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COMPUTER MODELLING OF THE PROPERTIES OF A DIAMOND PARTICLE IN A METAL MATRIX

Abstract

The results of computer simulation of properties of diamond particle in metallic-diamond segments has been presented in the paper. The segments constitute the working elements of a saw are produced by means of the technology of powder metallurgy.

The effective use of diamond impregnated tools is strongly depended on the retentive properties of the metal matrix, which must hold diamond grits firmly. The diamond retentive capability in a matrix is a complex property, affected by mechanical interactions during hot pressing and then cooled to room temperature. Due to mismatch between thermal expansion coefficients of the matrix and diamond, the stress/strain field is generated in the matrix at diamond surroundings, which plays a major role when retentive properties are considered.

It is postulated that the potential retentive capability of a matrix can be associated with the amount of elastic and plastic deformation energy which occurs in the matrix around diamond particles. The stress and the strain field generated in the diamond particle and in a matrix have been obtained using the Abaqus software. It was attempted to find any relationship between energy of elastic and plastic deformation of the matrix and its retentive capabilities.

INTRODUCTION

Diamond tools designed to cut construction materials and natural stone include circular saws with blade segments soldered to a steel disc (Fig. 1). The segments − the cutting elements of the saw − are produced using powder metallurgy.

The process of production of metal-diamond segments involves mixing the metal matrix powder with the natural or synthetic diamond powder, which is followed by die pressing and sintering or hot pressing [1, p. 21-25, 2, 3].

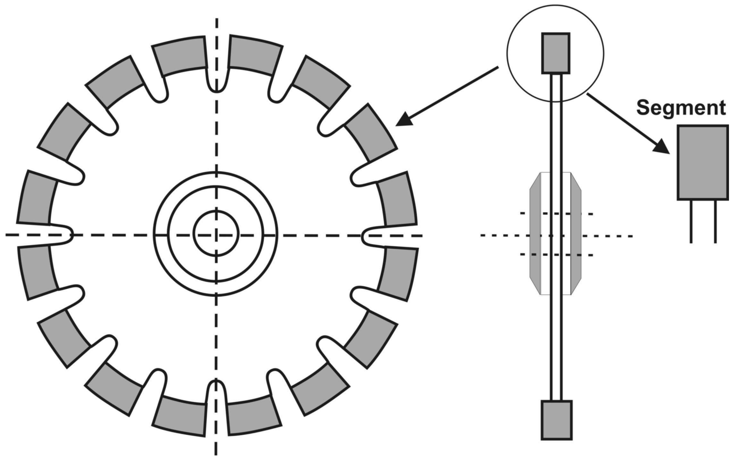

Fig. 1. Views of a circular saw disc

1. MECHANICAL AND THERMAL PROPERTIES OF THE METAL MATRIX

The specimens to be examined were produced by hot pressing. The pressing was performed in the atmosphere of an inert gas (nitrogen) [1, p. 29-30]. The process parameters were selected experimentally and they were as follows: pressure 35-40 MPa, duration 2 min. and temperature 850-980 C˚ (Table 1). The specimens were produced from the following elementary powders: SMS cobalt, EF (Extrafine) cobalt and 400 mesh cobalt. Additionally, one matrix was produced using 50 percent by mass of EF cobalt powder + 50 percent by mass of CN (Carbonyl) iron powder and another matrix was produced using 80 percent by mass of EF cobalt powder + 20 percent by mass of WP30 tungsten powder. The mechanical properties of the matrix materials were determined experimentally [2, 3], as depicted in Table 2.

Tab. 1. Content of the analyzed materials and the parameters of the hot pressing process

Material symbol	Chemical composition	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
Co(EF)Fe	50% Co Extrafine 50% Fe CN	900˚C/35MPa/2min
Co(EF)W	80% Co Extrafine 20% WP30	980˚C/40MPa/2min

Tab. 2. Results of the static tensile test

Material symbol	R_m, MPa	$R_{0.2}$, MPa	ΔL/L, %
Co (SMS)	865	405	19.5
Co (EF)	954	634	9.5
Co (400)	743	540	1.7
Co(EF)Fe	527	494	1.3
Co(EF)W	927	632	1.4

The coefficients of thermal expansion for cobalt, iron, tungsten and diamond are given in Table 3 [4, 5, p. 182, 294, 654, 1415]. The coefficients for the CoFe sinter and CoW sinter were assumed to be proportional to the amount of metals in the sinters.

