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THE EFFECT OF THE PROPERTIES OF THE METAL MATRIX ON THE RETENTION OF A DIAMOND PARTICLE

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This paper deals with the modelling of the mechanical properties of materials used as the matrix in diamond tools. Saw blade segments were fabricated by combining various metal powders with diamond crystals and then hot pressing them. After consolidation, the specimens were tested to analyse their density, hardness and tensile strength. The stress/strain fields around a diamond particle embedded in the metal matrix were determined by computer simulation. The effective use of diamond tools is strongly dependent on the mechanical properties of the matrix, which has to hold the diamond grits firmly. The retention capacity results from the interactions between the diamond crystals and the matrix during the segment fabrication process. The stress and strain fields generated in the matrix were calculated using the Abaqus software.

Keywords: diamond impregnated tools, Co, Fe and W powders, diamond retention, mechanical properties, computer modelling

INTRODUCTION

In the diamond tools industry, diamond segments of circular saws for cutting natural stone and other building materials are commonly made using the powder metallurgy process. Figure 1 shows a sintered metal-bonded diamond blade with segments brazed to a steel core.

The process of producing diamond segments consists in mixing a metallic matrix powder with synthetic or natural diamond crystals, cold shaping/pressing the segments and finally sintering or hot pressing them to full density.

The diamond segments (metal matrix composite containing diamond particle) are then brazed to the circular steel core (Figure 1) and as such they constitute the teeth of the saw blade used for cutting stone and ceramic materials [1-4].

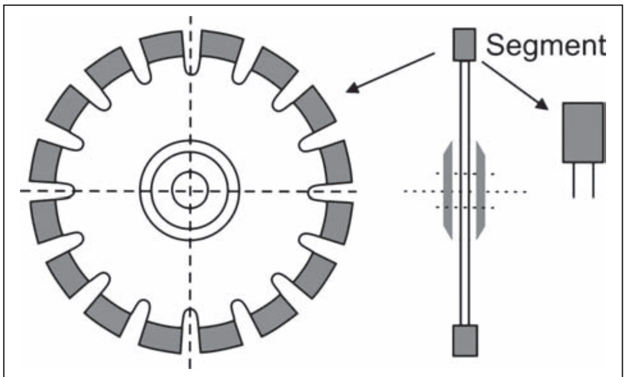

Figure 1 Schematic representation of a segmental circular saw blade

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Because of its excellent retention properties, cobalt is often used as a matrix in diamond impregnated tools designed for cutting natural stone and other building materials. Its price, however, is very high and unstable.

Statistical data concerning the price and production of cobalt have been collected since 1900 [5]. There are two main periods in the production of cobalt: 1900-1944 and 1945-now. At the beginning, the production of cobalt and, consequently, its consumption was not high. After the Second World War, this changed significantly. Since then, there has been a steady rise in its production (see Figure 2).

Until 1978 the price of cobalt remained relatively stable. On average it was at around 4 US$ per kg (Figure 3). Then, the price increased rapidly and there were considerable fluctuations due to the political instability in the countries where cobalt was mined.

Since synthetic diamond was introduced on an industrial scale, the use of metallic-diamond tools has risen significantly. With the price of synthetic diamond

