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Retention of a Diamond Particle in a Metallic Matrix

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Abstract. The paper deals with numerical and analytical modelling of retention of a diamond particle in a metallic matrix. The model of a diamond particle embedded in a metallic matrix was created using the Abaqus software. The analytical model of an elastic spherical particle in an elastic-plastic matrix was built. The aim of the paper was to determine the influence of the mechanical and thermal parameters of matrix materials on their retentive properties. The analysis has indicated mechanical parameters responsible for the retention of diamond particles in a metallic matrix. The pressure in the particle and the radius of plastic zone around particle were analyzed.

Introduction

Diamond segments (metal matrix composite containing diamond particles) of circular saws for cutting stone and ceramic materials are commonly made using the powder metallurgy process [1]. The process of the production of segments consists in mixing metallic matrix powder with diamond crystals and hot pressing them to nearly full density.

This paper discusses a mathematical model of a diamond particle in an elastic-plastic metallic matrix. The mechanical state of a particle embedded in a metal matrix results from the cooling of the sintered material required by the manufacturing process [2]. The coefficient of thermal expansion of the particle material is lower than that of the matrix and the particle is compressed by the contracting matrix. If the difference in the coefficients of thermal expansion is larger and there is a sufficient drop in temperature after hot pressing, a plastic zone around the particle is formed.

The term ‘matrix retention’ denotes the capacity of a metallic matrix material to retain diamond particles at the surface of a segment during cutting. This property is important in the case of matrices of diamond segments used for cutting materials.

The effect of mechanical properties of a matrix on its potential retentive capabilities is presented in this paper.

Numerical model of a diamond particle in a metallic matrix

Depending on the synthesis conditions, diamond crystallization leads to the formation of crystals with shapes ranging from a cube to an octahedron [3]. An intermediate shape of a diamond crystal is truncated octahedron. The 3D computer model of the truncated octahedron as a diamond crystal (Fig. 1a) was analyzed. The crystal size, i.e. the distance between the opposite square <100> facets (Fig. 1a), was assumed to be 350 μm. The calculations were performed for a deeply embedded particle as well as for the one protruding above the surface of the metal matrix (Fig. 1b).

The models of a diamond crystal embedded in a metallic matrix and protruding from its surface (Fig. 1b) were discussed in [3, 4]. Investigations were carried out by the finite elements method using the Abaqus software version 6.14 [5]. The values of the numerically calculated pressure inside a diamond particle was in agreement with those observed in the experiments [3, 6].

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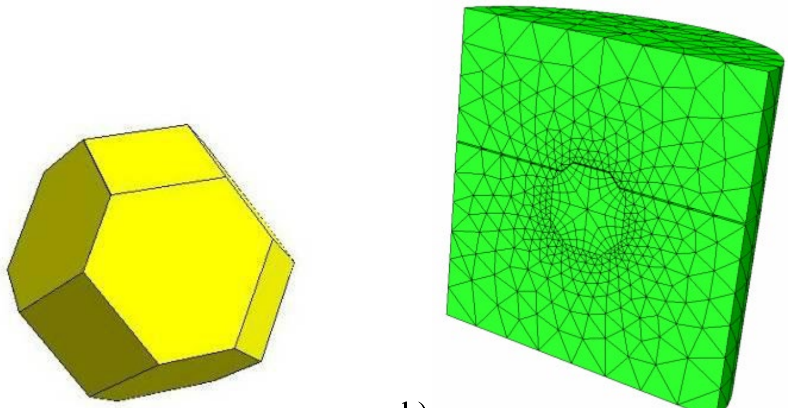
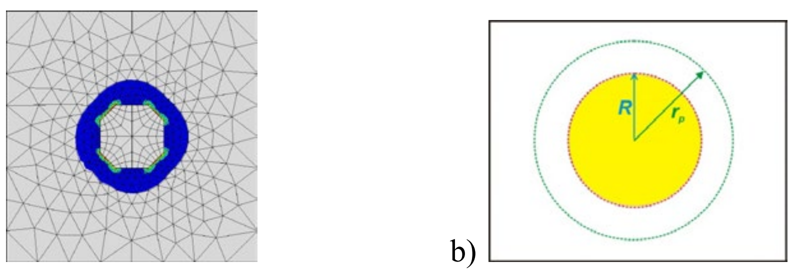


a) b)

Fig. 1. a) Truncated octahedron as a model of a diamond crystal, b) model of a diamond crystal inside the matrix and protruding above the matrix surface.

Mathematical model of a diamond particle in a metallic matrix

The truncated octahedron (Fig. 1a) is the most spherical object of all the semi-regular polyhedrons. Therefore, a spherical model of a diamond particle has been proposed. An analytical model of a spherical elastic particle in an elastic-ideally plastic matrix was presented in the paper [3]. The pressure inside the particle and the elastic energy of the particle are not essentially dependent on the particle shape, the particle is surrounded by the plastic zone with a relatively well defined radius (Fig. 2a) [3]. The mathematical model was verified by comparing the analytical results with the simulation results for the 3D numerical model of the spherical particle [3].



a) b)

Fig. 2. a) Plastic zone around the particle, b) model of the particle in the matrix,

