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EFFECT OF FRICTION COEFFICIENT ON DIAMOND RETENTION CAPABILITIES IN DIAMOND IMPREGNATED TOOLS

WPŁYW WSPÓŁCZYNNIKA TARCIA NA WŁASNOŚCI RETENCYJNE OSNOWY W NARZĘDZIOWYCH SPIEKACH METALICZNO-DIAMENTOWYCH

This paper presents the role of friction coefficient between diamond particle and metal matrix and the effect of mechanical properties of a matrix on its diamond retention capabilities in powder metallurgy (PM) diamond impregnated tools. Investigations were carried out by means of computer modelling technique using Abaqus software. In the proposed 2-D axisymmetric model, effects of varied mechanical properties on the energy of plastic deformation of the matrix during cooling to room temperature after hot pressing were analysed. In calculations, the diamond particle shape, mismatch between thermal expansion coefficients of the matrix and diamond were also taken into account. Potential retentive properties of the matrix were estimated by the force required to pull out the diamond particle from the matrix.

Obtained results have shown that potential retentive properties of the matrix strongly depend on the interactions taking place at the diamond-matrix interface. What is interesting, obtained results have proved that mechanical properties of the matrix are of secondary importance (in limited range), when retentive properties are considered.

Keywords: PM Diamond Tools, Diamond Retention, Computer Modelling, Mechanical Properties

W artykule opisano rolę współczynnika tarcia pomiędzy diamentem a metriałem osnowy oraz wpływ własności mechanicznych osnowy na zdolność utrzymywania cząstek diamentu w osnowie (jej zdolności retencyjne) w metaliczno-diamentowych narzędziach wytwarzanych techniką metalurgii proszków. Badania zostały wykonano z wykorzystaniem technik komputerowego modelowania przy użyciu programu Abaqus. W zaproponowanym dwuwymiarowym modelu osiowosymetrycznym poddano analizie wpływ zróżnicowanych własności mechanicznych osnowy na wielkość energii jej odkształcenia plastycznego w czasie chłodzenia do temperatury otoczenia po procesie prasowania na gorąco. W obliczeniach uwzględniono także kształt cząstki diamentu oraz różnicę we współczynnikach rozszerzalności cieplnej osnowy i diamentu. Potencjalne własności retencyjne osnowy szacowano wartością siły potrzebnej do wyrwania cząstki diamentu z osnowy.

Na podstawie uzyskanych wyników obliczeń stwierdzono, że własności retencyjne osnowy są silnie związane ze zjawiskami zachodzącymi na granicy faz diamentu i osnowy. Stwierdzono również, że w przypadku własności retencyjnych osnowy, jej własności mechaniczne, mają w ograniczonym zakresie drugorzędne znaczenie.

1. Introduction

Diamond impregnated tools are widely used for machining, polishing and finishing natural stones. Depending on stone's properties, its mineral structure, many types of diamond impregnated tools are in use. In order to maintain the highest productivity of the tool at the lowest cutting cost, the bond's properties must differ according to workpiece's wear behavior and cutting mode. It is very known rule that when hard and dense materials, e.g. granite and dolomite, are being cut, the lower resistance to wear of the matrix is required. It makes possible the new diamond crystals to emerge from the bond and maintain the cutting process. A well selected matrix must hold diamond particles firmly and also guarantee an adequate wear rate adjusted to diamond loss. The resistance to wear of the metal matrix can be easy changed in a very wide range by using soft or hard components according to the mode of cutting (frame or circular) and workpiece's properties [1]. Much more difficult is to change the retentive capabilities of the bond, which are a complex effect of mismatch between thermal expansion coefficients of diamond and matrix material. Additionally, the retentive properties depend

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on diamond-metal interface interactions. In most cases, bonding between diamond particles and matrix relies on mechanical locking. During cooling to room temperature, due to mismatch between thermal expansion coefficients, diamond particles are tightened by metal matrix, thus the stress and strain fields occur at particles surroundings. This type of connection can be associated with the metal to diamond (carbon) chemical bonding, which increases friction between diamond particle and the bond [2-5].

In this paper the effect of friction coefficient and mechanical properties of a matrix on its potential retentive capabilities is presented. Investigations were carried out by computer modelling technique using Abaqus software.

