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A. ROMAŃSKI*

FACTORS AFFECTING DIAMOND RETENTION IN POWDER METALLURGY DIAMOND TOOLS

CZYNNIKI DECYDUJĄCE O WŁASNOŚCIACH RETENCYJNYCH OSNOWY W NARZĘDZIOWYCH SPIEKACH METALICZNO-DIAMENTOWYCH

This paper describes the effects of principle factors which have an influence on potential diamond retention capabilities in powder metallurgy diamond tools. Investigations were carried out using a 3-D computer model of diamond particle embedded in a metallic matrix. The proposed model assumed that the material was fully densified by the hot pressing technique and then cooled down to room temperature. The energies of plastic and elastic deformation of the matrix around the diamond grit as well as recoverable strain energy accumulated in the grit on cooling were calculated. The effects of Young's modulus and yield strength of the matrix as well as friction between diamond and matrix on these energies were analysed. The obtained results have shown that a matrix characterised by high yield strength ensures better diamond retention capacity whereas high Young's modulus of the matrix and its chemical affinity to carbon, which increases friction at the diamond-matrix interface seem to have lower importance.

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

W pracy przedstawiono analizę wpływu podstawowych czynników mających wpływ na własności retencyjne materiału osnowy w narzędziowych spiekach metaliczno-diamentowych. Badania wykonano z zastosowaniem modeli 3-D cząstki diamentu osadzonej w osnowie. W zaproponowanym modelu założono, że materiał został zagęszczony do gęstości teoretycznej w wyniku prasowania na gorąco i następnie ochłodzony do temperatury otoczenia. Dla temperatury otoczenia obliczano całkowitą energię odkształcenia oraz energię odkształcenia plastycznego materiału osnowy wokół diamentu oraz energię odkształcenia sprężystego cząstki diamentu. Analizie poddano wpływ modułu Younga i granicy plastyczności osnowy oraz współczynnika tarcia pomiędzy cząstką diamentu i osnową na te energie.

W wyniku analizy otrzymanych rezultatów badań modelowych stwierdzono, że materiał osnowy odznaczający się większą granicą plastyczności zapewnia wyższe własności retencyjne osnowy. Natomiast większy moduł Younga oraz zwiększenie współczynnika tarcia, np. poprzez zastosowanie osnowy odznaczającej się powinowactwem chemicznym do węgla mają z punktu widzenia retencji diamentu mniejsze znaczenie.

1. Introduction

Powder metallurgy diamond tools are widely used for machining natural stones and other difficult to cut materials, such reinforced concrete or asphalt. In order to maintain the highest productivity of the tool at the lowest cost, the tool composition has to be properly adjusted to the workpiece properties and operating conditions. A well engineered matrix must hold the diamonds firmly and wear at a rate fast enough to discard degraded diamond grits in order to keep the tool sharp and ensure its long service. The wear resistance of the metallic matrix can be easily changed by adding soft or hard components to the powder mixture [1]. More difficult task is to control the hold on the diamond grits, which is affected by the matrix mechanical properties, mismatch between the thermal expansion coefficients of the matrix and diamond, and phenomena taking place at the diamond-metal interface. Most often the bonding between diamond crystals and matrix relies on mechanical locking. During cooling to room temperature, due to the mismatch between thermal expansion coefficients, diamond grits are tightened by the surrounding matrix wherein complex stress and strain fields occur. When coated diamond is used additional chemical bonding may occur which increases friction/adhesion at the diamond-matrix interface [2-5].

Computer aided modelling (CAM) seems to be a perfect technique to study phenomena affecting diamond

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* FACULTY OF METALS ENGINEERING AND INDUSTRIAL COMPUTER SCIENCE, AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, 30-059 KRAKOW, 30 MICKIEWICZA STR., POLAND

retention in the matrix, which has been utilised to evaluate residual stresses and local plastic deformation zones in diamond impregnated metal matrix composites [6-11]. Basing on the finite element modelling results it has been suggested that diamond retention depends on the energy of elastic and plastic deformation of the matrix around the diamond crystal. None of the above cited studies, however, did not scrutinized the effects of matrix characteristics, such as Young's modulus, yield strength, etc, on its retention properties. Therefore the main objective of the present research was to investigate the combined effects of mechanical properties of the matrix and friction between matrix and diamond on retention of the embedded grits. To this end the Abaqus software was used to create a 3-D model.

