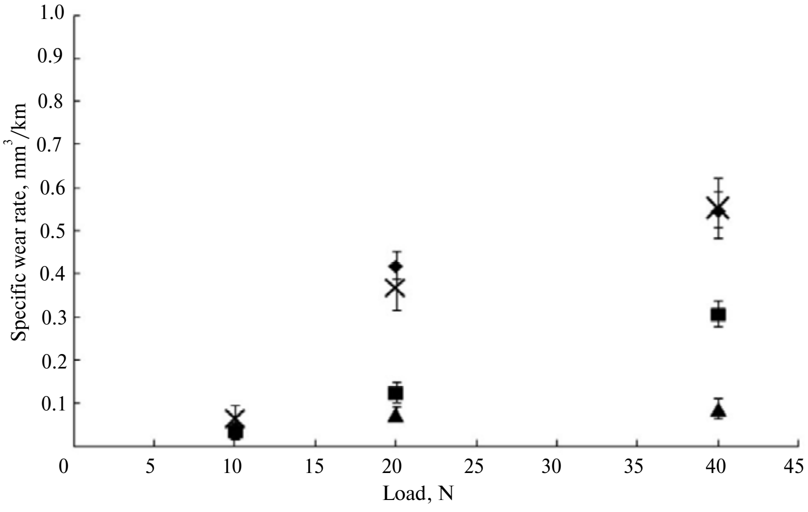


Fig. 4. Specific wear rate of specimens A (75 wt% Fe) (*a*), B (55 wt% Fe) (*b*), C (35 wt% Fe) (*c*) sintered at temperatures: 800 (♦), 900 (■), 1000 (▲) °C; D-commercial product (×) vs. normal load.



c

Fig. 4. (Contd.)

Table 3 compares the results of the Brinell hardness test values for composite samples prepared at 1000°C. The composites sintered at 1000 °C have similar hardness values with similar composites in the literature. It was observed that there is a linear increase in hardness with increasing Co content (or decreasing Fe content). This type of composites requires a higher sintering temperature or a long time for sintering. The maximum hardness value, 102 HBN, was measured from the composite specimens C. Liao and Luo [3] worked on the matrix composition (100 wt% Co + 5 % diamond concentration, and 95 wt% Co + 5 wt% Sn + 5 % diamond concentration) of the diamond-reinforced MMCs. The composite samples were produced by hot pressing in graphite molds at 820–840 °C for 15 min under nitrogen and a mild pressure. The maximum hardness was measured as 103 HBN for the sample consisting of 95 wt% Co + 5 wt% Sn + 5 % diamond concentration due to the presence of Sn powder. Because Sn metal has lower melting point and melts in the sintering process and fills the pores in the composite. Ucun et al. [14] investigated the effect of the matrix composition of the composite material in the sawing process. The highest hardness value of the composite was obtained for the composition (95 wt% (Co–W) + 5 wt% (Cu/Sn–Fe), 20 % diamond concentration). Therefore, addition of Co (decrease in Fe content) increases the hardness of the composite samples.

Wear tests

Figure 4 presents the results of the wear tests for the produced composites and the commercial product. Weight loss was calculated in terms of a specific wear rate. Specific wear rate is the volumetric loss per distance. Specific wear rate is calculated as:

$$\Delta V = \frac{\Delta m}{\rho} \times 1000 \qquad (2)$$

where ΔV is the volume loss in mm^3; Δm is the mass loss in g, and ρ is the density of the composite in g/cm^3.

Specific wear rate $= \frac{\Delta V}{d}$, where d is the distance and for each specimen it is kept constant = 3.6 km.

Table 3. The Brinell hardness test results of the composites produced at 1000 °C

Composites	HBN (avg.)
A – 75 wt% Fe + 15 wt% Co + 10 wt% bronze, 20 % diamond concentration	96
B – 55 wt% Fe + 35 wt% Co + 10 wt% bronze, 20 % diamond concentration	97
C – 35 wt% Fe + 55 wt% Co + 10 wt% bronze, 20 % diamond concentration	102
D-commercial product – 70 wt % Co + 25 wt % bronze, 20 % diamond concentration	96
100 wt% Co + 5 % diamond concentration	93 [3]
95 wt% Co + 5 wt% Sn + 5 % diamond concentration	103 [3]
95 wt% (Co–W) + 5 wt% (Cu/Sn–Fe), 20 % diamond concentration	98 [14]
80 wt% (Co–W) + 20 wt% (Cu/Sn–Fe), 20 % diamond concentration	86 [14]

Note. As a concentration of 100 % diamond grits was designated as 4.4 cts/cm^3, the 20 % diamond concentration is 0.88 cts/cm^3 and 5 % is 0.22 cts/cm^3.