2. Experimental

A 2-D axisymmetric model was proposed to evaluate the stress and strain fields generated in metal matrix by diamond crystal. It was assumed, that material was fully densified during hot pressing and then cooled down to room temperature. The number of combinations of diamond crystal shapes, diamond protrusion and mechanical properties of the bond were studied to evaluate the amount of deformation energy of the matrix around diamond crystal. The mesh configuration and mechanical properties of the matrices used in the proposed model are presented on Fig. 1 and summarised in Table 1, respectively. Calculations were done for the friction coefficient at matrix-diamond grit interface within the range of μ = 0 to 1.0. In order to examine the effect of friction coefficient on potential retentive capabilities of the matrix, following energies were calculated for each diamond's crystal shape and matrix configurations:

1. total strain energy – ALLIE,
2. energy dissipated by plastic deformation – ALLPD,
3. recoverable strain energy – ALLSE.

Also, to evaluate the strength of the matrix to diamond bonding, a force required to pull the diamond particle out of the matrix was calculate. This calculated force is an another factor, which can be taken into account if potential retentive properties of the matrix are considered.

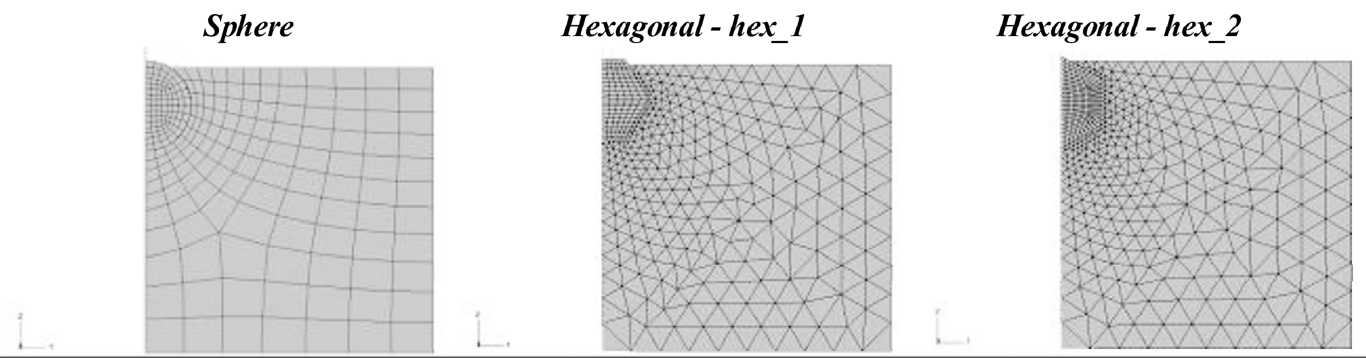

Fig. 1. Mesh configurations

TABLE 1

Input data used for calculations

	Diamond	Matrix 1	Matrix 2	Matrix 3
Hot pressing temperature, (°C)	–	850	750	950
Thermal linear expansion coefficient, (m·K^{-1})	10^{-6} (0-1200°C)	10^{-5} (0-1200°C)		
Poisson ratio	0.2	0.3		
Young's modulus, (GPa)	1000	202	140	204
Yield strength, (MPa)	–	650	360	350
Tensile strength, (MPa)	–	900	520	530
Strain, (%)	–	8.5	5.0	28.0
Size, (μm)	350	–	–	–
Height of diamond protrusion, (μm)	a) 25 b) 50 c) 70 d) 100	–	–	–

3. Results

Selected examples of stress and strain fields distribution generated at diamond's surroundings are presented on Fig. 2 and Fig. 3, respectively. All maps were calculated for cooling step after hot pressing, and show the final stage at room temperature. In addition to the maps, calculated values of following energies: total strain energy (ALLIE), energy dissipated by plastic deformation (ALLPD) and recoverable strain energy (ALLSE) are summarised in Table 2, whereas Fig. 4-6 show for selected cases the effect of friction coefficient on these energies.