Tab. 1. Coefficients of thermal expansion

Temperature [K]	Cobalt [K^{-1}]	Iron [K^{-1}]	Tungsten [K^{-1}]	Diamond [K^{-1}]
300	$13.4 \cdot 10^{-6}$	$12.0 \cdot 10^{-6}$	$4.4 \cdot 10^{-6}$	$1 \cdot 10^{-6}$
600	$16.5 \cdot 10^{-6}$	$13.1 \cdot 10^{-6}$	$4.7 \cdot 10^{-6}$	$3 \cdot 10^{-6}$
1200	$18.0 \cdot 10^{-6}$	$13.4 \cdot 10^{-6}$	$4.8 \cdot 10^{-6}$	$6 \cdot 10^{-6}$

2. RETENTION OF THE DIAMOND PARTICLE IN THE METAL MATRIX

An important property of the matrix material is retention of diamond particles (Fig. 2) during the operation of the tool. The retention occurs as a result of mechanical bonding. Mechanical bonding is achieved during cooling, which follows hot pressing. Compared with metals, diamond has a very low coefficient of thermal expansion, which causes that diamond particles are squeezed by the shrinking matrix [1]. Mechanical bonding is dependent on the elastic and plastic properties of the matrix. Retention of a diamond particle with respect to the mechanical properties of the matrix was analyzed in Refs. [6, 7, 8]. The most essential parameters affecting retention are the elastic and plastic energies of the deformed matrix around a diamond particle (Fig. 3) [9, 10].

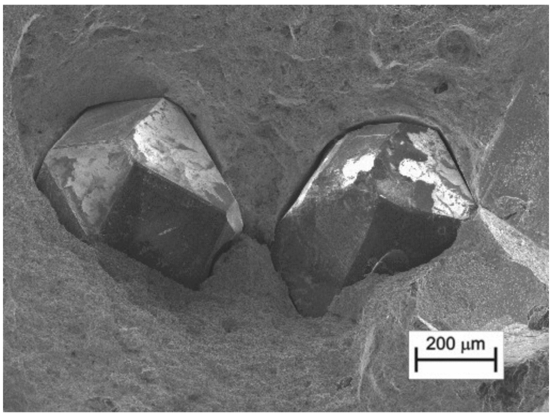

Fig. 2. Fracture of a segment with diamond particles

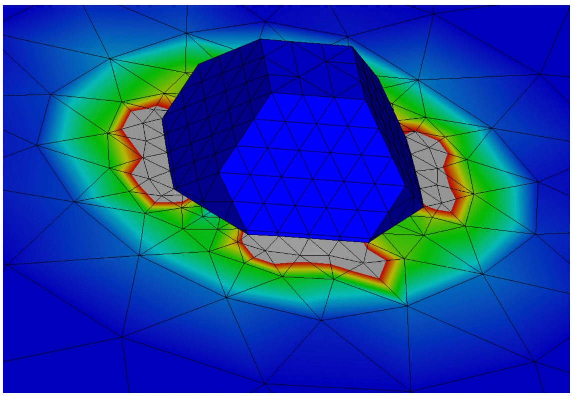

Fig. 3. Numerical model of a diamond particle with the plastic zone (inside red contour)

3. COMPUTER SIMULATION OF THE RETENTION OF A DIAMOND PARTICLE IN A METAL MATRIX

The amount of diamond grits in a segment of a metal-matrix diamond tool is determined basing on the so called diamond concentration. The 100 concentration is equivalent to 4.4

carats (0.2 g) of diamond per 1 cm^3, which constitutes 25% of the volume [1, p. 17]. The matrix fragment selected for the computer simulation contained only one diamond particle, with a relative measure of concentration being 15.

The data were obtained with the finite element method using ABAQUS program ver. 6.7. The 3D model with a cubo-octahedral diamond particle was analyzed (Fig. 4). The size of the particle (distance between the opposite square walls) was 350 μm. The calculations were performed for a deeply embedded particle and one protruding above the surface of a metal matrix (Fig. 5).

