Near net shape sintering diamond enhanced tungsten carbide DEC inserts for mining, road planning and drilling applications using pulse plasma technology

Spiekane płytki DEC z węglika wolframu o kształcie zbliżonym do finalnego z wykorzystaniem technologii PPC przeznaczonej do zastosowania w górnictwie, frezowaniu dróg i wierceniu

MAWEJA KASONDE
DAMIAN MĄTEWSKI
DANIEL WAŁOWSKI
MARCIN ROSIŃSKI *

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Pulse plasma sintering PPC of functionally graded tools containing cutting volumes made of diamond enhanced carbide DEC attached on tungsten carbide substrates intended for mining and road planning picks, and construction drills was successfully conducted and density near full theoretical achieved. Near net shape tool geometries were made including truncated tips for the picks and pre-fluted points for the drills.
KEYWORDS: diamond enhanced carbide, DEC, pulse plasma compaction, PPC, NNS, mining, drill

Przeprowadzono z powodzeniem spiekanie plazmą impulsową PPC (*pulse plasma compaction*) funkcjonalnie gradientowych narzędzi zawierających części tnące z węglika wzmocnionego diamentem DEC (*diamond enhanced cemented carbide*), na podłożu z węglika wolframu, przeznaczonych na ostrza górnicze, do planowania i frezowania dróg oraz jako wiertła budowlane, uzyskując gęstość bliską gęstości teoretycznej. Wykonano geometrie narzędzi o kształcie zbliżonym do finalnej, w tym stożkowe końcówki noży górniczych i wstępnie uformowane ostrza wierteł.
SŁOWA KLUCZOWE: węglik spiekany wzbogacony diamentem DEC, spiekanie PPC, NNS, górnictwo, wiertnictwo

Introduction

Polycrystalline diamond PCD sintered with transition metal catalysts such as cobalt and nickel are reckoned for its highest strength and hardness amongst engineering materials making it the first-choice materials for inserts used in abrasion applications. The sintering conducted by infiltration of liquid metal catalyst, however, requires the application of high pressure to prevent the conversion of diamond particles into graphite as shown in the equilibrium phase diagram in Fig. 1. Current sintering practice is conducted withing the catalytic HPHT synthesis region of pressure and temperature. The thermal degradation of PCD insert, and their cracking are ascribed to the graphitisation of diamond and to the thermal expansion

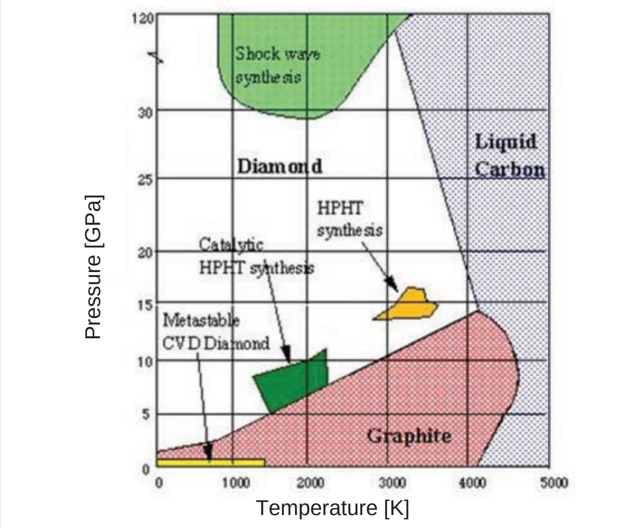

Fig. 1. Graphite–diamond equilibrium phase diagram

mismatch between the cobalt binder (12×10^{-6} K^{-1}) and the diamond particles (0.7×10^{-6} K^{-1}), which results in the occurrence of residual tensile stresses in diamond particles. Typical five hundred micrometres layers are leached to improve the performance of PCD cutters. However, leaching the PCD layer sintered under pressure above 6 GPa is time consuming, and takes weeks to achieve the required leached depth.