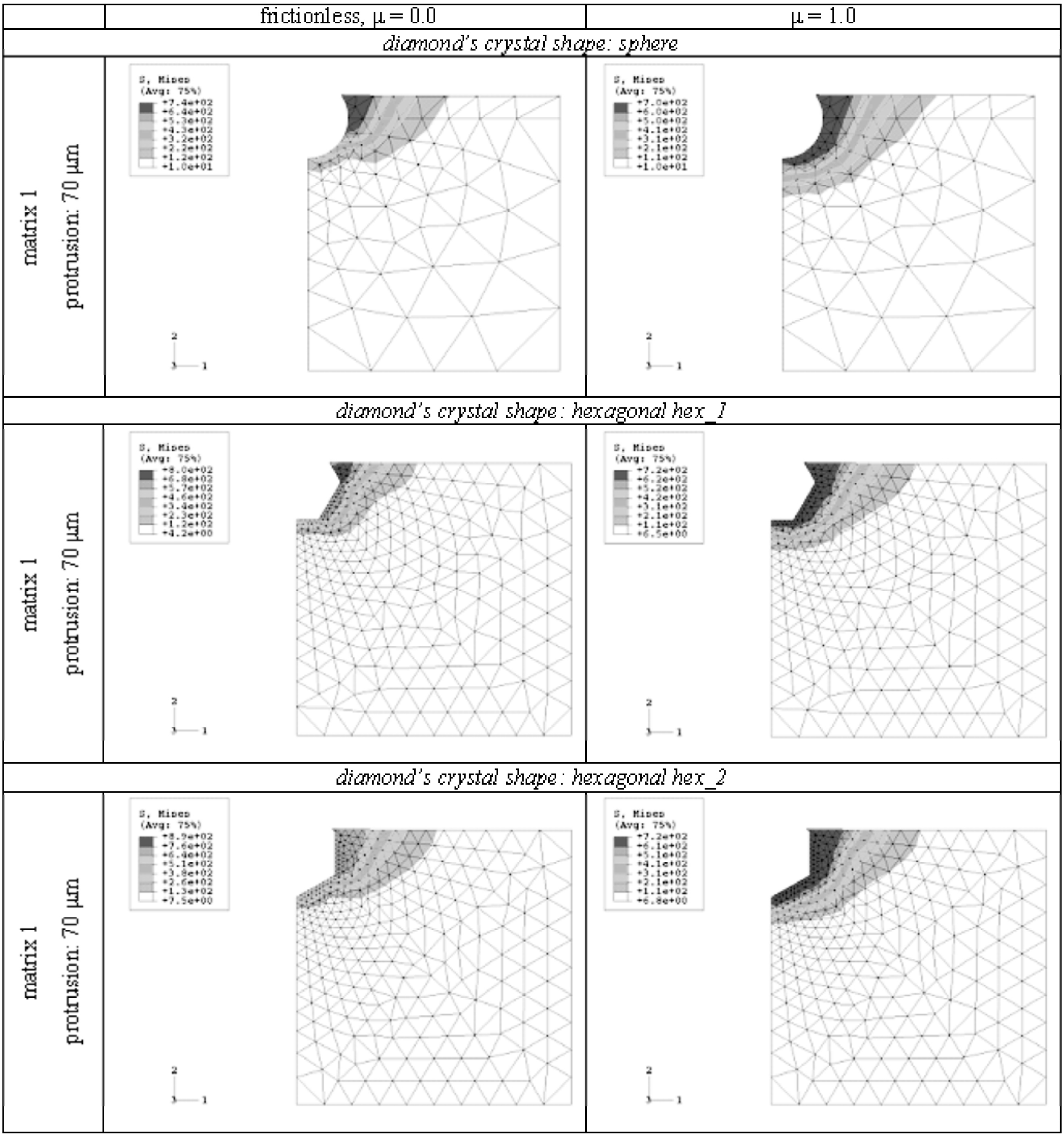

Fig. 2. Stress field distribution

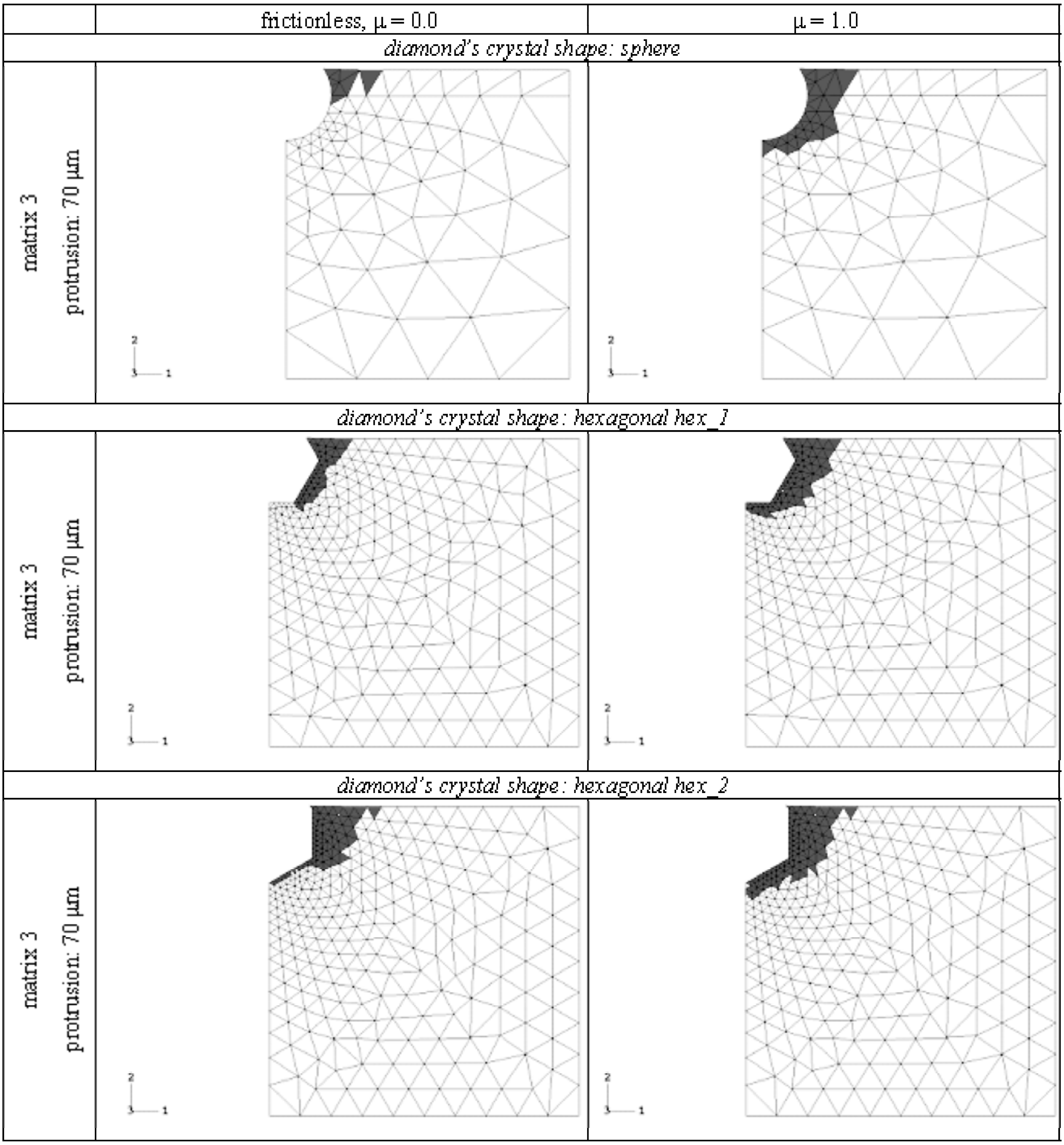

Fig. 3. Strain field distribution

TABLE 2

Strain and plastic deformation energies calculated for the matrix cooled to room temperature *(values in mJ)*

