



An Analysis of the Retention of a Diamond Particle in a Metallic Matrix after Hot Pressing

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Abstract

This paper deals with computer modelling of the retention of a synthetic diamond particle in a metallic matrix produced by powder metallurgy. The analyzed sintered powders can be used as matrices for diamond impregnated tools. First, the behaviour of sintered cobalt powder was analyzed. The model of a diamond particle embedded in a metallic matrix was created using Abaqus software. The preliminary analysis was performed to determine the mechanical parameters that are independent of the shape of the crystal. The calculation results were compared with the experimental data. Next, sintered specimens obtained from two commercially available powder mixtures were studied. The aim of the investigations was to determine the influence of the mechanical and thermal parameters of the matrix materials on their retentive properties. The analysis indicated the mechanical parameters that are responsible for the retention of diamond particles in a matrix. These mechanical variables have been: the elastic energy of particle, the elastic energy of matrix and the radius of plastic zone around particle.

Keywords: Composites, Mechanical properties, Diamond, Sinter, Computer modelling

1. Introduction

The term 'matrix retention' denotes the capacity of a metallic matrix material to retain diamond particles at the surface. This property is important in the case of matrices of metal-bonded diamond segments used for cutting difficult-to-machine materials [1,2].

When diamond particles are retained in the matrix, the embedment results from large differences in the coefficient of thermal expansion between diamond and the matrix material. For diamond, the linear coefficient of thermal expansion changes with temperature; it assumes values from about $1 \cdot 10^{-6} \text{ K}^{-1}$ at 20°C to $5 \cdot 10^{-6}$

K^{-1} at 930°C [3]. With regard to metals used for matrices of metal-bonded diamond products, the linear coefficient of thermal expansion is an order of magnitude higher [2]. The embedment of diamond particles in the matrix takes place during cooling that follows hot pressing.



Fig. 1. Typical shapes of a synthetic diamond crystal

2. Synthetic diamond crystals

Depending on the synthesis conditions, diamond crystallization leads to the formation of crystals with shapes ranging from a cube to an octahedron (Fig. 1) [1,2].

The cube, the truncated octahedron and the octahedron were selected for a preliminary numerical analysis. Each polyhedron had a volume of 0.0216 mm³, which corresponds to the volume of a sphere with a radius of 0.173 mm. The aim of the preliminary analysis was to determine the mechanical parameters that are independent of the shape of the crystal (Fig. 1).

The main analysis concerned the retentive properties of a diamond particle in the shape of a truncated octahedron. The distance between the opposite square faces was assumed to be 0.350 mm. The shape and size were appropriately selected to compare the computer simulation results with the experimental data [4].

3. Cobalt as the matrix material

A cobalt matrix has very good retentive properties. It can retain diamond particles at the surface during use of a metal-bonded diamond tool. From a technological point of view, the benefits of cobalt are numerous [1]. Sintered cobalt powders show high strength properties and good ductility. They can be compacted to a density similar to the theoretical density at a temperature not exceeding 850°C. During the consolidation of powders, cobalt has a moderate effect on graphitization of diamond.

The major drawback of cobalt is its high price [5]. Since the cost of industrial diamond has dropped considerably, the high production costs of cutting tools are now due to the application of cobalt as a matrix material. For this reason, producers of diamond impregnated tools as well as producers of metallic powders for tool matrices are looking for materials that can replace cobalt. The most technologically advanced companies offer ready-to-use metallic powder mixtures to be applied in the production of diamond impregnated tools [6,7]. The main advantage of commercially available powder mixtures is their reasonable price and ease of consolidation by hot pressing.

In the preliminary numerical analysis, model values of the mechanical parameters of the cobalt matrix (Table 1) were used as the average values for the sintered cobalt powders: Submicron Size Cobalt Powder and Extra Fine Cobalt Powder [8]. The elastic constants of diamond are typical values employed in the analysis of metal-bonded diamond composites [9]: the elastic modulus was 1050 GPa and Poisson ratio was 0.1. The temperature and pressure applied during the hot-pressing process to produce sintered materials were assumed to be 850°C and 35 MPa. The average values of the coefficient of thermal expansion for diamond and the cobalt matrix were 3·10⁻⁶ K⁻¹ and 14·10⁻⁶ K⁻¹, respectively.