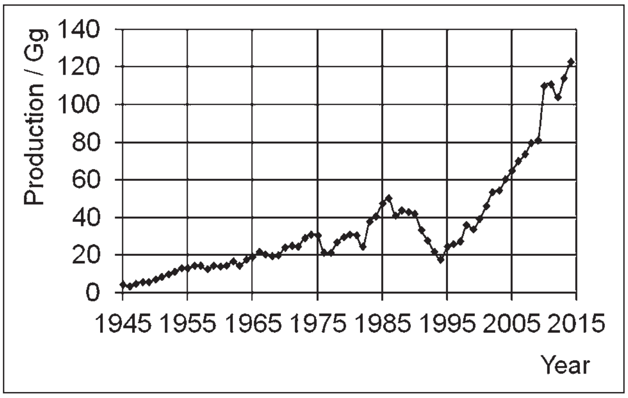

Figure 2 World mine production of cobalt from 1945 to 2015

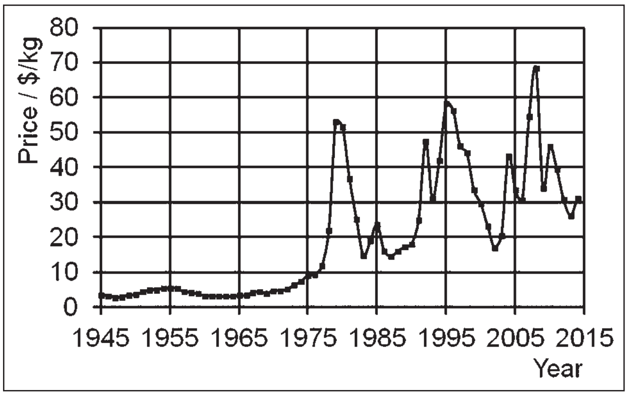

Figure 3 Price of cobalt between 1945 and 2015

becoming much lower than that of its natural counterpart, there has been a strong demand for cheaper but similar matrix materials to replace expensive cobalt.

An important property of the matrix material is diamond retention, i.e. the capacity to hold the cutting diamond crystals (Figure 4). Diamond particles are retained in the matrix by mechanical or chemical forces, or by a combination of the two [5].

Mechanical bonding occurs after the hot pressing operation during the cooling of a segment. Because diamonds have a very small coefficient of thermal expansion in relation to metals, diamond particles are compressed by the shrinking matrix [2]. The efficiency of the mechanical bonding depends on the elastic and plastic properties of the matrix material. The main objective of this paper is to analyse diamond retention in relation to the mechanical properties of the matrix. The most significant parameters used to assess the efficiency of retention is the elastic energy of a diamond particle and the strain of the deformed matrix around the particle [6,7].

EXPERIMENT AND RESULTS

The specimens to be analysed were produced from elemental cobalt, iron and tungsten powders. The basic properties and shapes of the experimental powders are presented in Table 1.

The elemental powders were used to prepare three alloys (Table 2). The powders were mixed for 1 hour using a Turbula T2C mixer. The elemental cobalt powder and the powder mixtures were hot pressed in a graphite die for 2 minutes at 850 - 980 °C under 35 - 40 MPa. The temperature and pressure were adjusted for each powder so that a maximum as-sintered porosity of 5% could be reached. The hot pressing process was performed in an AGRA CAR1001 pressing furnace under nitrogen atmosphere.

The sintered specimens were tested to determine their density, hardness and static tensile strength. The density was measured using the hydrostatic balance technique whereas the hardness was established at a load of 10 kG using the Vickers method.

The measurement results are provided in Table 3. The tensile tests were conducted at a traverse speed of

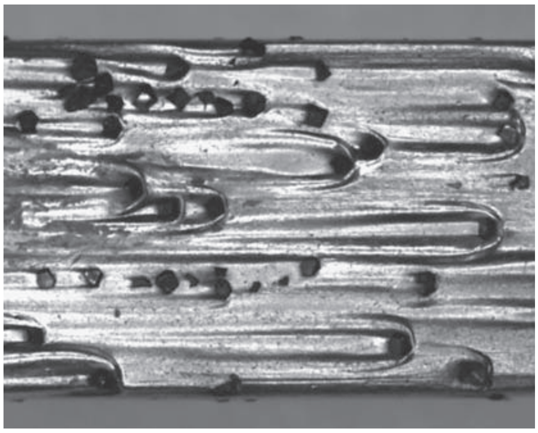

Figure 4 Diamond crystals retained on the cutting surface of a segment

Table 1 **Properties of the experimental powders**

Powder (commercial designation)	Particle size (1), / μm	Apparent density, / g/cm^3	Tap density, / g/cm^3
Co (*Co Extrafine*)	1,5	1,1	2,2
Fe (*Fe CN*)	6,9	3,6	-
W (*WP30*)	2,6	3,2	6,0

(1) – measured with a Fisher sub-sieve sizer

Table 2 **Material contents and the hot pressing parameters**

Material	Content	Hot pressing parameters
Co	100 % Co Extrafine	850 °C/35 MPa/2min
Co-Fe	50 % Fe CN 50 % Co Extrafine	900 °C/35 MPa/2min
Co-Fe-W	40 % Fe CN 40 % Co Extrafine 20 % WP30	980 °C/40 MPa/2min

Table 3 **Densities and Vickers hardness**

Material	Density (1) / g/cm^3	Hardness (1) / HV10
Co	8,73±0,01	271±4
Co-Fe	8,11±0,05	254±2
Co-Fe-W	8,84±0,09	351±7

(1) 95 % confidence intervals

0,5 mm/min using an INSTRON 4502 universal testing machine equipped with a digital data acquisition system. The sample elongation was registered with a 10 mm extensometer. The test results (average values from three measurements) are shown in Table 4.