Friction coefficient	d.p.*=25μm			d.p.=50μm			d.p.=70μm			d.p.=100μm		
	ALLIE	ALLPD	ALLSE	ALLIE	ALLPD	ALLSE	ALLIE	ALLPD	ALLSE	ALLIE	ALLPD	ALLSE
diamond's crystal shape: sphere, matrix 1												
μ=0.0	0.325	0.214	0.111	0.280	0.183	0.096	0.227	0.153	0.074	0.174	0.126	0.048
μ=1.0	0.378	0.242	0.136	0.339	0.220	0.120	0.307	0.198	0.108	0.267	0.175	0.092
diamond's crystal shape: sphere, matrix .2												
μ=0.0	0.167	0.111	0.055	0.144	0.096	0.048	0.117	0.079	0.038	0.090	0.065	0.025
μ=1.0	0.193	0.126	0.068	0.174	0.115	0.059	0.157	0.104	0.054	0.137	0.091	0.046
diamond's crystal shape: sphere, matrix 3												
μ=0.0	0.247	0.191	0.056	0.212	0.164	0.047	0.165	0.141	0.024	0.120	0.106	0.014
μ=1.0	0.294	0.221	0.072	0.262	0.199	0.063	0.237	0.181	0.056	0.206	0.159	0.047
diamond's crystal shape: hexagonal hex_ 1, matrix 1												
μ=0.0	0.219	0.145	0.074	0.184	0.125	0.058	0.150	0.100	0.050	0.095	0.074	0.022
μ=1.0	0.254	0.162	0.092	0.227	0.145	0.082	0.195	0.127	0.068	0.162	0.105	0.057
diamond's crystal shape: hexagonal hex_1, matrix 2												
μ=0.0	0.113	0.076	0.037	0.095	0.065	0.030	0.078	0.052	0.026	0.050	0.039	0.011
μ=1.0	0.131	0.085	0.045	0.117	0.077	0.040	0.100	0.067	0.034	0.084	0.056	0.028
diamond's crystal shape: hexagonal hex_1, matrix 3												
μ=0.0	0.166	0.127	0.040	0.137	0.105	0.032	0.114	0.084	0.029	0.064	0.057	0.008
μ=1.0	0.199	0.152	0.047	0.178	0.135	0.043	0.151	0.116	0.034	0.126	0.097	0.030
diamond's crystal shape: hexagonal hex_2, matrix 1												
μ=0.0	0.263	0.167	0.097	0.201	0.121	0.080	0.179	0.103	0.076	0.154	0.088	0.066
μ=1.0	0.293	0.185	0.107	0.238	0.154	0.084	0.214	0.138	0.077	0.191	0.122	0.069
diamond's crystal shape: hexagonal hex_2, matrix 2												
μ=0.0	0.135	0.087	0.048	0.103	0.064	0.039	0.093	0.055	0.038	0.080	0.048	0.033
μ=1.0	0.150	0.098	0.053	0.122	0.081	0.041	0.110	0.072	0.038	0.098	0.064	0.034
diamond's crystal shape: hexagonal hex_2, matrix 3												
μ=0.0	0.207	0.155	0.052	0.160	0.120	0.040	0.145	0.105	0.041	0.126	0.092	0.033
μ=1.0	0.229	0.172	0.057	0.183	0.142	0.041	0.166	0.128	0.039	0.148	0.113	0.035

* *d.p. – diamond protrusion*

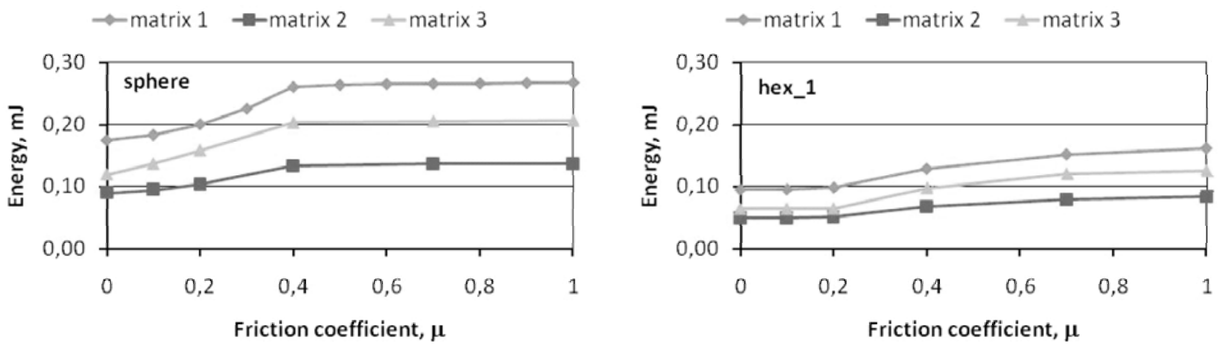

Fig. 4. Total strain energy (ALLIE) vs. friction coefficient for diamond protrusion of 100 μm