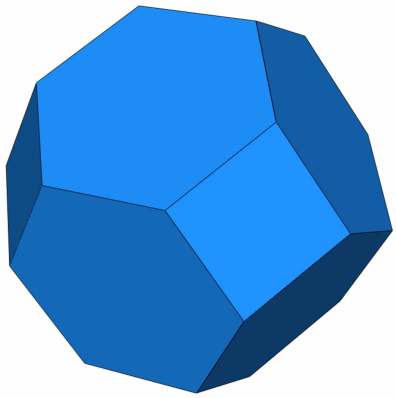

Fig. 4. Model of a diamond particle – cubo-octahedron

A numerical analysis was conducted for a diamond particle with protrusion ranging from 25 μm to 150 μm, as well as for a particle with a negative protrusion value. Protrusion is the height of a diamond particle projecting above the matrix surface (Fig. 5). Negative protrusion is the distance of the particle from the surface in the case of a particle completely submerged in the matrix.

For all the materials analyzed here, the strain energy of the matrix around a diamond particle was largely affected by protrusion.

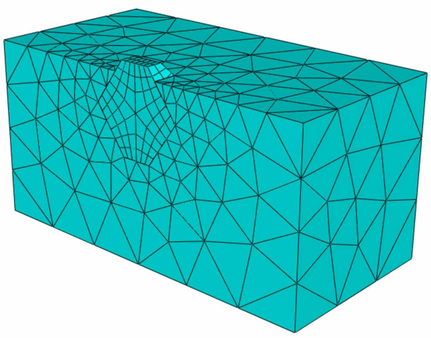

Fig. 5. Model of a diamond particle protruding above the matrix surface

4. MODELLING OF THE DIAMOND PARTICLE-METAL MATRIX SYSTEM AFTER HOT PRESSING

The cooling of the diamond particle–metal matrix system was simulated for all the matrix materials tested. The total strain energy of the matrix around a diamond particle shows a clear relationship with protrusion of the diamond particle (Fig. 6). For protrusion ranging from 0 to 150 μm, the relationship is linear with different inclinations.

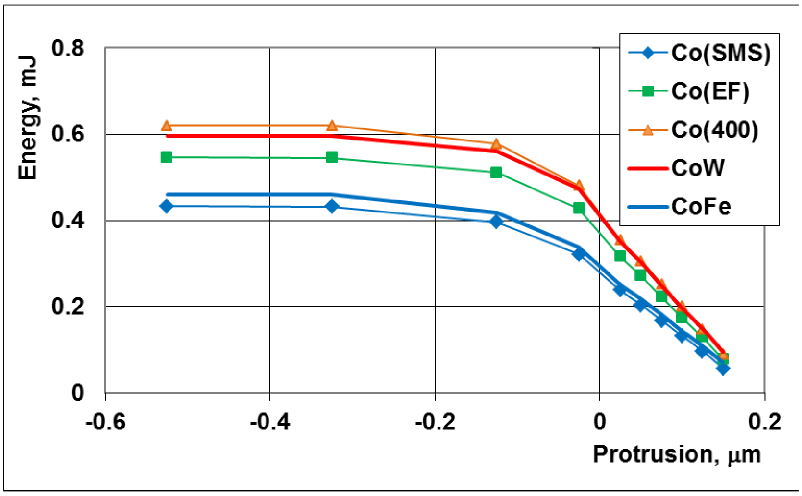

Fig. 6. Total strain energy vs. protrusion

The percentage share of the plastic strain energy in the total strain energy shows little influence on the type of the matrix material (Fig. 7). All the matrices indicate similar and uniform share of the plastic energy with regard to the particle protrusion.

