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The Application of a Ball-milled Fe-Cu-Ni Powder Mixture to Fabricate Sintered Diamond Tools

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Abstract

This article discusses results of an analysis of mechanical properties of a sintered material obtained from a mixture of elemental iron, copper and nickel powders ball milled for 60 hours. The powder consolidation was performed by hot pressing in a graphite mould. The hot pressing was carried out for 3 minutes at 900 °C and under a pressure of 35 MPa. The sintered specimens were tested for density, porosity, hardness and tensile strength. Their microstructures and fracture surfaces were also examined using a scanning electron microscope (SEM). The study was conducted in order to determine the suitability of the sintered material for the manufacture of metal-bonded diamond tools. It was important to assess the effects of chemical composition and microstructure of the sintered material on its mechanical properties, which were compared with those of conventional metal bond material produced from a hot-pressed SMS grade cobalt powder.
Although the studied material shows slightly lower strength and ductility as compared with cobalt, its hardness and offset yield strength are sufficiently high to meet the criteria for less demanding applications.

Keywords: Metallography, Mechanical properties, Sintered diamond tools, Powder mixtures, Hot pressing

1. Introduction

Metal bonded diamond composites were not developed or applied until World War II. The recent advancements in the manufacturing of cutting tools have resulted from the progress in powder metallurgy (PM) technologies but increasing industrial production of synthetic diamond has also been of great importance. The cutting elements (diamond segments) of tools, such as circular and wire saws, drills, milling cutters or grinding wheels have been traditionally fabricated by PM consolidation of diamond-cobalt mixtures [1,2,3,4].

The tool selection depends both on properties of the workpiece material (its hardness and abrasivity) and cutting conditions (linear speed, cooling efficiency and cutting rate, etc.). These factors affect both the tool geometry as well as the composition and structure of diamond segments. The knowledge of these factors allows engineers to design a tool with a desired shape and diamond segments with an appropriate form, structure and composition. The service life of diamond-impregnated segments is primarily dependent on the retention of diamond crystals and tribological properties of the metal bond (matrix). It is essential that the metal bond material should wear along with the diamond grits to induce self-sharpening of segments. The best and most common metal bond material which meets this requirement is cobalt. It has been widely used in diamond tools for several decades. The major shortcoming of cobalt, however, is its high and unstable price, which has increasingly contributed to the tool production costs since the beginning of the new millennium, when diamond became a commodity product [5]. Significant changes in the cost of raw materials as well as a relative decrease in the other production costs have exerted an increasing pressure on toolmakers to look for cheaper alternatives to cobalt powders [5,6].

Over the past years, a number of unsuccessful attempts have been made to fabricate diamond-impregnated tools using mixtures of relatively cheap elemental powders, e.g. carbonyl iron powder or carbon-reduced iron with copper and/or bronze. Extensive research has shown that such sintered materials have a coarse-grained, inhomogeneous microstructure, which results in low mechanical strength [7-9]. It is assumed that a sintered material characterized by a fine-grained microstructure is obtained from powder particles with a fine crystalline structure, which prevents grain growth during the sintering process [10,11].

The main objective of this study was to determine the suitability of ball-milled Fe-Cu-Ni powder mixtures for fabrication of sintered diamond-impregnated metal-matrix composites. The combined effects of chemical composition, powder milling conditions and sintering parameters on the as-consolidated microstructure and mechanical properties were studied. The obtained results were compared with properties of a hot pressed SMS (sub-micron size) grade cobalt powder.

2. Experimental Procedure and Results

The experimental powder mixture was made from:

a) Höganäs NC100.24 grade, carbon-reduced iron powder (20-180 μm)
b) ECKA CH-L10 grade, electrolytic copper powder (<45μm)
c) Vale T255 grade, carbonyl nickel powder (Fisher Sub-Sieve Size = 2.4 μm).

Morphologies of the starting powders are shown in Fig. 1.

Prior to consolidation, the powder mixture containing 60% Fe, 28% Cu and 12% Ni was prepared by blending the constituent powders in a Turbula-type mixer for 30 minutes. Then, the powders were ball-milled for 60 hours in air using the EnviSense RJM-102 laboratory mill. The milling vial was filled to half of its volume with 12 mm diameter 100Cr6 steel balls. The ball-to-powder mass ratio was maintained at 10:1. The milling vial was set to run at about 70% of the critical rotational speed.