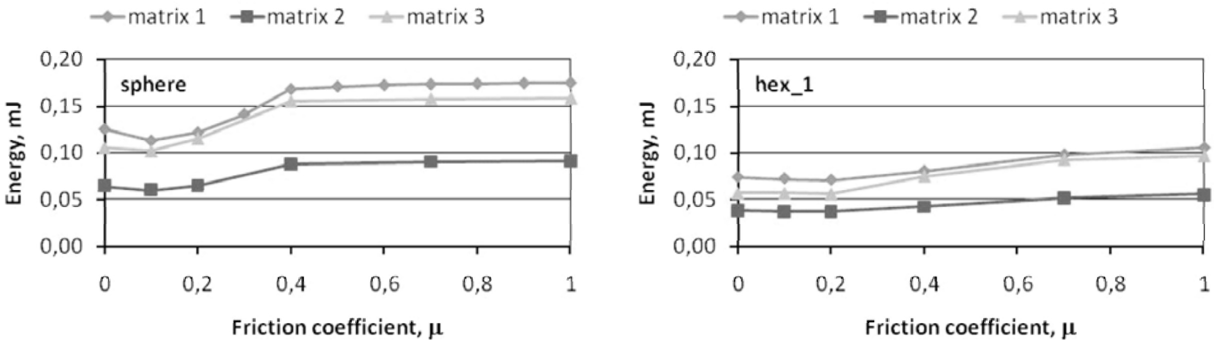

Fig. 5. Plastic deformation energy (ALLPD) vs. friction coefficient for diamond protrusion of 100 μm

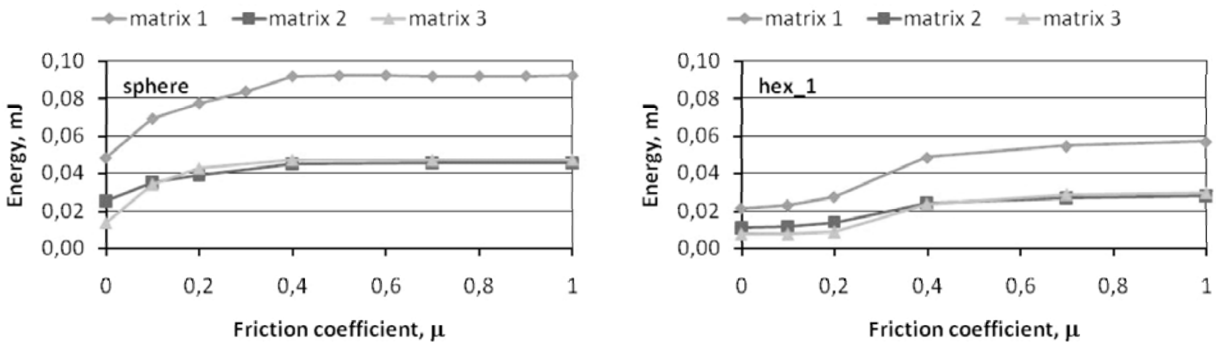

Fig. 6. Recoverable strain energy (ALLSE) vs. friction coefficient for diamond protrusion of 100 μm

In order to evaluate the effect of friction coefficient on the strength of the bonding between diamond particle and the matrix, the values of a normal force (in '2' direction), required to pull the diamond crystal out of the matrix was calculated. Obtained results are presented in Table 3. Figures 7-9 illustrate the relationship between the pull out force and friction coefficient.

TABLE 3

Calculated values of the pull out force

Diamond protrusion	**Pull out force, (N)**								
	diamond's crystal shape: sphere								
	matrix 1			*matrix 2*			*matrix 3*		
	μ=0.0	μ=0.4	μ=1.0	μ=0.0	μ=0.4	μ=1.0	μ=0.0	μ=0.4	μ=1.0
25 μm	62	76	116	38	46	70	30	41	64
100 μm	14	41	82	8	24	49	7	23	46
	diamond's crystal shape: hexagonal hex_1								
	matrix 1			*matrix 2*			*matrix 3*		
25 μm	78	95	69	47	58	41	41	50	*n. d.**
100 μm	27	33	38	16	19	23	16	19	22
	diamond's crystal shape: hexagonal hex_2								
	matrix 1			*matrix 2*			*matrix 3*		
25 μm	96	156	201	61	95	122	65	83	106
100 μm	9	97	153	6	59	93	5	57	86

