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NUMERICAL MODELLING OF STRESS/STRAIN FIELD ARISING IN DIAMOND-IMPREGNATED COBALT

NUMERYCZNE MODELOWANIE PÓL NAPRĘŻEŃ I ODKSZTAŁCEŃ W KOMPOZYTOWYCH MATERIAŁACH DIAMENT-KOBALT

The paper presents results of computer simulations of the stress/strain field built up in a cobalt matrix diamond impregnated saw blade segment during its fabrication and after loading the protruding diamond with an external force. The main objective of this work was to create better understanding of the factors affecting retention of diamond particles in a metallic matrix of saw blade segments, which are produced by means of the powder metallurgy technology.

The effective use of diamond impregnated tools strongly depends on mechanical and tribological properties of the matrix, which has to hold the diamond grits firmly. The diamond retention capability of the matrix is affected in a complex manner by chemical or mechanical interactions between the diamond crystal and the matrix during the segment manufacture. Due to the difference between the thermal expansion coefficients of the diamond and metallic matrix, a complex stress/strain field is generated in the matrix surrounding each diamond crystal.

It is assumed that the matrix potential for diamond retention can be associated with the amount of the elastic and plastic deformation energy and the size of the deformation zone occurring in the matrix around diamonds. The stress and strain fields generated in the matrix were calculated using the Abaqus software. It was found that the stress and strain fields generated during segment fabrication change to a large extent as the diamond crystal emerges from the cobalt matrix to reach its working height of protrusion.

Keywords: diamond impregnated tools, matrix, stress/strain field, diamond retention, numerical modelling

W pracy przedstawiono wyniki symulacji komputerowych pól naprężeń i odkształceń wytworzonych w kobaltowej osnowie segmentu piły tarczowej. Pola naprężeń i odkształceń powstają w procesie produkcji i po obciążeniu wystającego diamentu przez zewnętrzną siłę. Głównym celem prezentowanej pracy było lepsze zrozumienie czynników dotyczących retencji cząstki diamentu w osnowie metalicznej segmentów piły, które są wytwarzane za pomocą technologii metalurgii proszków.

Efektywne stosowanie narzędzi metaliczno-diamentowych w dużym stopniu zależy od mechanicznych i tribologicznych właściwości osnowy, która musi mocno utrzymywać cząstki diamentowe. Zdolność osnowy retencji diamentu jest uzależniona w skomplikowany sposób od chemicznych i mechanicznych oddziaływań pomiędzy kryształem diamentu i osnową podczas wytwarzania segmentu. Wskutek różnicy współczynników rozszerzalności cieplnej diamentu i metalicznej osnowy, złożone pole naprężeń i odkształceń powstaje w materiale osnowy otaczającej każdą cząstkę diamentu.

Założono, że potencjalna zdolność osnowy do retencji diamentu może być skojarzona z sumą sprężystej i plastycznej energii deformacji i z wielkością strefy odkształcenia występującej w osnowie otaczającej diament. Pola naprężeń i odkształceń w osnowie były obliczane przy użyciu systemu Abaqus. Stwierdzono, że pola naprężeń i odkształceń wytwarzane w czasie produkcji segmentu zmieniają się w szerokim zakresie, gdy cząstka diamentu wynurza się z kobaltowej osnowy osiągając roboczą wysokość protruzji.

1. Introduction

Diamond tools designed to cut construction materials and natural stone include circular steel blades containing diamond-impregnated segments brazed to their peripheries at regular intervals (Fig 1) The segments are usually produced by the hot pressing process.

The production process involves mixing the metallic matrix powder with synthetic diamond grit, pressing the mixture in a rigid die to produce green segments having the desired shape and internal structure, and then hot pressing the green segments in a graphite mould by passing an electric current directly through the mould held under uniaxial load [1-6].

An important property of the matrix material is to retain the diamond particles as long as possible while sawing materials difficult to process (Fig 2), such as granite and dense ceramics. The retention occurs as a result of either mechanical or a combination of mechanical and chemical bonding [7].