Effect of sintering temperature. The influence of sintering temperature is shown in Figs. 4, *a–c*, which indicates the variation of the specific wear rate with respect to the applied normal load at sintering temperatures of 800, 900, and 1000 °C. For the composite specimen A (75 % Fe) produced at 1000 °C, the specific wear rate was measured as 0.1543, 0.2366, and 0.2434 mm^3/km under a 10, 20, and 40 N applied normal load, respectively. The specific wear rate increases with increasing applied normal load for each sample and the commercial product. The same condition was found for composite specimens B (55 % Fe) and C (35 % Fe). As it is seen, a decrease in sintering temperature causes an increase in the specific wear rate for each produced composite sample. The sintering temperature directly influences mechanical properties of a composite.

Effect of the matrix composition. The wear property of diamond-reinforced MMCs mainly depends on reaction bonds between the diamond surface and the metal matrix. A few materials react or wet the diamond. Metals used in a diamond-reinforced composite should support the diamonds without damaging them. During the cutting process, the metal matrix is expected to wear to some extent, thereby allowing the tips of the diamond particles to run with ease and allowing the chip to flow smoothly. Therefore, the reaction bond influences the cutting performance of the diamond-reinforced MMCs. In this study, Co and Fe were used as the binding metals in the composite. The addition of Fe metal powder increases the weight loss of the composites during a wear test. The specific wear rates of the composite specimens A (75 wt% Fe), B (55 wt% Fe), and C (35 wt% Fe) sintered at 1000 °C under the 40 N load were measured as 0.2434, 0.1901, and 0.0882 mm^3/km, respectively. Similar results for 20 N and 10 N loads were obtained for the composite sample produced at 800, 900 and 1000 °C (see Figs. 4, *a–c*). Thus, the capability of Fe to react with diamond is lower than that of Co metal because the chemical affinity of Fe for diamond is lower than that of Co. However, this is not necessarily a bad condition. It is known that the sawing process for natural stone is a process of optimization. The metal matrix should have neither a high wear rate nor a low wear rate, and it should be at an optimum value; otherwise, diamond particles are removed from the metal matrix or the diamond tips are blunted. Therefore, metal matrix wear can be controlled with the addition of Fe. For this reason, the microstructure of the composite was examined using an optical microscope. After grinding and polishing, the composite samples were etched with a solution of 10 g of 15 $(NH_4)_2S_2O_3$ in 90 ml of distilled water. Figure 5 shows the microstructure of the matrix (× 400). The bronze metal is depicted as bright yellow, Co is shown as light grey, and Fe is shown as black under the optical microscope. As is shown, bronze is a continuous phase in the powder due to its limited solubility in the Fe–Co solid solution. It was expected that the interface between the Fe and Co metal powders would form through diffusion bonding because a solid solution forms at the interface as a result of the solubility of Fe and Co metals. The microstructure is affected by the composition of the metal matrix. Barbosa et al. [8] revealed that the microstructure of Fe–Cu–Co alloys is very sensitive to the Cu content and that Fe–Co, Fe–Cu, and Co–Cu solid solutions exist in this system. Dai et al. [6] demonstrated that the addition of the rare earth compound (CeO_2, $LaNi_5$) in Fe-based diamond composites causes a decrease in sintering temperature and makes the metal powder more active, thereby accelerating the sintering process and inducing a finer structure in metal matrix. In our study, the grain size was not measured but it is expected that an increase in the sintering temperature causes an increase in the grain size of the composite specimens. Additionally, increasing of the sintering temperature decreases the weight loss as explained above.