2. Experimental procedure and results

The simulations were performed on an elastic-plastic model, where the linear tetrahedral type C3D4 elements and linear hexahedral type C3D8R elements were used to generate the mesh in the matrix and diamond, respectively.

The mesh configuration is presented in Fig. 1, whereas mechanical and thermal properties of the analysed matrices are summarised in Table 1.

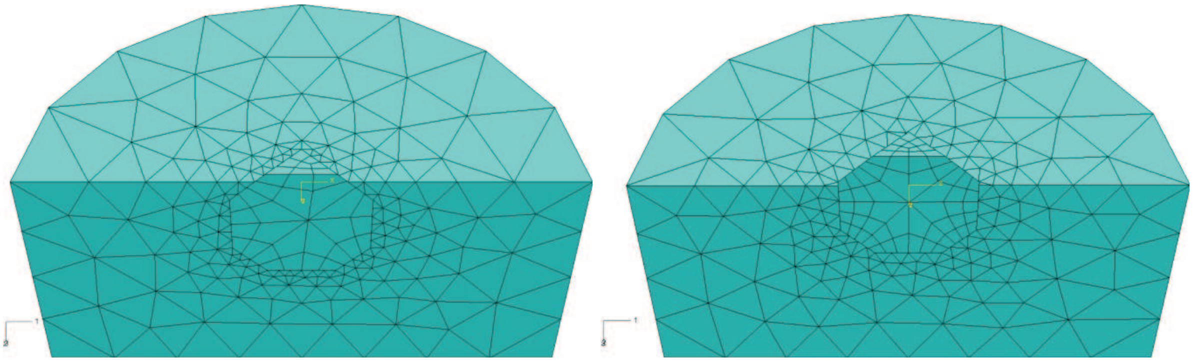


Fig. 1. Mesh used in the numerical analysis

TABLE 1

Input data used for calculations

	Diamond	Matrix
Hot pressing temperature, (°C)	850	
Thermal linear expansion coefficient, ($m\cdot K^{-1}$)	$1.05\cdot10^{-6}$ (0-1200°C)	$1.6\cdot10^{-5}$ (0-1200°C)
Poisson ratio	0.2	0.3
Young's modulus E, (GPa)	1000	160 180 200 220
Yield strength $R_{0.2}$, (MPa)	–	350 500 650 750
Tensile strength, (MPa)	–	900
Strain, (%)	–	10
Size, (μm)	350	–
Height of diamond protrusion*, (μm)	25 100	–
Friction coefficient μ at diamond-matrix interface	0; 0.2; 0.4; 0.6; 0.8; 1.0	

* – *the height of diamond projected out over the matrix level*

To simplify calculations it has been assumed that the matrix is an ideally plastic material which retains its room temperature properties up to the hot pressing temperature. The thermal properties of diamond were taken from ref [12]. It has been assumed that the matrix expands thermally in a similar manner to cobalt, widely used as a matrix in the diamond tools industry.

As already mentioned, the potential retention properties of the matrix can be associated with energies of its local deformation. Therefore the following energies were calculated:

- total strain energy of the matrix being the sum of elastic and plastic deformation energies (ALLIE),
- energy dissipated by plastic deformation of the matrix (ALLPD),
- recoverable strain energy accumulated in the diamond grit (RSE).

During the cooling step the matrix grips the embedded diamond thus generating a complex residual stress field in the crystal. It is postulated that the higher stress is generated in the diamond grit the better is the hold on the grit by the matrix (better diamond retention). Hence RSE becomes the key parameter used to assess retention.