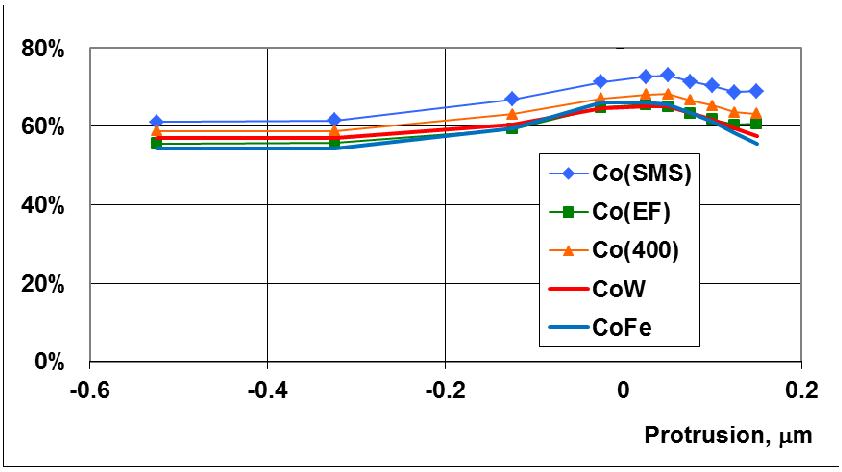

Fig. 7. Percentage share of the plastic strain energy in the total energy of a diamond particle

5. MODELLING OF A DIAMOND PARTICLE SUBJECTED TO AN EXTERNAL LOAD

The simulation was repeated for a diamond particle subjected to a load normal to the matrix surface. A maximum force applied to the diamond particle was 50 N.

The force acting on the particle contributes to a change in the stress field around the particle (Figs. 8 and 9). An increase in the energy of the matrix deformation resulting from the external load is significant. It constitutes more than ten percent of the strain energy caused by thermal shrinkage of the sinter during pressing. Table 4 gives an average increase in the energy of the matrix for a typical protrusion of 75 µm. The elastic energy of the particle increases more clearly than the energy of the matrix (Table 4).

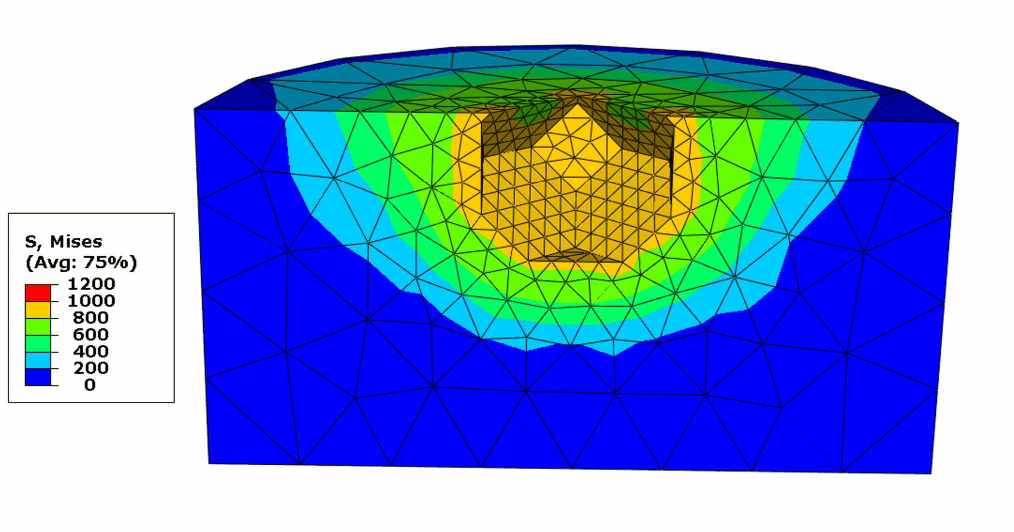

Fig. 8. Stress field [MPa] around a diamond particle in the CoW matrix with a protrusion of 75 μm

