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DEC – diamond enhanced carbides: a new super-hard material with enhanced wear resistance

The paper presents the application of the pulse plasma consolidation (PPC) method in the field of diamond composites sintered under conditions of thermodynamic instability of diamond for the manufacture of tools intended for the cutting of different stones. Diamond enhanced carbides (DEC) are a composite material containing 30% vol of diamond particles and were produced using a mixture of submicron WC6Co (wt %). Due to PPC sintering conditions, dense sinters with a strong bond between the diamond particles and the sintered carbide matrix were obtained. The values of the specific cutting energy and the apparent friction coefficient of DEC cutter were investigated in comparison with the similar devices from PCD and ordinary tungsten carbide. DEC materials sintered in GeniCore confirmed the good market prospects for these materials in both cutting and mining applications.

Key words: *metal matrix composite, DEC, SPS, sintering, diamond, cemented carbide*

1. INTRODUCTION

Diamond enhanced carbides were developed at the beginning of the XXI century [1, 2] as materials which should combine the best properties of Polycrystalline Diamonds (PCD) based metal matrix composites (MMC) and cemented carbides as known superhard materials. However, there was a technological difficulty in the production of DEC, since diamond is in a metastable phase at the temperature of the sintering of cemented carbides (1400–1500°C) and transforms into graphite. Under high vacuum (at low partial oxygen pressure) at temperatures up to 1400°C, the graphitization proceeds slowly and only occurs on the surface of the diamond particles, whereas above this temperature, the transformation proceeds quickly and occurs throughout the entire particle. In order to avoid graphitization, it is therefore necessary to conduct the sintering process quickly in a vacuum, and at a relatively low temperature. The innovatory Pulse – Plasma – Compaction (PPC) technology met mentioned requirements, because of using of electric current impulses, with the amplitude of the order of several hundred kA, which are generated by discharging a capacitor battery. The patented solution of an electronic switcher and the transformation of PPC puts that technology Pulse – Plasma – Compaction ready for the industrial application and sintering of DEC based composites with improved performance characteristics.

2. EXPERIMENTAL PART

2.1. Materials

The WC-6Co (weight %) composites were produced from mixtures of tungsten carbide (94 weight %)

powder with an average grain size of 0.4 μm and ultra-fine-grained cobalt powder (6 weight %). At the second stage 30% vol. of the diamond powder with an average size of about 60 mμ was added to the basic carbide mixture. The powders were dry mixed in a Turbo Mixer made in China according to Schatz's geometry [3] using carbide balls with a 1:1 ball-to--powder mass ratio. The mixing time was 5 hours.

2.2. The PPC sintering process

The sintering process was conducted in an apparatus which uses PPC technology, shown in Figure 1, under the following basic conditions. Before the sintering, the chamber was pumped out to a pressure of 1.5×10^{-3} Pa. Then, under a loading force of 100 kN, the sample was heated to a temperature of 800°C for 10 min so as to remove the gases adsorbed on the powder particle surfaces. After degassing, the sample was further heated to reach the required sintering temperature of 1250°C and was maintained at this temperature for 3 min. At the beginning of this stage, the loading force was increased to 212 kN. The final stage included cooling the sample to room temperature, still under a loading force of 212 MPa. All the operations were performed in a vacuum of 1.5×10^{-3} Pa.

Fig. 1. The production system for sintering by the PPC technology manufactured by GeniCore in Poland

2.3. Testing methods

Wear resistance testing of materials by friction against loosely fixed abrasive particles was made in accordance to GOST 23.208-79 [4], as presented in Figure 2.

Cutting tool characterization was made in cooperation with the Mining Engineering Department of the University of Mons based on a series of standardized cutting tests performed on a Rock Strength Device (RSD) developed in the United States of America [5]. Shown in Figure 3, RSD was used to carry out cutting tests at constant speed and depth of cut. It was composed of a two parts frame, one fixed and one mobile, a stepper motor, and a two-dimensional load sensor.