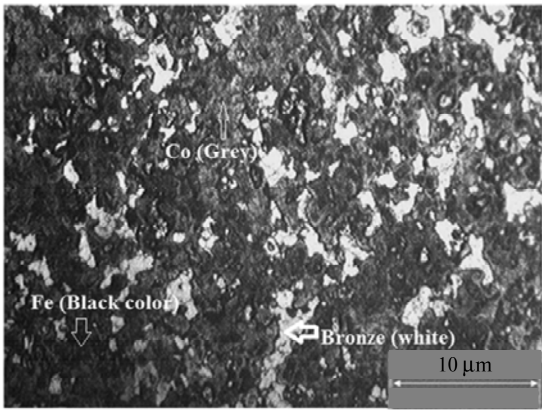


Fig. 5. Microstructure of composite specimen C sintered at 1000 °C.

In the commercial product, there is no Fe metal powder (Co+25 wt% bronze). The specific wear rates were measured as 0.0659, 0.3676, and 0.553 mm^3/km at 10, 20, and 40 N normal loads, respectively. The specific wear rate of the commercial product is lower than that of the composite specimens in group A (75 % Fe) produced at 800 and 900 ^oC (Fig. 4, *a*). However, this value is higher than that of the composite specimen in group A (75 % Fe) produced at 1000 °C (except when the wear is under 10 N normal load) (Fig. 4, *a*). Similar conditions were observed for the composite specimens in group B (55 % Fe) produced at 800 and 900 °C, except the wear test under 40 N normal load (Fig. 4, *b*). However, for the composite produced at 1000 °C, the specific wear rate is lower than that of the commercial product. As is shown in Fig. 4, *c*, the specific wear rate of the composite specimens in group C (35 % Fe) produced at 900 and 1000 °C is lower than that of the commercial product. The specific wear rate values are close to each other for the composite produced at 800 °C and the commercial product. As the sintering temperature is increased during the production of the composite material, the wear resistance of the composite material is improved, leading to a better material than the commercial product.

SEM ANALYSIS

The wear mechanism of diamond-reinforced MMCs was discussed clearly by Karagöz and Zeren [21, 22] and Konstanty [18]. The abrasive wear mechanism has been observed in previous studies as well. The retention of the diamond by the metal matrix is important for determining the mechanical properties (i.e., wear, transverse rupture strength). Figure 6, *a* shows the wear of diamond. As is seen in Fig. 6, *a*, corners of the diamond were broken during the wear test. It is desirable that the metal matrix and diamond grits must be worn at an optimum level. These corners are the evidence of wear of diamond. Figure 6b is the magnified part of interface region A in Fig. 6, *a*. It reveals the excellent metallurgical bonding of the diamond by the metal matrix. The most important point is to form a high bonding strength between the matrix and the diamond surface. It is observed that the fracture occurred mainly at the side of the matrix and at the tip of the diamond grit. The retention of diamond in the matrix is obtained with the mechanically and chemically bonding according to affinity of metal for carbon. It is observed that the diamond was not pulled out of the metal matrix for the composite specimens in group C (35 % Fe) produced at 800, 900, and 1000 °C. Similar results were observed for the composite specimen in group A (75 % Fe) produced at 1000 °C and the composite specimens in group B (55 % Fe) produced at 900 and 1000 °C. However, the diamond pull-out mechanism was observed as the sintering temperature decreased and the addition of Fe metal increased [17].

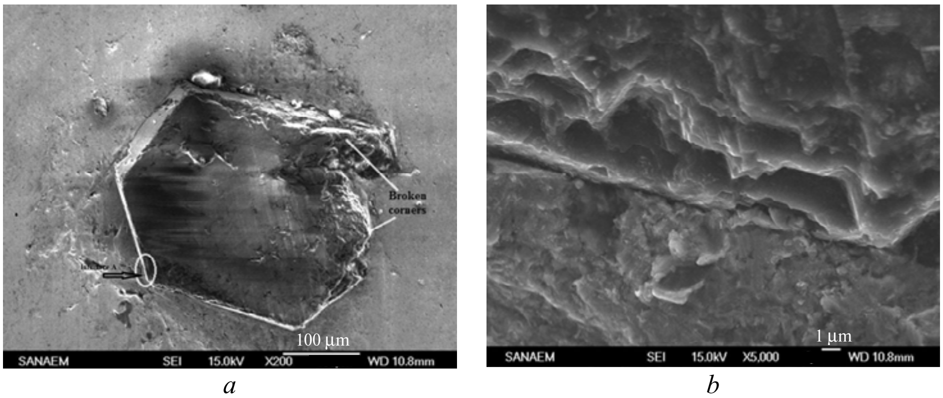


Fig. 6. Wear of a diamond in the composite specimen C sintered at 1000 °C: (*a*) broken corners of diamond, (*b*) interface between diamond and matrix metal (magnified interface region A).