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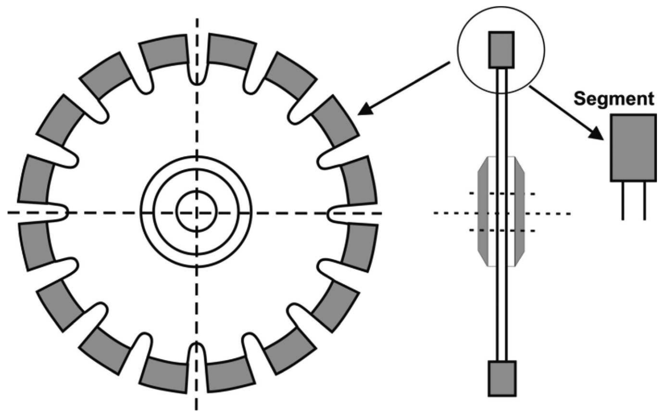

Fig. 1. Schematic representation of a segmental circular saw blade

Mechanical bonding is achieved during cooling, which follows the hot pressing stage. Compared with metals, diamond has a very low coefficient of thermal expansion, which tightens the diamond grits up by the shrinking matrix [1]. Mechanical bonding depends on both elastic and plastic properties of the matrix. Retention of diamond crystals with respect to the mechanical properties of the matrix was analyzed in refs [8-10]. The most essential parameters affecting retention are the elastic and plastic strain energies of the matrix in the proximity of a diamond grit (Fig 3) [11,12].

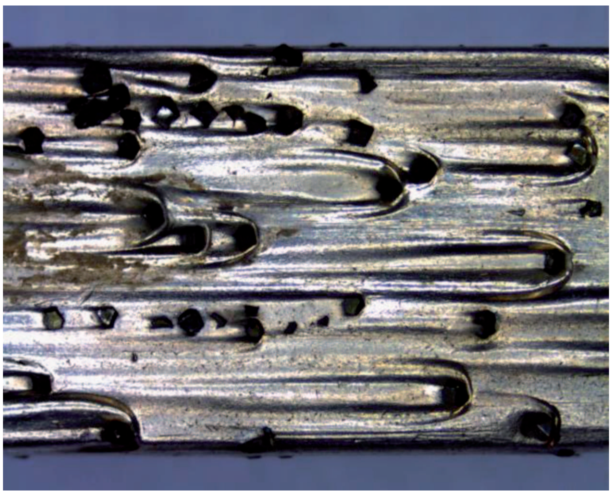

Fig. 2. Diamond grits retained on a working surface of a segment

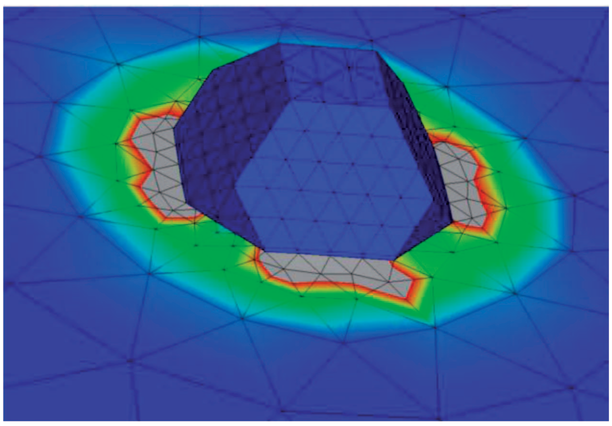

Fig. 3. Numerical model of a diamond particle with the strain zone

2. Experimental procedure and results

A series of cobalt specimens were produced by the hot press route from various cobalt powders, delivered by Umicore (Olen, Belgium), using a fully automatic hot press equipped with an inert gas (nitrogen) chamber. The powders were held for 2 minutes at the hot pressing temperature which was individually chosen using the full densification criterion.

The powder grades and hot pressing conditions are given in Table 1.

TABLE 1
Powder grades and consolidation conditions

Material	Powder composition	Hot pressing parameters
Co-SMS	100% Co SMS	850°C/35MPa/2min
Co-EF	100% Co Extrafine	850°C/35MPa/2min
Co-400	100% Co 400 mesh	950°C/35MPa/2min

2.1. Mechanical tests

The mechanical properties of the matrix materials were determined in a tensile test with the intention to use them as the input data for numerical modelling.

The experimental data is summarised in Table 2.

TABLE 2
Results of static tensile test

Material	R_m [MPa]	$R_{0.2}$ [MPa]	$\Delta L/L$ [%]
Co-SMS	865	405	19.5
Co-EF	954	634	9.5
Co-400	743	540	1.7

2.2. Computer modelling

The coefficients of thermal expansion for cobalt and diamond, which were used in the finite element modelling, are given in Table 3 [13].

TABLE 3
Coefficients of thermal expansion of cobalt and diamond as a function of temperature

Temperature [K]	Cobalt [K^{-1}]	Diamond [K^{-1}]
300	$134{\cdot}10^{-6}$	$1{\cdot}10^{-6}$
600	$165{\cdot}10^{-6}$	$3{\cdot}10^{-6}$
1200	$180{\cdot}10^{-6}$	$6{\cdot}10^{-6}$

The data were obtained with the finite element method using ABAQUS Version 612 software [14]. 3D computer model of a cubo-octahedral diamond crystal (Fig. 4) embedded in a cobalt matrix was analysed. The calculations were performed for a deeply embedded particle as well as for ones protruding above the surface of the metal matrix (Fig. 5). The height of diamond protrusion (HDP) was varied between 25 and 150 μm. The crystal size, i.e. the distance between the opposite square {100} facets, was assumed to be 350 μm.