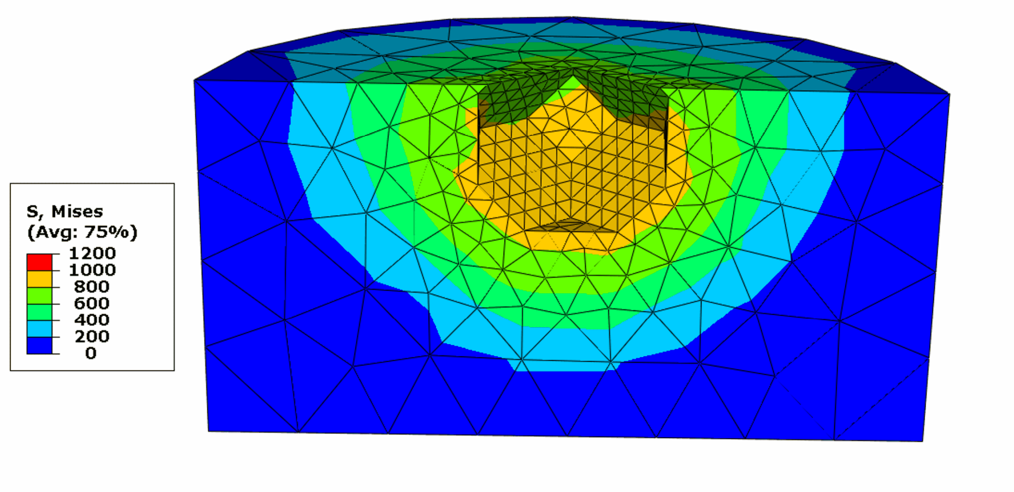

Fig. 9. Stress field [MPa] around a diamond particle under loading in the CoW matrix with a protrusion of 75 μm

Tab. 4. Increase in the strain energy of the matrix and the diamond particle under loading

Matrix material	Increase in the total strain energy of the matrix	Increase in the plastic strain energy of the matrix	Increase in the elastic strain energy of the particle
Co(SMS)	17%	21%	133%
Co(EF)	11%	12%	68%
Co(400)	12%	12%	62%
CoFe	26%	35%	64%
Co(EF)W	10%	9%	40%

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. A force normal to the surface as well as a tangential force were applied. The force needed to remove the particle show strong relationship with the particle protrusion (Figs. 10, 11, and 12).

The amount of force required to remove a particle out of the matrix shows correlation with the total strain energy of the matrix around the particle (Fig. 13). In their previous works [9,10], the authors suggested that the plastic strain energy of the matrix can be used as an indicator of retention of the diamond particle. The results of the computer simulations confirm the thesis that the strain energy of the matrix caused by thermal shrinkage during cooling is a measure of retention of a diamond particle in a metal matrix.

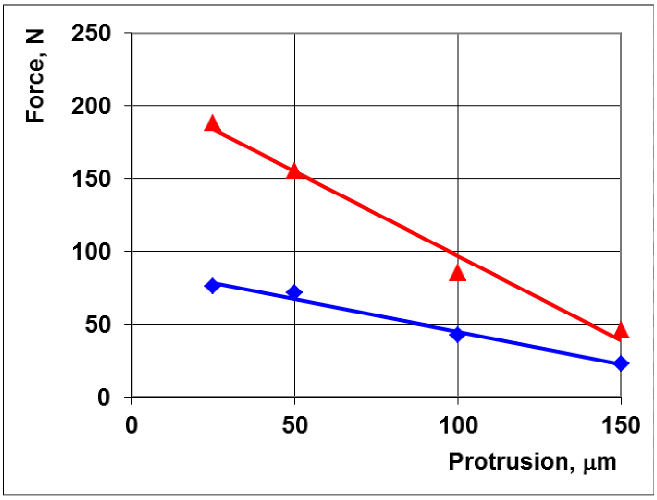

Fig. 10. Force pulling a particle out of the Co(SMS) matrix, red – force tangent to the surface, blue – force normal to the surface

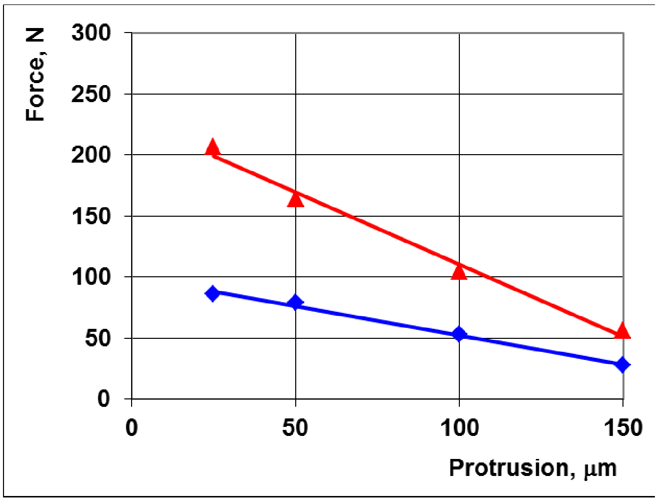

Fig. 11. Force pulling a particle out of the Co(EF)Fe matrix, red – force tangent to the surface, blue – force normal to the surface