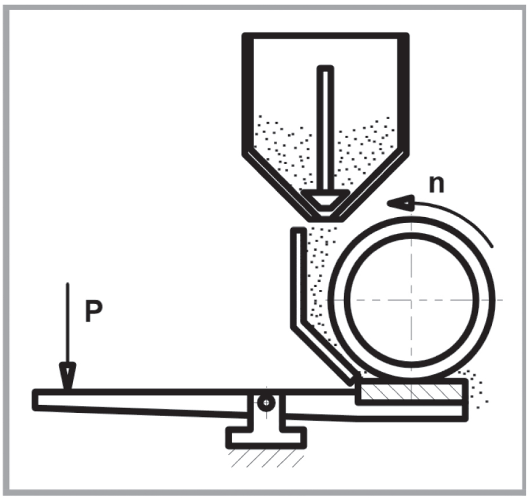

Fig. 2. Test setup diagram according to GOST 23.208-79

Table 1

Main parameters of wear resistance testing according to GOST 23.208-79

Parameter name	Value, unit
Abrasive material (type)	SiC 97C 150–180 μm
Pressure	44 N
Test roller diameter	50 mm
Rotation speed	60 rpm
Time of test	4 hours

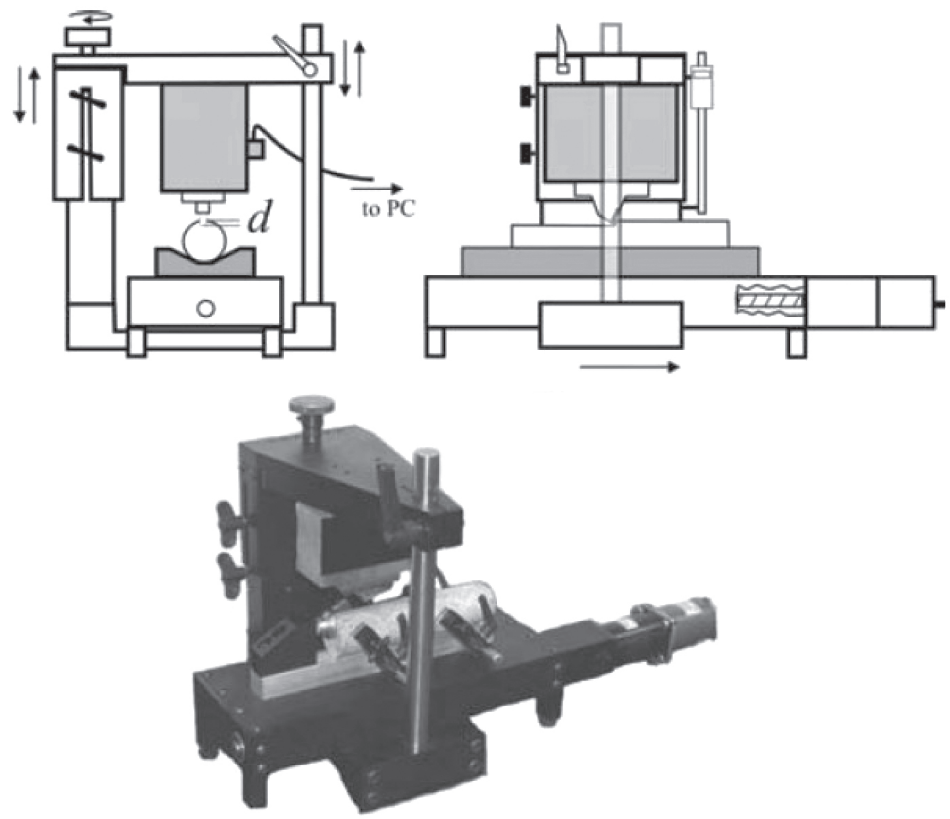

Fig. 3. Device for testing friction and wear resistance [6]

The whole device was controlled by a microcomputer which manages both the displacement of the mobile part and the processing of the data coming from the load sensor. The load sensor measured the horizontal F_h and vertical F_v, components of the force F acting on the cutter.