Table 1.

Mechanical properties of cobalt

| Modulus of elasticity [GPa] | Poisson ratio | Yield strength [MPa] | Tensile strength [MPa] | Maximum elongation [%] |
|--------------------------------|---------------|-------------------------|---------------------------|---------------------------|
| 205 | 0.3 | 520 | 900 | 15 |

4. Modelling the retention of a diamond particle in the cobalt matrix

The model of an elastic diamond particle embedded in a metallic matrix was created using Abaqus, software for finite element analysis [10]. The truncated octahedron was analyzed with an octagonal cross-section (Fig. 2). The size of the diamond particle was assumed on the basis of the distance between the opposite square faces, which was 0.350 mm. The models of diamond crystals in the shape of a cube or an octahedron were created in a similar manner.

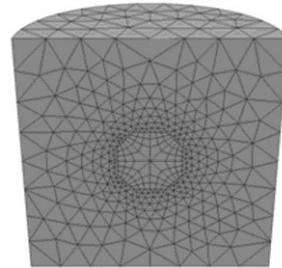


Fig. 2. Model of diamond in matrix

The simulation of the hot-pressing process was conducted by applying a maximum pressure and a maximum temperature. The temperature was then reduced to ambient temperature and the pressure was removed. The global mechanical variables studied were: the elastic energy of particle, the elastic energy of matrix and the radius of plastic zone around particle (Table 2). As can be seen from the findings, the quantities provided in Table 2 are little affected by the crystal shape. They can be considered as indicators of the mechanical state of a diamond particle in the matrix.

Table 2.

Energies of diamond and matrix, radius of plastic zone

| Shape of diamond | Elastic energy of particle [mJ] | Elastic energy of matrix [mJ] | Radius of plastic zone [μm] |
|----------------------|---------------------------------|-------------------------------|-----------------------------|
| Cube | 0.0185 | 0.1518 | 315 |
| Truncated octahedron | 0.0195 | 0.1471 | 338 |
| Octahedron | 0.0191 | 0.1590 | 328 |

Other mechanical variables determined through computer simulation such as the Huber-Mises stress in the matrix, maximum normal stress in the matrix, plastic strain in the matrix, maximum pressure in the matrix and maximum pressure in the diamond particle, show a large scatter of values depending on the

crystal shape (Fig. 1). These parameters cannot be good indicators of retention of diamond in the matrix.

5. Stress state of the diamond particle at the matrix surface

The studies described in [9,11] involved performing simulation for a diamond particle with a constant protrusion during hot pressing.

In this study, it was assumed that initially the particle was placed inside the matrix and then it was exposed during use of a tool. The problem was analyzed by performing simulations for a model containing a particle and two layers of the matrix (Fig. 3).

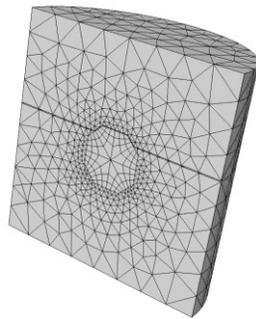


Fig. 3. The analysis model for the diamond particle state at the matrix surface, the depth of the upper layer is 570 μm

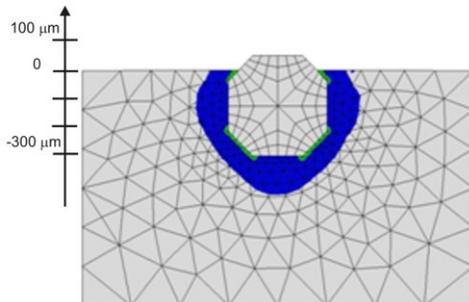


Fig. 4. Plastic zone ($\epsilon_{pl} > 0.1\%$) around a diamond particle at the segment surface

The upper layer of the matrix was removed during use of the tool and the particle was exposed to a predetermined value of protrusion. Numerically, the upper layer was pressed down during the cooling simulation, and then moved away from the particle and the lower layer. The simulations were carried out for the value of protrusion equal to 50 μm . Then, the values of energy of the particle and the layer holding the particle were determined.