EFFECT OF BORON CARBIDE (B_4C)

Up to now, effects of matrix composition and sintering temperature of the Fe–Co based MMCs were investigated. To improve the mechanical properties (especially wear resistance) of the Fe–Co based MMCs, B_4C (0.75 wt%) was added to the composite specimens. The same production conditions were applied to produce A-B_4C, B-B_4C and C-B_4C composite specimens. Figure 7 presents the EDX analysis of the composite specimen C-B_4C produced at 1000 °C and boron

(B) peak is shown. Intensity of the B peak is very low since the amount of B_4C is low (0.75 wt%.).

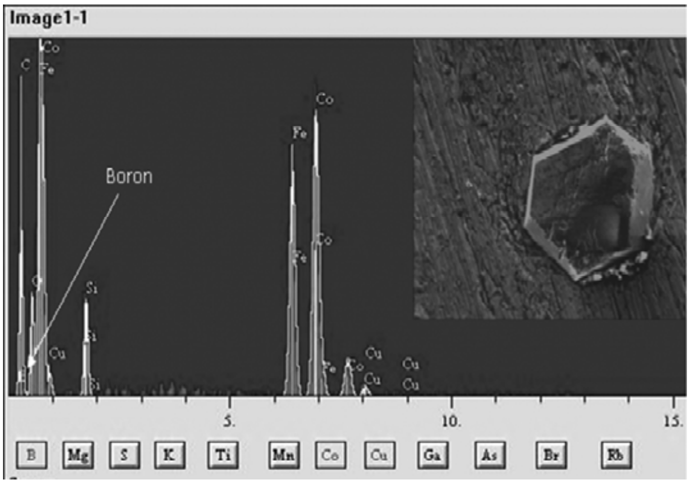


Fig. 7. Boron peak from EDS analysis.

Hardness

Figure 8 shows the variation of the hardness of the composite specimen with B_4C. The hardness of the composite specimen increases with increasing sintering temperature. The composite specimens A-B_4C sintered at 800 and 900 °C have almost the same hardness values (88 and 89 HBN). However, the composite specimen A-B_4C sintered at 1000 °C has 12.5 % higher hardness than the composite specimen A-B_4C sintered at 800 °C. The temperature of 800 or 900 °C is not sufficient to sinter the matrix composition and B_4C. Sintering of B_4C requires a temperature of 1000 °C.

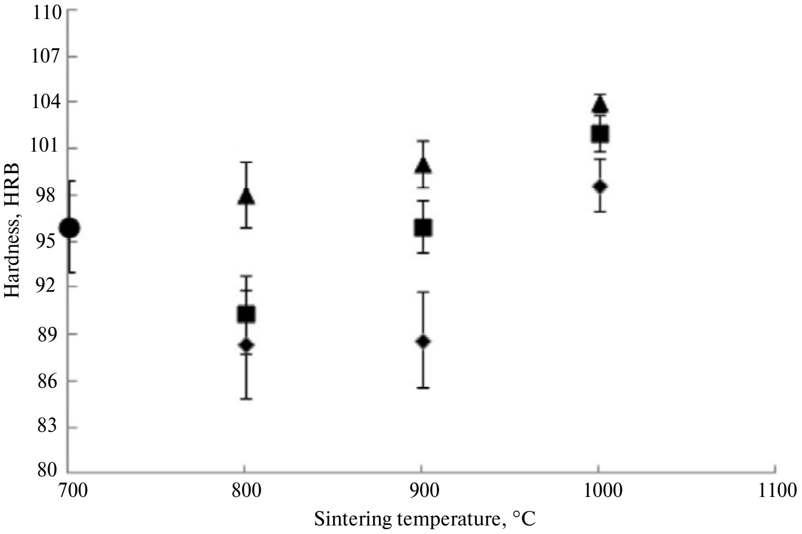


Fig. 8. Brinell hardness of the composite specimens with B_4C: A (♦), B (■), C (▲) and D-commercial product (●) vs. sintering temperature.