The alternative material for cutting inserts used in mining, road planning and construction applications is sintered tungsten carbide with cobalt binder. These cutters are much tougher, with better resistance to impact loading than PCD cutters. They also come cheaper, being sintered at lower pressure and are easy to shape by grinding and lapping processes than the PCD parts. However, these advantages are limited by the relatively lower abrasion resistance than sintered PCD. Typical properties of sintered PCD and tungsten carbide are shown in Table I. These properties vary significantly with the particle size of diamond particles or tungsten carbide particles.

* Dr inż. Maweja Kasonde, genicore@genicore.pl, https://orcid.org/0000-0003-0989-2132 – Genicore PL, Warsaw, Poland
Mgr inż. Damian Mątewski, genicore@genicore.pl – Genicore PL, Warsaw, Poland
Mgr inż. Daniel Wałowski, genicore@genicore.pl – Genicore PL, Warsaw, Poland
Dr inż. Marcin Rosiński, genicore@genicore.pl – Genicore PL, Warsaw, Poland

The novel formulation of diamond enhanced tungsten carbide DEC sintered with similar transition metals such as cobalt, nickel or manganese is therefore introduced to balance the properties such resilience or toughness with the abrasion resistance in a composite product. Such composite can be sintered at pressure similar to tungsten carbide processes. It will also be versatile as its properties can be tailored to fit specific requirements by changing the proportions and particle sizes of the three phases present; i.e. tungsten carbide, diamond and metal binders.

TABLE I. Typical properties of sintered tungsten carbide and polycrystalline diamond [1, 2]

	K_{IC} [MPa m$^{1/2}$]	Hardness [GPa]	Stiffness [GPa]	Friction
WC (6%Co)	12	7÷23	630	0.25
PCD (8%Co)	5.7÷13.1	167	850÷1000	< 0.1

Materials processing and sintering

Diamond enhanced tungsten carbide mixtures are made by pulse plasma compaction sintering of mixtures of compositions shown in Table II.

TABLE II. Compositions of powder mixtures for DEC sintering

	Particle size [μm]	wt [%]	Vol. [%]
Tungsten carbide	1÷10	83.5	63
Diamond grit	10÷60	8.3	27
Cobalt powder	0.8÷2.0	9.2	10

Manganese and nickel are used to replace fraction or whole cobalt contents in the mixtures. The homogenisation of large quantities of powders is carried out in wet conditions. Dry mixing is preferred for smaller quantities, i.e. less than 50 g. In case of wet mixing, slurries are dried at about 80°C under vacuum to evaporate the alcohol used as carrying fluid.

The applied pressure during sintering ranges from 60 to 90 MPa, and varies with the geometry of the graphite dies to prevent cracking in the sharp corners of the tooling. This pressure range is a hundred times lower than typical ranges for liquid phase sintering of polycrystalline diamond PCD cutters in HPHT presses. In pulse plasma compaction sintering method, full density is achieved in DEC parts sintered at about 1240°C, well below the melting temperature of cobalt. It is believed that solid state sintering of the DEC powder mixtures prevents full catalyst activity of cobalt for graphitisation of diamond particles due to the low solubility of carbon in solid cobalt particles and the luck of wetability of diamond particles. Thus, limiting the conversion of diamond to graphite by fast heating under low pressure below the Birman–Simon line.

Products

■ **Case 1. Near net shaped DEC picks.** Mining and road planning applications require tools that offer both abrasion and impact resistance. PCD inserts would have high abrasion resistance with low impact