The plastic zone for the diamond particle moving to the matrix surface (Fig. 4) has the same shape and radius as that reported for the particle inside a segment. The radius of the plastic zone around the particle was also calculated. The radius was similar for crystals with different shapes but the same volume. This variable can be indicator of the state of the diamond particle in the matrix.

6. Comparison of the simulation results with the experimental data

There is one experiment that can be used to determine stresses inside a diamond crystal embedded in a cobalt matrix. The technique of Raman spectroscopy was employed to measure pressure in a particle at the surface of a cobalt matrix [4].

By analogy, it was assumed that the particle at the matrix surface had a protrusion of 50 μm , and its shape and dimensions are the same as those illustrated in Figure 3. The yield point of matrix material was assumed to be 450 MPa [4]. The pressure was measured at the diamond symmetry axis and at the distance d from the top crystal facet (Fig. 3). Figure 5 compares the numerical results with the experimental data of two diamond crystals.

The numerical results are in agreement with the experimental curves; the shapes and the maximum values are similar. The results suggest that the particle is surrounded by the plastic zone.



Fig. 5. Calculation results (triangle markers) compared with the experimental data (dashed plots)

7. Properties of the sintered specimens produced from commercially available powder mixtures

The results of the numerical analysis described above were employed to assess the particle retention in two sintered materials produced from commercially available powder mixtures denoted by symbols CSA and CSA800 [7]. The information provided by the producer indicates that the mixtures contain Fe, Cu, Zn and Sn, as well as small amounts of rare earth metals. The hot-pressing process was performed under following conditions: 850°C / 35MPa / 3 min for CSA sinter and 880°C / 35MPa / 3 min for CSA800 sinter.

A dilatometer analysis was conducted to determine the average values of the coefficient of thermal expansion; they were $1.55 \cdot 10^{-5} \text{ K}^{-1}$ and $1.63 \cdot 10^{-5} \text{ K}^{-1}$ for the CSA and CSA800 sinters, respectively. Their mechanical parameters were determined through tensile testing (Table 3).

Table 3.

Mechanical parameters of the matrices studied.

| Sintered specimen | Modulus of elasticity [GPa] | Poisson ratio | Offset yield strength $R_{0.2}$ [MPa] | Tensile strength R_m [MPa] | Maximum elongation [%] |
|-------------------|-----------------------------|---------------|---------------------------------------|------------------------------|------------------------|
| CSA | 163 | 0.32 | 251 | 382 | 8.2 |
| CSA800 | 164 | 0.32 | 401 | 594 | 3.6 |

Table 4.

Results of computer simulation for diamond particle and the matrices.

| Material | Pressure in the centre of the diamond [MPa] | Elastic energy of the particle [mJ] | Elastic energy of the matrix (the lower part in Fig. 3) [mJ] | Radius of plastic zone [μm] |
|--|---|-------------------------------------|--|--|
| CSA sinter, particle inside the matrix | 640.5 | 0.0095 | 0.0788 | 373 |
| CSA sinter, particle at the surface of the matrix | | 0.0032 | 0.0515 | |
| CSA800 sinter, particle inside the matrix | 876.0 | 0.0208 | 0.1609 | 334 |
| CSA800 sinter, particle at the surface of the matrix | | 0.0074 | 0.0893 | |

8. Conclusions

The analysis conducted for the sintered specimens shows that the diamond particle inside the matrix and the matrix around it have the following mechanical characteristics:

- the pressure inside the particle and the elastic energy of the particle are not dependent on the particle shape,
- the particle is surrounded by the plastic zone with a relatively well defined radius.

The diamond particle located at the segment surface can be characterized as follows:

- the pressure inside the particle decreases; the distribution of pressure along the axis of symmetry follows a curve the shape of which is presented in Fig. 5,
- the plastic zone radius does not change.

The conclusions that can be drawn from the above data are:

- for a diamond particle embedded in the matrix, the pressure and the elastic energy density can be good indicators of retention,
- the radius of the plastic zone around the diamond particle can also be treated as an additional factor determining the state of the particle at the segment surface.

The best parameters were reported for the cobalt sinter (Tab. 2). The CSA800 sintered specimen had similar properties to the cobalt sinter (Tab. 4).

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