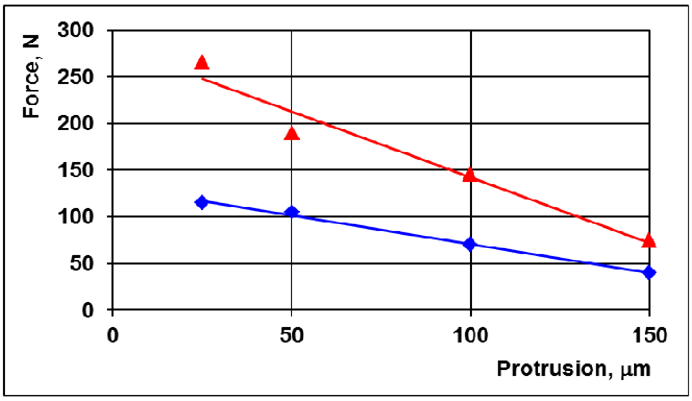

Fig. 12. Force pulling a particle out of the Co(EF)W matrix, red – force tangent to the surface, blue – force normal to the surface

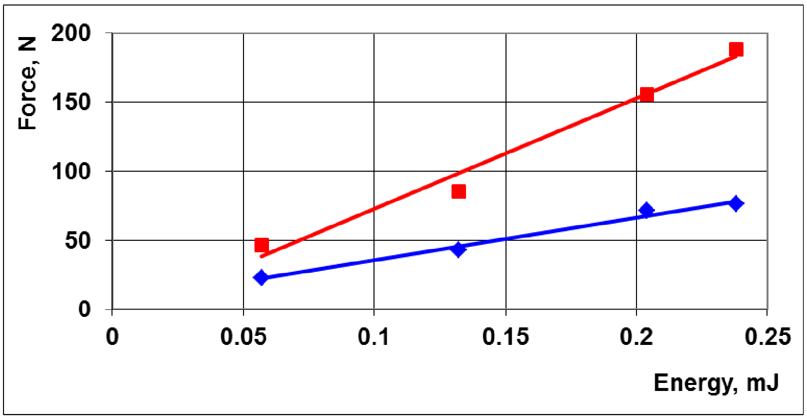

Fig. 13. Force vs. energy of the Co(SMS) matrix, red –force tangent to the surface, blue –force normal to the surface

SUMMARY

The following conclusions have been drawn from the analysis:

- the stress and strain fields generated during cooling are largely dependent on the protrusion of the diamond particle and, to a smaller extent, on the type of matrix,
- the total strain energy (i.e. elastic and plastic energies) of the matrix deformation around the diamond particle can be a good estimator of the retention properties of the matrix,
- further research should focus on numerical modelling of abrasive and erosive wear of the matrix to verify all the results.

MODELOWANIE KOMPUTEROWE WŁAŚCIWOŚCI CZĄSTKI DIAMENTU W OSNOWIE METALICZNEJ

Streszczenie

W pracy przedstawiono wyniki symulacji komputerowych właściwości cząstki diamentu w segmencie metaliczno-diamentowym. Segmenty stanowią elementy skrawające pił diamentowych i są wytwarzane za pomocą technologii metalurgii proszków.

Istotną właściwością materiału osnowy jest retencja, czyli utrzymywanie cząstek diamentu przez otaczającą osnowę podczas pracy narzędzia metaliczno-diamentowego. Cząstki diamentu są utrzymywane w osnowie w wyniku połączenia mechanicznego podczas procesu prasowania na gorąco. Połączenie mechaniczne jest wynikiem różnicy współczynnika rozszerzalności termicznej pomiędzy diamentem, a materiałem osnowy. Cząstka diamentu jest zakleszczana przez otaczającą osnowę, która ulega odkształceniu sprężystemu i plastycznemu.

Uzyskanie odpowiedniego połączenia mechanicznego zależy od własności sprężystych i plastycznych materiału osnowy. Analiza retencji cząstki diamentu w zależności od właściwości mechanicznych osnowy została przeprowadzona metodą elementów skończonych z wykorzystaniem programu Abaqus. Wyznaczono pola mechaniczne naprężeń i odkształceń w cząstce diamentu oraz w osnowie otaczającej cząstkę. Obliczono energię sprężystą i plastyczną osnowy, jako parametry retencji cząstki diamentu

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