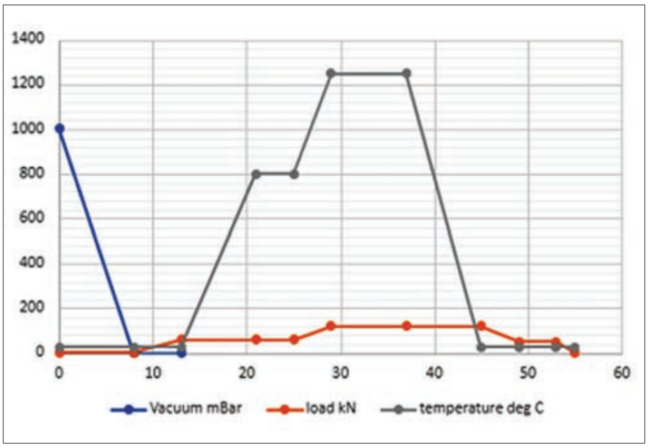

Fig. 2. Pulse plasma compaction sintering profile of near net size picks

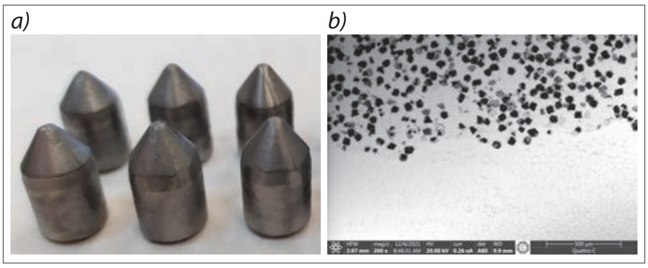

Fig. 3. NNS mining picks sintered using pulse plasma compaction technology: *a)* near net shape picks; *b)* SEM micrograph of DEC tip and tungsten carbide substrate

resistance, whereas tungsten carbide tools would resist impact loading. Thus, the functionally graded picks with diamond enhanced carbide tips on tungsten carbide substrates are introduced for these applications. The NNS picks were sintered using pulse plasma compaction sintering method PPC. Fig. 2 represents typical sintering profile of the picks.

Fig. 3 illustrates the NNS products thus manufactured and typical microstructures of the tip volume of the picks made of DEC bonded on tungsten carbide substrates. The PPC method of sintering produced crack-free picks with no-delamination between the DEC and the tungsten carbide layers. Delamination often decreases the production yield of liquid phase sintering with infiltration of the metal catalyst in this type of products. In that case, solidification shrinkage of large volume of liquid under the DEC – tungsten carbide substrate interface would generate elevated tensile residual stresses that lead to its delamination.

The hardness of the tungsten carbide layers thus sintered varied between 15.5 and 16.5 GPa and the K_{IC} calculated using the Anstis and JISR 607 formula varied between 22 and 34 MPa m$^{1/2}$, almost twice that of PCD. These values are on the upper end of tungsten carbide of submicron particle sizes sintered with low cobalt contents.

■ **Case 2. Pre-shaped DEC tips of twist drill blanks for CFRP machining.** Dry machining of CFRP and some construction tiles generates temperatures elevated enough to degrade the hardness of conventional tungsten carbide tools. In particular brazed PCD and diamond coated inserts have, in some cases,