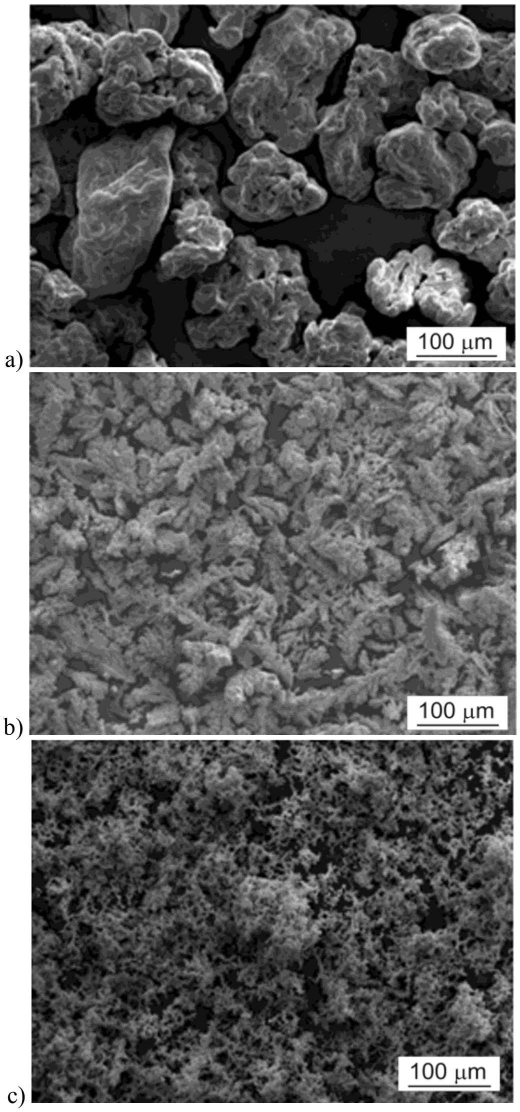

Fig. 1. Experimental powders: a) NC100.24; b) CH-L10; c) T255

The particle shape of the ball-milled powder is shown in Fig. 2.

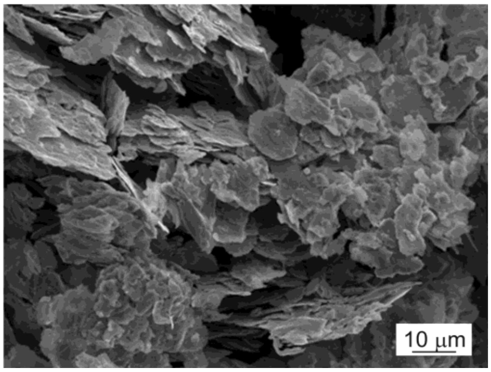

Fig. 2. Ball-milled Fe-Cu-Ni powder

The hot pressing process was performed in the *ARGA CAR1001* hot press furnace in nitrogen. The mixture was hot pressed in a graphite mould, having three 12x40 mm cavities. The pressing temperature was properly selected to obtain the as-sintered porosity lower than 3%. Hence, the powder was held at 900 °C and 35 MPa for 3 minutes.

The sintered specimens were first tested for density and hardness. The density measurements involved weighing the specimens in air and water using the WPA120 hydrostatic weighing system, according to the PN EN ISO 2738:2001 standard. The results were also used to assess the as-sintered porosity. The Vickers hardness was determined at a 10 kgf load. The results are summarized in Table 1.

Table 1.
Density, porosity and hardness (1)

Density [g/cm^3]	Theoretical density [g/cm^3]	Porosity [%]	HV10
8.06 ± 0.03	8.25	2.34 ± 0.03	288.7 ± 9.3

(1) scatter intervals estimated at 90% confidence level

The specimens were then machined, by turning, to produce non-standard specimens for static tensile tests.

The tensile strength tests were carried out using the INSTRON 4502 universal testing machine The diameter of the gage section of specimens was 3.5 mm. The cross head speed was set to 0.5 mm/min. The specimen elongation was registered by means of an extensometer with a gauge length of 10 mm. The results were then used to calculate the offset yield strength $R_{0.2,}$ ultimate tensile strength R_m and elongation (ε).

The results of the static tensile strength test and a typical stress-strain curve are given in Table 2 and plotted in Fig. 3, respectively.

The fractured specimens were examined fractographically using the JSM-7100F scanning electron microscope fitted with an OXFORD INSTRUMENTS X-Max-AZtec EDS system. The grip sections of tensile specimens were also used to produce metallographic specimens for microstructural observations. A typical fracture surface and microstructure are shown in Figs 4 and 5, respectively.