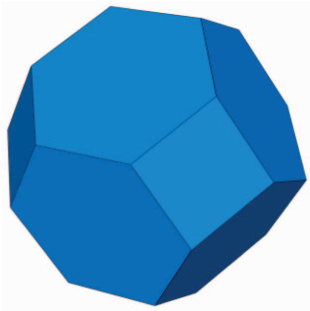

Fig. 4. Model of a cubo-octahedral diamond crystal

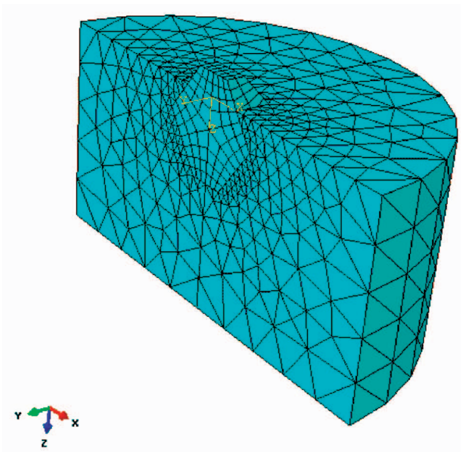

Fig. 5. Model of a diamond crystal protruding above the matrix surface

The cooling of the diamond crystal-metal matrix system (Table 1) was simulated for all tested matrix materials. The total strain energy of the matrix around a diamond crystal shows a clear dependence on the height of diamond protrusion (Fig. 6), whereas the percentage of the plastic strain energy in the total strain energy shows very weak dependence on the starting cobalt powder (Fig. 7).

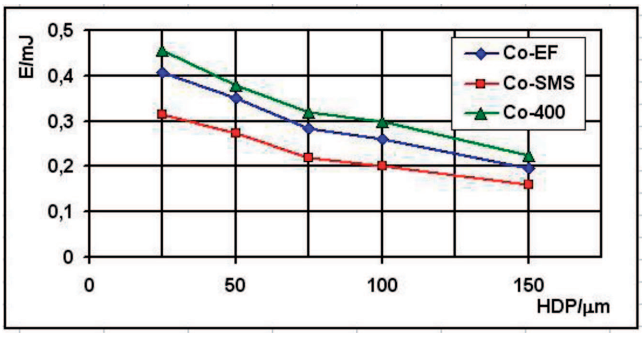

Fig. 6. Total strain energy as a function of height of diamond protrusion

The simulation was repeated for a diamond crystal subjected to a load applied normal to the surface of the matrix. A maximum force applied to the diamond was 200 N. The tangential component was neglected because it was about 10 times smaller than the normal component [8].

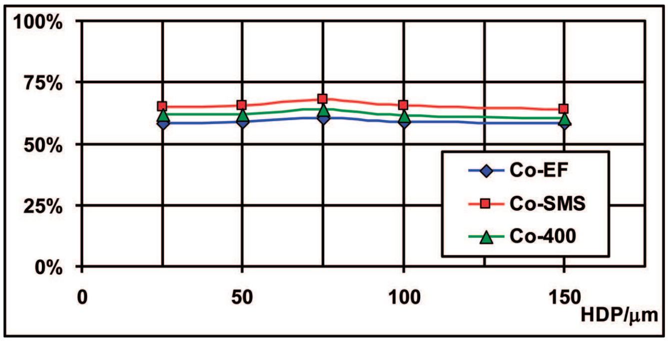

Fig. 7. Contribution of plastic strain energy to the total strain energy generated by a diamond crystal partially embedded in cobalt

The stress field around both unloaded and loaded particle is compared in Figs 8 and 9.