**n.d.* – not determined

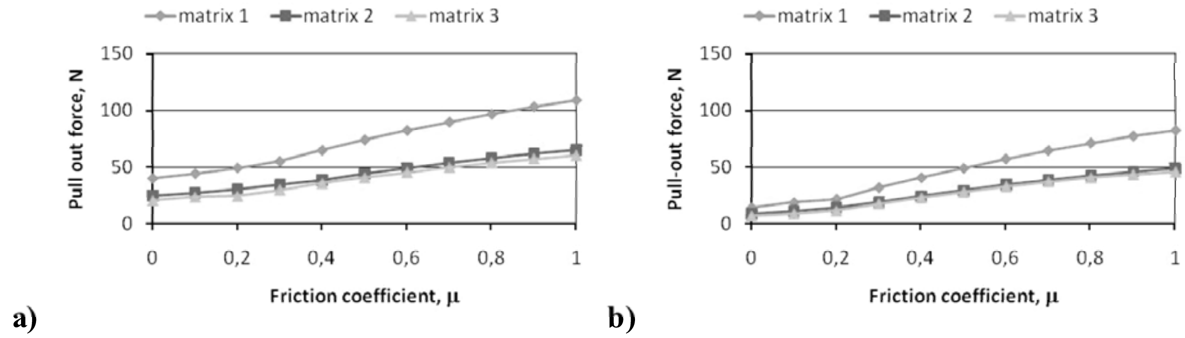

Fig. 7. Dependence of the pull out force and friction coefficient. Diamond's crystal shape: sphere; protrusion: 50 μm (a) and 100 μm (b)

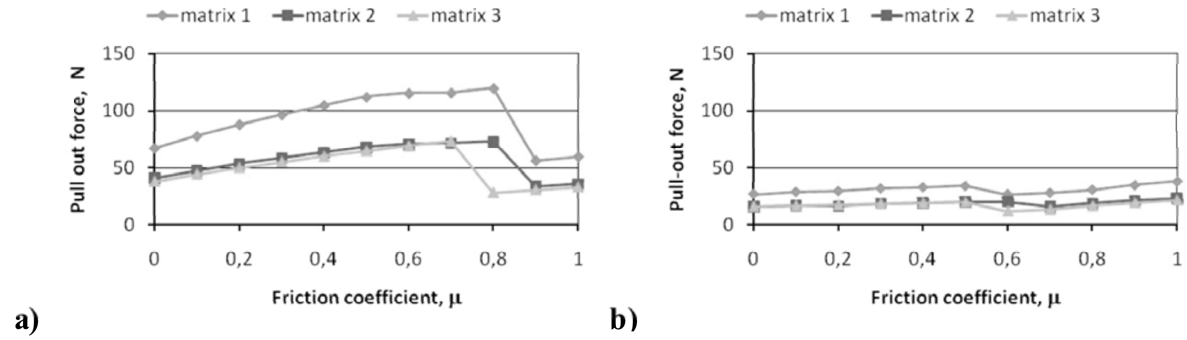

Fig. 8. Dependence of the pull out force and friction coefficient. Diamond's crystal shape: hexagonal hex_1; protrusion: 50 μm (a) and 100 μm (b)

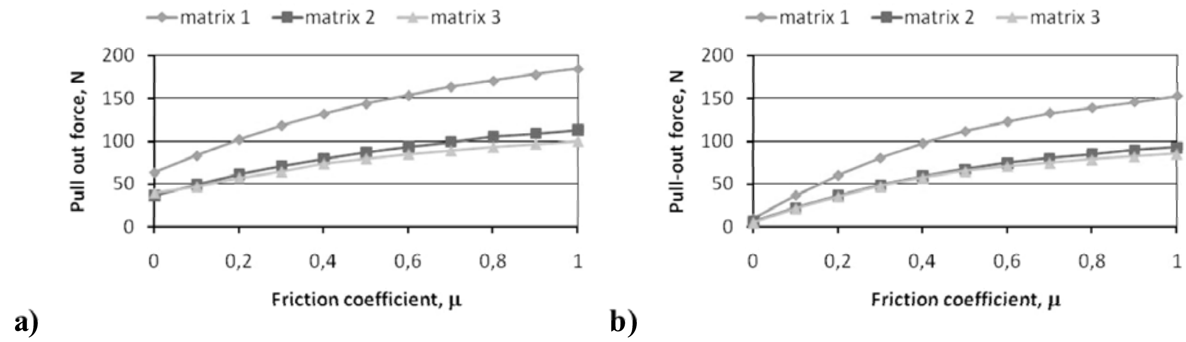

Fig. 9. Dependence of the pull out force and friction coefficient. Diamond's crystal shape: hexagonal hex_2; protrusion: 50 μm (a) and 100 μm (b)