Table 3 provides chemical compositions obtained from the EDS analysis in micro-areas indicated in Fig. 5.

Fig. 3. Stress-strain curve

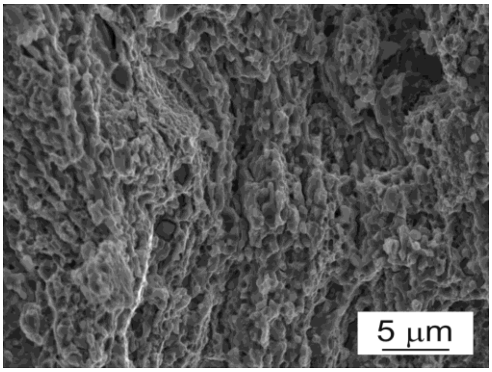

Fig. 4. Typical fracture surface after a tensile strength test

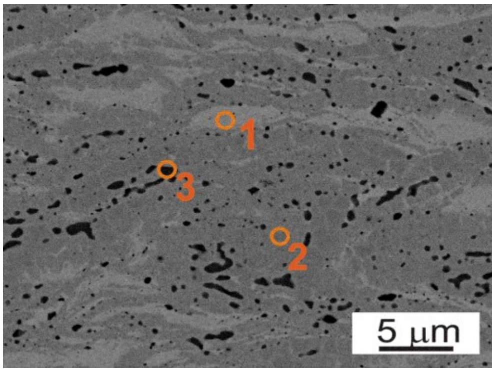

Fig. 5. Microstructure of the sintered Fe-Cu-Ni material

Table 3.
Chemical compositions in areas shown in Fig. 5

Weight %	O	Fe	Ni	Cu	Total
Spectrum 1		11.7	4.1	84.2	100
Spectrum 2		91.6	4.6	3.8	100
Spectrum 3	17.5	75.5	2.9	4.1	100

3. Discussion

The objective of the present study was to fabricate sintered materials using inexpensive iron-based powders and to assess their potential use as a sintered matrix in diamond impregnated tools. The hot pressing parameters were carefully selected to obtain the as-sintered density approaching the theoretical (full) density (Table 1).

Table 2.
Static tensile test results (1)

Powder	Offset yield strength $R_{0.2}$ [MPa]	Ultimate tensile strength R_m [MPa]	Elongation ε [%]
Fe-Cu-Ni	355.0 ± 15	716.6 ± 16.7	9.35 ± 0.7
Co (SMS)	404.5 ± 25.4	865.0 ± 12.0	19.5 ± 1.5

(1) scatter intervals estimated at 90% confidence level

It was found that the ball-milled powders could be consolidated to a virtually pore-free state by the hot press route at a temperature of 900°C. The density of the consolidated material ranged from 8.05 to 8.11 g/cm^3. As shown in Table 1, the Fe-Cu-Ni alloy combines high hardness (290.5 HV10), tensile strength (716.6 MPa) and offset yield strength (355 ±15 MPa) with high elongation of around 9.35%.

The fractographic analysis revealed that a dimpled ductile failure had occurred in all specimens subjected to tension. The EDS analysis indicated that the metallographic specimens of the sintered material obtained from the finely ground powders showed a complex, multi-phase microstructure. The EDS data included in Table 3 indicated that the sintered Fe-Cu-Ni alloy consisted of solid solutions of (α-Fe) and (Cu), and iron oxides.

The addition of nickel and copper to iron resulted in high hardness and tensile strength of the alloy and acceptable ductility. It seems that the properties of the material can still be improved by fine tuning its chemical composition and powder processing (milling) conditions.

4. Conclusion

The experimental data imply that the material obtained from the powders ball-milled for 60 hours and hot consolidated to near-full density at 900°C is characterized by a fine-grained microstructure and inhomogeneous microstructure. It should be emphasized that although the studied material shows slightly lower strength and ductility as compared with cobalt, its hardness and offset yield strength are sufficiently high to meet the criteria for less demanding applications, such as DIY and professional general-purpose tools.

Undoubtedly, the tested Fe-Cu-Ni material deserves further attention because of its attractive price and ease of consolidation through hot pressing. Presumably its strength and plastic properties can be improved by fine tuning its chemical and powder composition as well as the powder processing and consolidation conditions.

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