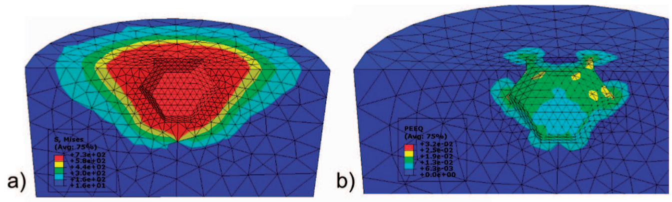

Fig. 8. Stress (a) and plastic strain (b) field around an unloaded diamond crystal in Co-EF (HDP=75 μm)

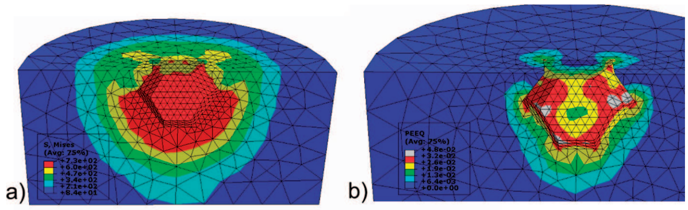

Fig. 9. Stress (a) and plastic strain (b) field around a loaded diamond crystal in Co-EF (200 N; HDP=75 μm)

An increase in the energy of the matrix deformation resulting from the external load is significant It ranges between 15 and 75% of the strain energy induced by thermal shrinkage of the hot pressed specimen (Table 4).

TABLE 4

Increase in the strain energy of the matrix and the diamond particle under loading

Material	Percentage increase in		
	total strain energy of matrix	plastic strain energy of matrix	elastic strain energy of diamond
Co-SMS	75.8	67.0	452.7
Co-EF	24.1	21.3	188.3
Co-400	15.2	14.6	95.6

Figure 10 shows the total energy accumulated in the matrix surrounding a loaded diamond crystal as a function of its height of protrusion, whereas Table 4 gives an average increase in the energy of the matrix for the protrusion of 75 μm, after application of a normal load of 200 N. As can be seen, the Co-SMS matrix shows the highest susceptibility to external loads. It is also evident that the elastic energy accumulated in the diamond crystal increases to a larger extent than the energy accumulated in the surrounding matrix (Table 4).

The dependence of energies accumulated in the Co-EF matrix and in diamond on the magnitude of external load is shown in Fig. 11.

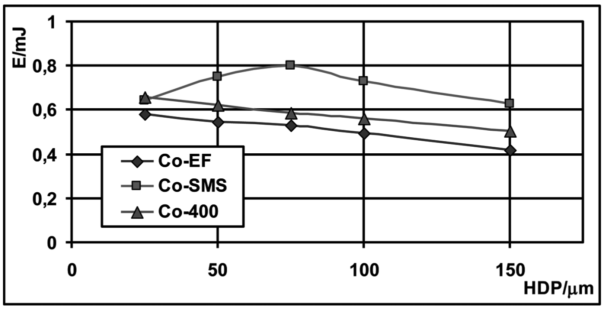

Fig. 10. Total energy accumulated in the matrix around a diamond loaded with a normal force of 200 N as a function of its height of protrusion

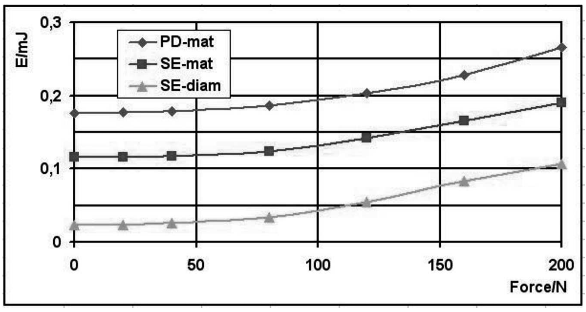

Fig. 11. Plastic strain (PD-mat) and elastic strain (SE-mat) energies of Co-EF, and elastic strain energy (SE-diam) of diamond (HDP=75 μm) as a function of normal load

In the previous works [11,12] it was suggested that the plastic strain energy of the matrix could be used as an indicator of its capacity for diamond retention. The results of the computer simulations seem to confirm the thesis that the strain energy of the matrix caused by thermal shrinkage during cooling after the hot pressing step is also a potential measure of retention of a diamond crystal in the matrix.

3. Conclusions

This work has shown that:

- Numerical modelling is instrumental in providing comprehensive insights into the stresses and strains generated in the diamond-cobalt composites during their fabrication and use.
- Total strain energy accumulated in the cobalt matrix around a protruding diamond crystal decreases as the height of diamond protrusion increases.
- Plastic-to-elastic energy ratio is ˜2 and weakly depends on the matrix properties and height of diamond protrusion.
- Application of a normal force to the protruding diamond has a major influence on stress spread and distribution within the surrounding matrix, whereas its magnitude remains nearly unaffected.
- Total energy accumulated in the matrix around a loaded diamond decreases with increasing yield strength of the matrix and height of diamond protrusion.
- Contribution of elastic strain energy to the total strain energy stored within the cobalt matrix increases with increasing the magnitude of external load on the protruding diamond.

To be attempted is search for relationship between the strain energy components and diamond retention data acquired from field sawing tests utilising saw blade segments made from the investigated cobalt powders.

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