The hardness value is 90 HBN for the composite specimen B-B_4C sintered at 800 °C. As the sintering temperature increases, 6.67 and 13.33 % higher hardness values for sintering at 900 and 1000 °C were measured with respect to sintering at 800 °C.

The maximum hardness was measured as 104 HBN for the composite specimen C-B_4C sintered at 1000 °C. This hardness value is 6.12 and 4.0 % greater than the hardness of the same specimen sintered at 800 and 900 °C, respectively. By adding 1 % SiC Oliveira et al. [4] increased hardness of the Fe-Cu alloys by 14.0 %.

As is seen in Fig. 3 and Fig. 8, the hardness of the composite specimens with B_4C are almost the same with the composite specimen without B_4C. However, the maximum hardness values were measured in the composite specimens sintered at 1000 °C. Furthermore, the composite specimen B-B_4C prepared at 900 °C has the same hardness as the commercial product, but the hardness values of the composite specimens A-B_4C and B-B_4C sintered at 1000 °C are 3.13 and 6.25 % higher than the commercial product. The hardness of composite specimens C-B_4C prepared at 800, 900, and 1000 °C are 2.08, 4.17, and 8.33% higher than that of commercial product, respectively.

Wear resistance

Figures 9, *a–c* show the specific wear rate of the composites specimens prepared at 800, 900, and 1000 °C. When the applied load increases, the specific volume wear rate increases and the wear resistance (inverse of wear rate) increases with increase in the sintering temperature for all composite specimens. Clearly for specimens sintered at 800 °C, the specific volume wear rate is the maximum. For the same condition, the composite specimens A-B_4C and B-B_4C have sequentially 37.51 and 9.56 % higher specific wear rate than the C-B_4C composite. For the composite specimen sintered at 900 °C, the minimum specific rate is 0.1405 mm^3/km for the composite specimen C-B_4C. The composite specimens A-B_4C and B-B_4C have sequentially 278.29 and 231.81 % higher specific volume rate with respect to C-B_4C composite. For the composite specimen sintered at 1000°C, the minimum specific volume rate is 0.0849 mm^3/km for the composite specimen C-B_4C. The composite specimens A-B_4C and B-B_4C have sequentially 146.29 and 79.15 % higher specific rate with respect to C-B_4C composite. It can be concluded that the boron carbide greatly decreases the specific wear rate. Oliveira et al. [4] by adding 1 % SiC revealed that Fe–20Cu–1 wt% SiC composite material has the best mechanical properties (yield strength, hardness, and wear resistance) among the produced composites. Also it is reported that the addition of WC (0.5–2 wt% with a mean particle size of 5 μm) increases the matrix wear resistance. Wang et al. [11] worked on the coated diamond with Ti by the vacuum slow vapor deposition method. Continuous and compact TC shielding layer was investigated and as a result the life of a blade was increased by 36 % with respect to the blade produced with uncoated diamond. Similar results were obtained by Xu [12].

B_4C particles have effect on the grain size in the microstructure since B_4C particles inhibit growth of grains in the microstructure. Furthermore, it is expected that the composite with B_4C specimens have finer grain size than that of without B_4C in all situations.

Table 4 shows the comparison of the produced composite specimens and the commercial product (specimen D). It is shown whether the composite specimens can be used instead of the commercial product or not. The composite specimens having a lower specific wear rate than the commercial product are suitable for sawing of natural stones.