MODELLING OF THE DIAMOND/MATRIX SYSTEM BEHAVIOUR DURING HOT PRESSING

The values of the coefficient of thermal expansion for the sintered materials and diamond, which were used in the finite element modelling, are given in Tables 5 and 6. The mechanical parameters, which were used in the modelling, are given in Table 4.

The modelling was carried out using the finite element method and the ABAQUS Ver. 6.14 software [11]. 3D computer models were created for a diamond crystal

Table 4 **Results of the static tensile test**

Material	Modulus of elasticity / GPa	Strength R_m, / MPa	Yield stress R_e / MPa	A_5 / %
Co	207	954	634[(1)]	9,5
Co-Fe	233	527	494[(2)]	1,3
Co-Fe-W	233	762	721[(1)]	0,7

[(1)] offset yield stress, [(2)] physical yield stress

Table 5 **Coefficient of thermal expansion for the sintered materials (dylatometric measure)**

Material	Temperature range (cooling) / °C	Coefficient α / K^{-1}
Co	850 - 100	$15,54\cdot 10^{-6,}$
Co-Fe	900 - 100	$11,63\cdot 10^{-6,}$
Co-Fe-W	900 - 100	$11,11\cdot 10^{-6,}$

Table 6 **Coefficient of thermal expansion for diamond as a function of temperature [8-10]**

Temp. / K	300	600	900	1 200
α / K^{-1}	$1,0\cdot 10^{-6}$	$3,1\cdot 10^{-6}$	$4,1\cdot 10^{-6}$	$4,8\cdot 10^{-6}$

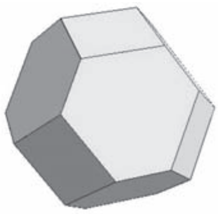

Figure 5 Model of a diamond crystal (truncated octahedron)

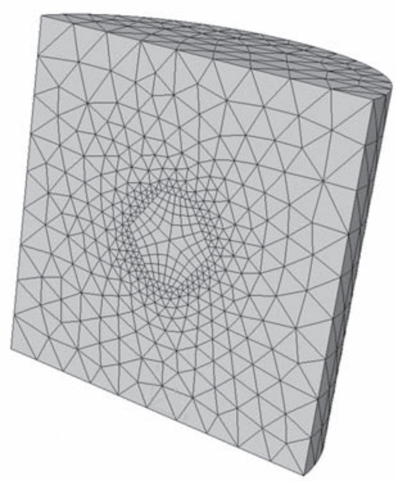

Figure 6 Model of a diamond crystal inside the matrix

(Figure 5), a diamond crystal embedded in the matrix (Figure 6) and a diamond crystal protruding above the matrix surface (Figure 7). The height of diamond protrusion (HDP) varied between 25 µm and 75 µm. The crystal size, i.e. the distance between the opposite square {100} facets, was 350 µm.

The cooling of the diamond crystal-metal matrix system was simulated for all the matrix materials tested (Table 2). The total strain energy of the diamond crystal shows a clear dependence on the height of diamond protrusion (Figure 8).