Elastic stresses in the particle and in the matrix were determined using the Lame solution [7]; the plastic zone around the particle was determined from the theory of plasticity [8]. The radius of the plastic zone r_p can be calculated numerically using the following equation [3]:

$$(1-\nu_p)\frac{r_p^{\,3}}{R^3} - 2\left((1-2\nu_m)-(1-2\nu_p)\frac{E_m}{E_p}\right)\left(\ln\left(\frac{r_p}{R}\right)+\frac{1}{3}\right) = \frac{E_m}{\sigma_0}(\alpha_m-\alpha_p)\Delta T \tag{1}$$

where E is elastic modulus, ν is Poisson ratio, R is radius of the diamond particle, r_p is radius of the plastic zone around the particle (Fig. 2b), α_m and α_p are respectively the coefficients of thermal expansion of the matrix and the particle, ΔT is the decrease of temperature during cooling after hot pressing and σ_0 is the yield stress of the matrix. The p index denotes the particle parameters and the *m* index denotes the matrix parameters. The *p* pressure inside the particle is calculated from the following formula [3]:

$$p_p = 2\sigma_0 \ln\left(\frac{r_p}{R}\right) + \frac{2}{3}\sigma_0 \qquad (2)$$

The stress components (the radial stress and the hoop stress) in the particle are equal to $-p_p$.

Retention of a diamond particle in a metallic matrix

A significant property of matrix material is diamond retention efficiency. Diamond particles are retained in the matrix as a result of mechanical and/or chemical bonding. Mechanical bonding is achieved through cooling that follows the process of hot pressing. Diamond particles are squeezed by the shrinking matrix. Mechanical bonding depends on the elastic and plastic properties of matrix material.

The mechanical properties of the matrices used in the proposed model are summarised in Table 1 [9]. It was assumed that materials were fully densified at hot pressing temperature and then cooled to the room temperature. Thus, the strain field generated in the diamond's surroundings was only an effect of thermal shrinkage of the metal matrix.

Table 1. Material data used for calculations [9]

	Diamond	Cobalt	Cobalt-Bronze
Composition		100%Co	54%Cu40%Co6%Sn
Hot pressing temperature [^{O}C]	-	850	750
Thermal linear expansion coefficient, [$m\cdot K^{-1}$] [10]	$2.9\cdot10^{-6}$	$13.36\cdot10^{-6}$	$15.5\cdot10^{-6}$
Young's modulus, [GPa]	1050	202	140
Poisson ratio	0.1	0.3	0.3
Yield strength, [MPa]	-	650	360
Tensile strength, [MPa]	-	900	520
Elongation, [%]	-	8.5	5.0

In order to verify the mathematical model, the analytical calculation results were compared with the simulation results in the 3D numerical model. The calculations were performed for two sinters: cobalt sinter and cobalt-bronze sinter (Table 1). The results of this analysis are shown in Table 2. The differences between numerical and analytical models are less than 10%.

The obtained values of pressure were correlated with the diamond retention index (DRI) of the matrices. The diamond retention index is the ratio of the total number of diamonds retained on the surface of segment to the total number of diamonds and pullout sites on the surface [11]. The DRI parameter was calculated on working surfaces of diamond segments after granite machining. The last row of Table 2 shows that the pressure in the particle can be taken as a matrix retention index.

Conclusions

Computer modeling enables the examination of the effect of different parameters on the potential retentive properties of the matrix in a very easy and cheap way. The presented results allow the following conclusions to be made:

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1. potential retentive properties of the matrix strongly depend on the interactions taking place at the diamond-matrix interface,
2. the pressure inside the particle is not essentially dependent on the particle shape,
3. the particle is surrounded by the plastic zone with a relatively well defined radius.

The above parameters (2 and 3) could be used as the indexes diamond particle retention in the metal matrix.

Table 2. Results of the analysis

Matrix	DRI	Pressure inside particle, analytical model [MPa]	Pressure inside particle, numerical model [MPa]
Co	74	965	1045
CuSnCo	49	605	652
Ratio of Co/CuSnCo values	1.51	1.59	1.60

References

[1] J. Konstanty, Powder metallurgy diamond tools, Elsevier, Oxford, 2005.

[2] J. Borowiecka-Jamrozek, J. Konstanty, Microstructure and mechanical properties a new iron-base material used for the fabrication of sintered diamond tools, Advanced Materials Research 1052 (2014) 520–523. https://doi.org/10.4028/www.scientific.net/AMR.1052.520

[3] J. Lachowski, J. Borowiecka-Jamrozek, Modelling Thermomechanical Response of a Diamond Particle in a Metallic Matrix, Engineering Transactions, 65 (2017) 105–112.

[4] J. Borowiecka-Jamrozek, J. Lachowski, Modelling of retention of a diamond particle in matrices based on Fe and Cu, Procedia Engineering 177 (2017) 289 – 296. https://doi.org/10.1016/j.proeng.2017.02.227

[5] SIMULIA Dassault System, Abaqus Analysis User's Guide, ver. 6.14 (2014).

[6] D.A. Akyuz, Interface and microstructure in cobalt-based diamond tools containing chromium, PhD thesis, Ecole Polytechnique Federale de Lausanne, Lausanne, 1999, pp.105–108.

[7] L.D. Landau and E.M. Lifszic, Theory of Elasticity, 2nd ed. , Pergamon Press Ltd., Oxford, 1975.

[8] R. Hill, The Mathematical Theory of Plasticity, Clarendon Press, Oxford, (1950, reprinted 2009) pp. 97-101.

[9] A. Romański, J. Lachowski, H. Frydrych, Energy of plastic deformation as an estimator of the retentive properties of the metal matrix in diamond impregnated tools, Diamond Tooling Journal 1 (2009) 28-32.

[10] Spinger Handbook of Condensed Matter and Materials Data, eds. W. Martienssen & H. Warlimont, Springer Berlin Heidelberg 2005.

[11] A. Romański, Development of metal matrix for sintered diamond tools, AGH, Dissertations-Monographs, No 303, Kraków 2015 (in polish).