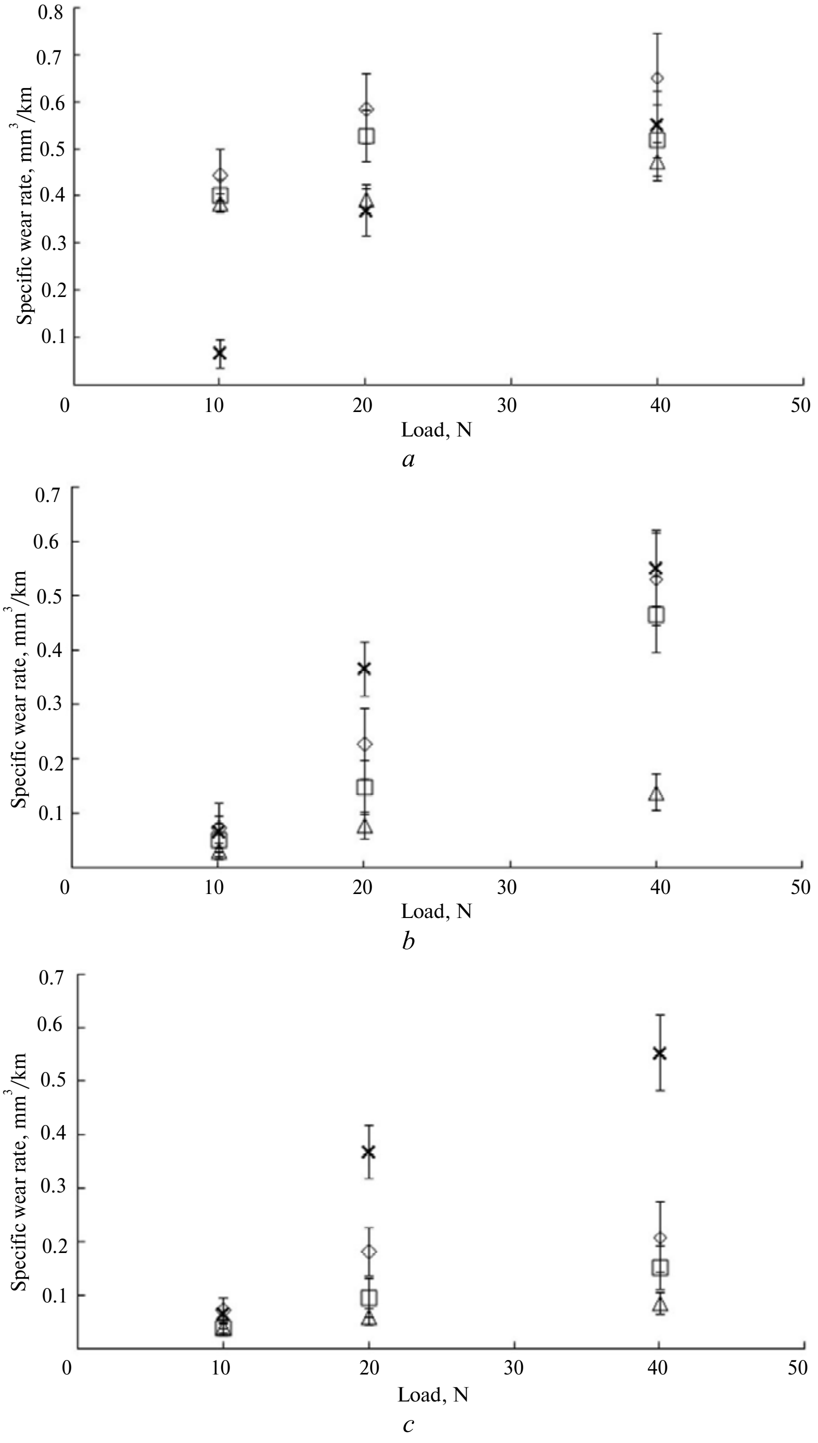


Fig. 9. Specific wear rate of the composite specimens with B_4C (A (◊), B (□), C (Δ)) and D-commercial product (×) sintered at 800 (*a*), 900 (*b*), 1000 (*c*) °C vs. normal load.

CONCLUSION

In this experimental study, the effects of sintering temperature and of the addition of B_4C and Fe metal into Co matrix composites have been investigated.

B_4C has been used as a wear rate controller for a diamond tool. Diamond-reinforced Fe–Co matrix composites have been produced at sintering temperatures of 800, 900 and 1000 °C under pressure of 25 MPa using a powder metallurgy method (i.e., hot pressing). The following conclusions can be drawn:

– The minimum porosity (3.88 %) has been obtained for the composite specimen C (35 % Fe) sintered at 1000 °C. As the sintering temperature increases from 800 to 1000 °C, the decrement in % porosity is 22.52 % for the composite specimen A, 3.05 % for the composite specimen B, and 5.83 % for the composite specimen C. For all composite specimens (A-75 wt% Fe, B-55 wt% Fe, and C-35wt% Fe), the porosity decreases with an increase in sintering temperature (i.e., densification increases with an increase in the sintering temperature). As the Fe content in composite decreases from A-75 wt% Fe to C-35 wt% Fe, there is a slight decrease in porosity. The minimum porosity (i.e., the maximum densification) was obtained for the composite specimen C sintered at 1000 °C.