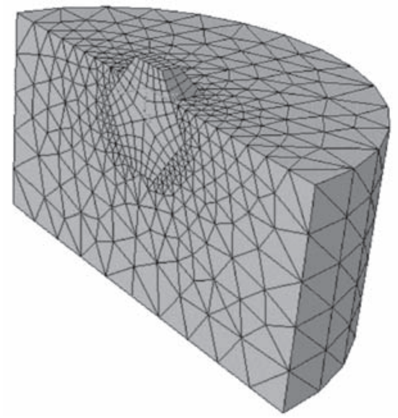

Figure 7 Model of a diamond crystal protruding above the matrix surface

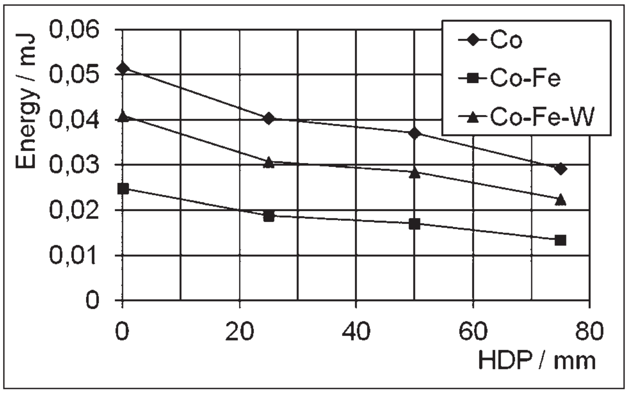

Figure 8 Total strain energy of diamond as a function of the height of diamond protrusion

The pressure inside the diamond is mainly dependent on the mechanical parameters and the coefficient of thermal expansion of the matrix (Table 7). The elastic energy of the diamond is proportional to the second power of the pressure.

The elastic energy of the diamond and the radius of the plastic zone around the diamond change substantially (Table 7).

Table 7 **Pressure inside the diamond and the radius of the plastic zone around the diamond**

Material	Pressure in diamond / MPa	Elastic energy of diamond / mJ	Radius of plastic zone / µm
Co	1 365	0.041	326
Co-Fe	884	0.019	370
Co-Fe-W	1 186	0.034	294

MODELLING OF THE MATRIX BEHAVIOUR AFTER APPLYING AN EXTERNAL LOAD TO THE DIAMOND

The simulation was repeated for a diamond crystal subjected to a load applied tangential to the surface of the matrix.

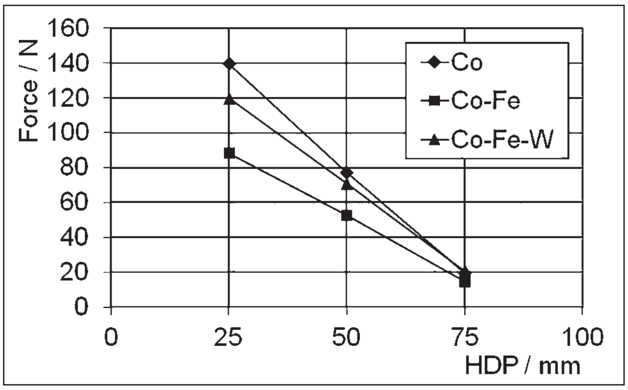

Figure 9 Tangential force pulling a diamond crystal out of the matrices

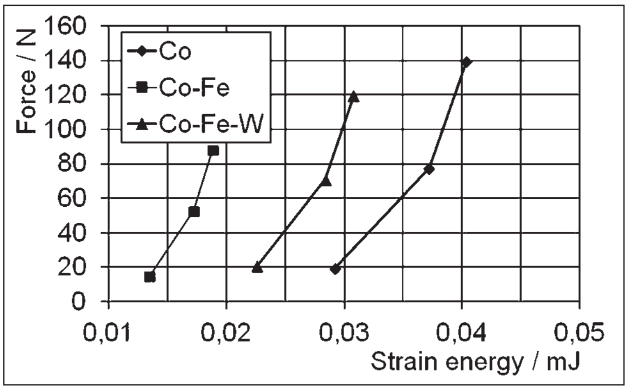

Figure 10 Pulling force (tangent to the surface) vs. elastic strain energy of the diamond in the matrices

The retention of the diamond particle in the matrix was assessed by performing a simulation of a pullout of the particle by an external force. The force needed to remove the particle shows a strong relationship with the particle protrusion (Figure 9).

The magnitude of the force required to remove a particle out of the matrix shows correlation with the total strain energy of the diamond particle (Figure 10).

CONCLUSIONS

This work has shown that:

- numerical modelling is useful in providing comprehensive insights into the stresses and strains generated in the diamond-metal composites during their fabrication and use,
- total strain energy of diamond decreases as the HDP increases,
- tangential force pulling a diamond crystal out of the matrices decreases with an increase in HDP (Figure 9) and an increase in the strain energy of the diamond particle (Figure 10).

The results of the computer simulations imply that the pressure and the strain energy of the diamond particle caused by thermal contraction during cooling which follows hot pressing can be used as a measure of retention of a diamond particle in a metal matrix.

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Note: Translated by Małgorzata Laczek, Kielce, Poland