The standard test procedure [6] to characterize a cutter consists of 10 cutting tests performed on a reference rock sample (generally Vosges sandstone) and on two other rocks – the Mocca limestone and the Soignies limestone – for a depth of cut going from 0.1 to 1 mm. To perform these tests, the cutting speed is set at 4 mm/s while the back rake angle θ is fixed at 15°. Generally, the tests are carried out on 4 cm lengths. After testing, the effective groove depths are measured with a probe indicator to avoid errors due to the mechanical deformation of the experimental frame.

Based on these tests, two parameters can be determined to characterize the DEC cutter – the specific cutting energy ***E***, which was defined as the horizontal cutting energy required to cut a unit volume of rock (1) and the apparent friction coefficient on the cutting face ζ, which was calculated based on the diagram of the evolution of horizontal and vertical forces versus the active surface of the cutter (2) [7–9, 10].

Due to the similar geometry between DEC cutters and the cutters usually tested in the University of Mons, it was possible to compare the results from tests on Vosges sandstone with those of PDC or Tungsten Carbide cutters from the database of the University of Mons.

$$E = \frac{\int_C^2 F_t \, d\vec{u}}{\int_C^2 S_g \, d\vec{u}} \tag{1}$$

where:
- E – specific energy of cutting,
- F_t – tangential cutting force,
- S_G – vertical cross section of the groove,
- $\vec{u}$ – tool displacement vector,
- C – tool path.

$$\zeta = \frac{S_v}{S_h} \tag{2}$$

where:
- S_v – slope of the vertical regression line of the component of the force acting on the active surface,
- S_h – slope of the regression line of the horizontal component of the force acting on the active surface.

3. RESULTS AND DISCUSSION

Comparative results of wear resistance testing of WC-6Co and DEC composites by friction against loosely fixed SiC abrasive particles are presented in Table 2 and confirm the advances of DEC material sintering by means of the new PPC technology.

The values of the specific cutting energy and the apparent friction coefficient of DEC cutter determined for different stones is provided in Table 3.

Comparison of the wear of DEC cutters for different types of stone is presented in Figures 4 and 5. The DEC cutter tested on Vosges sandstone started to show wear after ten cutting tests (Figs 4 and 5 (a)).

In comparison, the cutters tested on the Mocca limestone (Fig. 5b) or on the Soignies limestone (Fig. 5c) were intact. Although the Soignies limestone is a rock with a higher compressive strength than the other two rocks, no wear by chipping was observed on the DEC cutter tested on this rock. Such wear results were consistent with the abrasiveness of the different rocks. However, for wear by chipping due to repeated impacts, it would be necessary to carry out specific tests for this type of wear to draw final conclusions.

Since the comparison between cutters must be done under specific conditions (same rocks studied, same cutter geometry), only the results obtained with the DEC cutter tested on Vosges sandstone were compared with the results of the database of the University of Mons. Table 4 compares the results of the DEC cutter with the ones of two PCD cutters and one Tungsten Carbide cutter. Based on this comparison, it is possible to state that DEC cutters have an intermediate efficiency to PCD and Tungsten Carbide cutters.

Table 2

Comparative wear resistance of WC-6Co and DEC composites

Sample Name	Density [g/cm^3]	Δm [mg]	Relative wear resistance [cm^3/turn]
DEC	11.23	52	6×10^{-6}
WC-6Co	14.88	104	1.2×10^{-5}

Table 3

Results of the tests performed with the DEC cutters for different rocks and the basic properties of rocks

Rock tested	Density	Compressive strength	E [J/m^3]	ζ
Vosges sandstone	2.2–2.8 g/cm^3	95 MPa	3.75×10^7	0.90
Mocca limestone	2.7 g/cm^3	91 MPa	4.38×10^7	0.75
Soignies limestone	2.7 g/cm^3	159,4 MPa	8.84×10^7	0.89