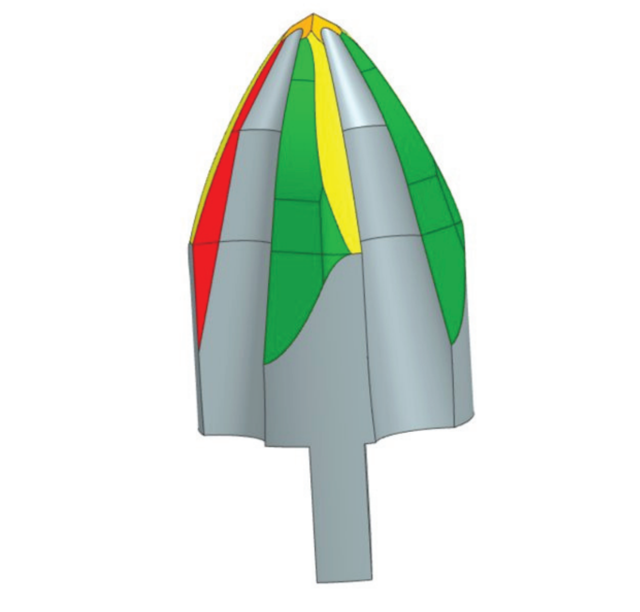

Fig. 4. 3D-model of DEC drill tip sintered using PPC technology

increased the productivity in drilling and milling of CFRP plates. However, the sensitivity to cracking during brazing of PCD inserts, the thermal degradation and the weakening of the brazed interface between inserts on tool shanks have limited the successful introduction of such tools in these applications despite an intense air cooling applied. The small achievable heights of PCD inserts, about 20 mm, are restricted due to the limitation of the capsules used in HPHT sintering vehicles. Pulse plasma compaction sintering technology enables sintering functionally graded drill and mill tips made of DEC layer on longer tungsten carbide substrates, thus making drills and mills where the brazed interface between the cutting edges and the shanks are away from the tip. Fig. 4 illustrate the model used in manufacturing graphite capsule for sintering up to 40 mm height blanks in PPC machine.

Abrasion wear of diamond enhanced carbide tools in rock cutting

Laboratory testing of cutting in Vosges sandstone samples were conducted. The results are discussed by I. Tsybulia et al. [3]. Their results of Table III infer that DEC cutters presented intermediate contact pressure, thus load on cutter and coefficient of friction on hard rock between PCD and tungsten carbide. Table III summarises the results. The results also reported better resistance to thermal degradation such as chipping and spalling comparatively to PCD.

TABLE III. Wear on hard rock cutting testing

	Contact pressure on the cutter	Coefficient of friction on hard rocks	Wear mechanism
PCD	21÷26	0.55 ÷0.57	Thermal degradation, chipping, spalling
DEC	25÷47	0.87÷0.97	Non-uniform wear, thermal degradation
WC(Co)	76	1	Smooth wear, thermal softening

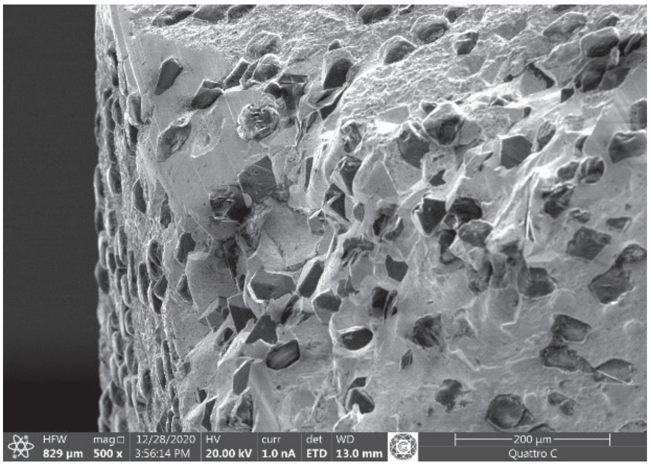

Fig. 5. SEM image showing worn surface of DEC cutting edge

Typical wear pattern of DEC in rock abrasion and impact dominated applications is illustrated in Fig. 5. The non-uniform contributes to the increased coefficient of friction comparatively to PCD.

Conclusion

- The pulse plasma compaction technology has enabled the sintering of near net shape prototype cutters for mining, road planning and drilling applications.
- The large volume sintering chambers accommodate longer capsules than the HPHT vehicles used in PCD sintering, thus enabling sintering large functionally graded tools with DEC pre-shaped tips on tungsten carbide shanks.
- Pulse plasma compaction solid state sintering prevents the volume shrinkage near the interfaces between DEC and tungsten carbide layers, thus avoiding the residual tensile stress state that would lead to delamination between the layers.
- The sintered DEC layers typically have intermediate performance in hard rock cutting between polycrystalline diamond and tungsten carbide cemented inserts.
- The hardness and the fracture toughness values of the tungsten carbide substrate shanks of the functionally graded picks sintered by pulse plasma compaction technology are on the upper end of incumbent fine grain materials sintered by infiltration of liquid cobalt.

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