4. Discussion

The effect of friction coefficient on potential diamond retention capabilities of the matrix cannot be deprecated. The friction coefficient between diamond crystal and matrix is a very important factor, which has an influence on deformation energy of the matrix at diamond particle surroundings and on the strength of bonding between diamond particle and the matrix. From examples shown on Figures 2 and 3 it becomes evident, that the size of stress/strain fields, for the same protrusion, depends on the friction between diamond and the matrix material. It can be also seen, that shape of diamond particle plays a major role in both stress and strain distribution. Higher values of friction coefficient lead to increasing the size of deformed zone. Also, if the contact surface between diamond and the matrix extends, the stress/strain fields get wider in consequence. It is noteworthy, that independently of matrix material being considerated, stress/strain field behave in the same manner with increasing friction coefficient.

The data summarised in Table 2 indicate, that the effect of friction coefficient on deformation energies of the matrix is much more evident if diamond protrusion is higher. For diamond protrusion of 100 μm, the recoverable strain energy can be over three times higher in comparison with 25 μm of diamond protrusion. Also, it is evident, that mechanical properties of the matrix play a major role when the deformation energies are considered. The main factor which affects deformation energies is the bond's Young modulus. From Fig. 4-6 it is clearly seen, that all investigated energies rapidly increase if friction coefficient changes from μ=0 to μ=0.4. From this rule, the plastic deformation energy is excluded, for which a little drop was recorded for μ=0.1 and 0.2. Friction coefficient over μ=0.4 has a minor effect on calculated values of the deformation energies. As it was postulated in [6] the recoverable strain energy can be associated with potential retentive capabilities of the matrix. Thus, on the base of theoretical considerations, it can be assumed, that higher friction between diamond particle and metal matrix must lead to better diamond retention.

Very interesting data were acquired for the calculated values of the pull out force. The obtained results are very well correlated with the deformation energies. In all investigated configurations of diamond's particle shape and its protrusion, in order to pull the diamond particle out of the matrix, it is necessary to apply a higher load for higher values of the friction coefficient, even for lower diamond's particle protrusion. As it can be seen in Table 3, it is possible to rise the pull out force even 17 times (!) nearly, only by increasing the friction coefficient between diamond grit and metal matrix. Such huge increment was calculated for the model with hexagonal 'hex_2' diamond particle and the highest protrusion, irrespectively of the metal matrix. It is also interesting, that when diamond particle is deep embedded in the matrix (low diamond protrusion), the pull out force for μ=1.0 is only twice as calculated for μ=0. This rule is not applicable for the model with hexagonal 'hex_1' diamond particle. It indicates, that the pull out force is sensitive to diamond particle shape and orientation. From analysis of data summarised in Table 3 and presented on Fig. 7-9, it arises that it is possible to maintain a high value of the pull out force only by increasing the friction between diamond grit and metal matrix, even if matrix is characterised by lower mechanical properties. This behavior is of very importance, that could be helpful in tools designing, because typical static coefficient of friction for diamond on most metals is very low, and equals μ=0.1 [7].

5. Concluding remarks

Computer modeling techniques which were applied to investigate the role of different parameters on the potential retentive capabilities of the matrix are very advantageous technique. It enables to examine the effect of different parameters on the potential retentive properties of the matrix in a very easy and cheap way. It is much more precious, if the created model can be verified by investigations taken in field conditions. It seems that presented results are in good agreement with already published data [4,5], and allow to put following conclusions:

1. potential retentive properties of the matrix strongly depend on the interactions taking place at the diamond-matrix interface,
2. it is possible to improve potential retentive capabilities of the matrix by increasing the friction between diamond particle and metal matrix,
3. thus, theoretically, mechanical properties of the matrix are of secondary importance (in limited range), when retentive properties are considered.

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