Table 4. The specific volumes wear rates (mm^3/km) of the produced composites and commercial product

Composites	Sintering temperature, °C		
	1000	900	800
A	0.2434	0.6893	0.8161
B	0.1901	0.5125	0.7142
C	0.0882	0.3088	0.5490
A-B_4C	0.2091	0.5315	0.6515
B-B_4C	0.1521	0.4662	0.5191
C-B_4C	0.0849	0.1405	0.4738
D-Com	0.553		

– As the sintering temperature increases from 800 to 1000 °C, the increment in hardness is 17.86% for the composite specimen A, 11.11% for the composite specimen B, and 6.25 % for the composite specimen C. The maximum hardness value, 102 HBN, was measured from the composite specimen C (35 % Fe) sintered at 1000 °C. The hardness of the composite increases with increasing sintering temperature, but it decreases with addition of Fe.

– The minimum specific wear rate values were measured for all the composite specimens sintered at 1000 °C. For example, the specific wear rates for the composite specimen C (35 % Fe) sintered at 800, 900 and 1000 °C were measured as 0.549, 0.3088, and 0.0882 mm^3/km under a 40 N applied normal load, respectively. The wear resistance is enhanced by increasing the sintering temperature. The addition of Fe (instead of Co) causes an increase in the specific wear rate. The maximum wear rate under 40 N load, 0.8161 mm^3/km, was measured from the composite specimen A (75 wt% Fe) sintered at 800 °C. This is compensated by adjusting the sintering temperature.

– Addition of B_4C increases the hardness of the produced composite specimens and decreases the specific wear rate. The maximum hardness and minimum specific wear rate were measured from the specimen C-B_4C. The minimum specific wear rate is measured as 0.4738, 0.1405, and 0.0849 mm^3/km for the specimen C-B_4C sintered at 800, 900 and 1000 °C, respectively. The composite specimens A-B_4C and B-B_4C sintered at 1000 °C have sequentially 146.29 and

79.15 % higher specific wear rate with respect to C-B_4C composite. B_4C can be used as a wear rate controller in diamond-reinforced MMCs.

– The hardness and specific wear rate of the composites were compared with that of a commercial product, and the better results are obtained with the composite specimen sintered at 1000 °C under 25 MPa pressure. The use of Fe instead of Co causes the production of commercial diamond-reinforced MMCs to be more economical.

The design of diamond cutting tools is basically an optimization problem. The composition of the matrix and sintering temperature are input variables for optimization techniques, such as the Taguchi method, factorial design and surface response method, among others. The performance of the diamond cutting tool can be improved by increasing the number of input variables.

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Досліджено армовані алмазом композити з металевою матрицею на основі Fe–Co-композицій (різні співвідношення Fe/Co) з добавкою або без добавки карбіду бору (B_4C). Вивчено вплив температури спікання і зміни співвідношення Fe і Co у складі матриці на механічні властивості композитів. Композити отримані спіканням в азоті при різних (800, 900 і 1000 °C) температурах при тиску 25 МПа. Вивчено та обговорено механічні властивості отриманих після спікання композитів. Встановлено, що добавка B_4C покращує їхню твердість і зносостійкість.

***Ключові слова**: алмаз, порошкова металургія, композити з металевою матрицею на основі Fe, твердість, зносостійкість.*

Исследованы армированные алмазом композиты с металлической матрицей на основе Fe–Co-композиций (разные соотношения Fe/Co) с добавкой или без добавки карбида бора (B_4C). Изучено влияние температуры спекания и изменения соотношения Fe и Co в составе матрицы на механические свойства композитов. Композиты получены спеканием в азоте при различных (800, 900 и 1000 °C) температурах при давлении 25 МПа. Изучены и обсуждены механические свойства полученных после спекания композитов. Установлено, что добавка B_4C улучшает их твердость и износостойкость.

***Ключевые слова**: алмаз, порошковая металлургия, композиты с металлической матрицей на основе Fe, твердость, износостойкость.*

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