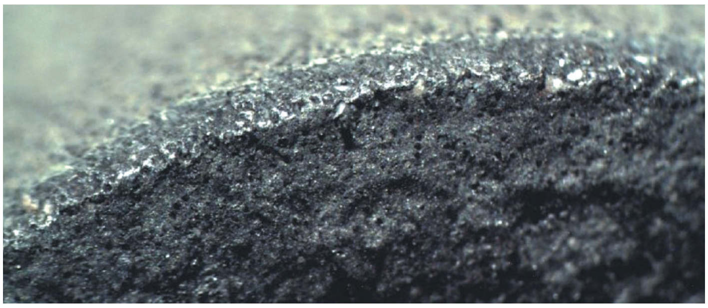

Fig. 4. Worn out edge of cutter after tests on Vosges sandstone

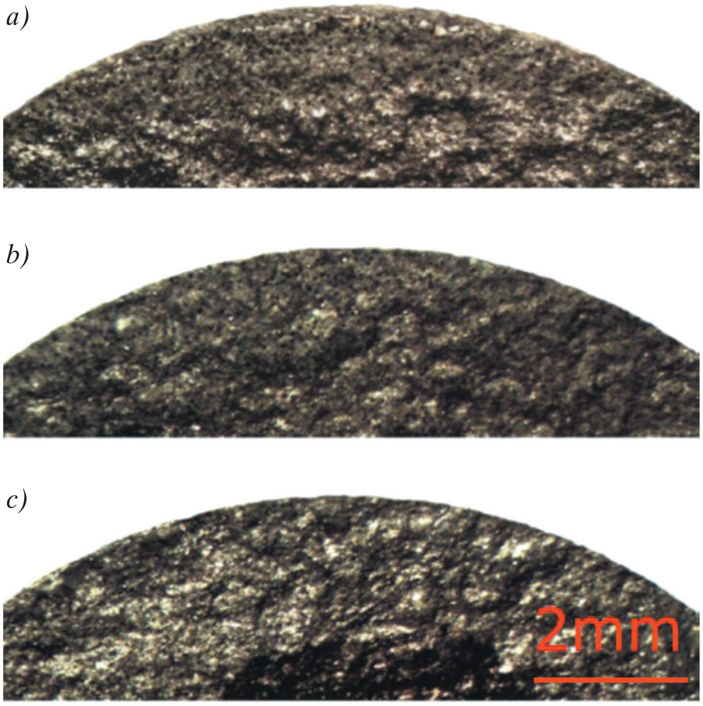

Fig. 5. Comparison of the cutting edges after tests performed on: a) Vosges sandstone; b) Mocca limestone; c) Soignies limestone

Table 4

Comparison of DEC cutters with PCD and Tungsten Carbide (WC) ones

Cutter's material type	E [MPa]	ζ
PCD typ 1	26.5	0.55
PCD typ 2	20.5	0.57
DEC	37.5	0.90
WC	76	1.00

The higher value of the apparent friction coefficient for DEC materials than PDC cutters is mainly due to the surface condition of DEC cutters. Indeed, the cutting surface is very rough, which tends to increase this coefficient.

It is also important to note that the Tungsten Carbide cutter did not have the same geometry and had a chamfer, in the case of DEC and PCD cutters, the clearance angle was zero degrees, while in the case of a tungsten carbide tool, this angle was non-zero. Therefore, the above comparative data can be only indicative, and more detailed investigations would be necessary to verify the real difference in performance characteristics of DEC and WC based cutters for wider range of rocks.

4. CONCLUSIONS

DEC has tremendous prospects in finding a niche for itself between the PCD and cemented carbides via synergy of the best consumer properties of both known products. The advanced specific features of PPC machines that has been designed and produced by GeniCore, such as extremely high heating speed (up to 1000 K per min) and unique form of the high energy pulses open up the possibility for the sintering of DEC materials based on polycrystalline diamond and with improved wear performance characteristics. The results of preliminary comparative tests of wear resistance of DEC materials which were sintered by GeniCore confirmed the bright market prospects of these materials. Further investigations are needed to meet the different challenges of such important markets as wood machining or the drilling of hard ceramic tiles, concrete, machining of CFRP composites and mining applications.

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