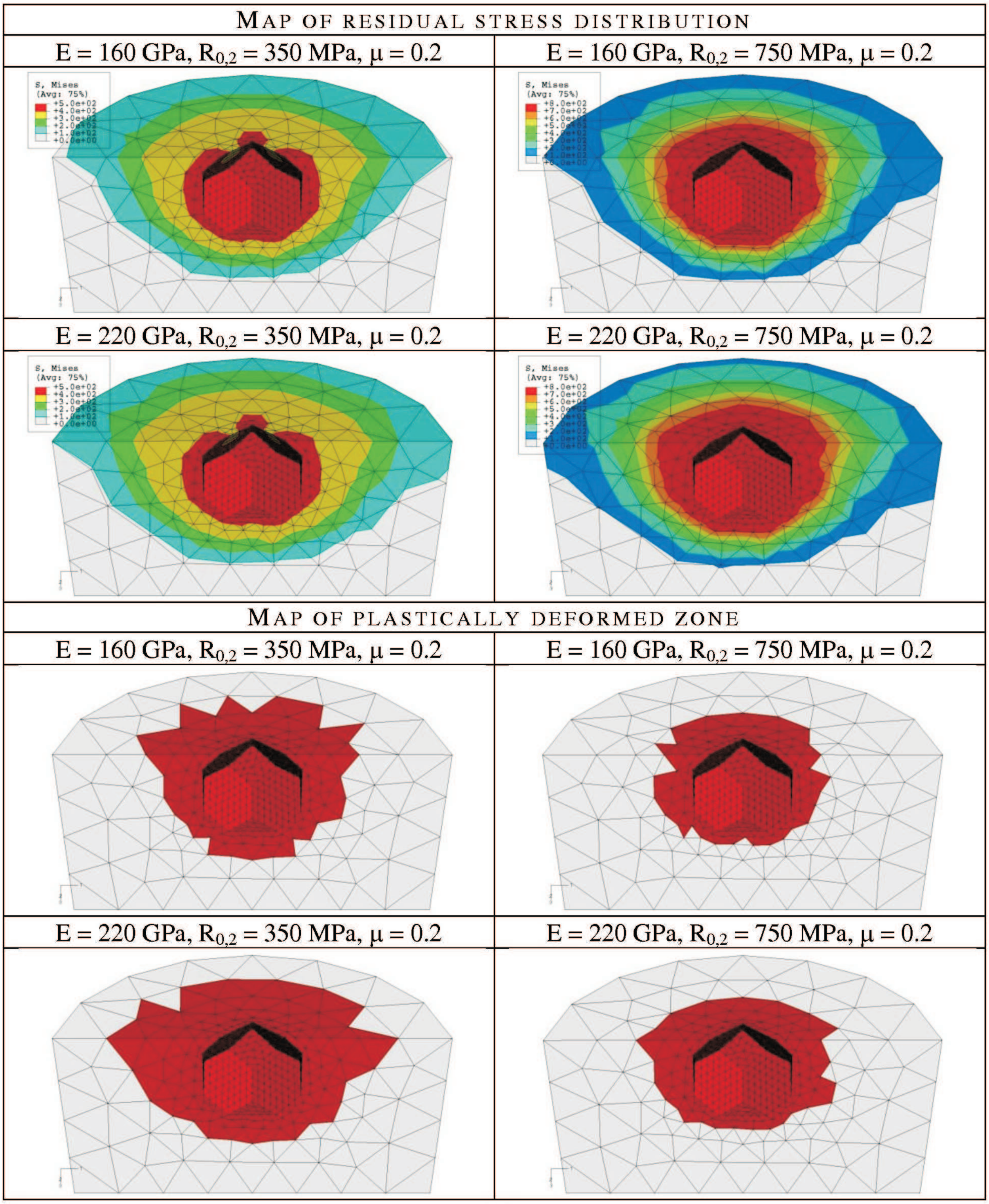
The other two energies (ALLIE and ALLPD) being accumulated in the matrix may, presumably, have an effect on its deformation when the tool is being exploited, i.e. when the diamonds are loaded.

All investigated parameters were calculated for each combination of mechanical properties of the matrix and friction coefficients. Examples of maps showing distribution of stress/strain generated around diamond crystals are presented in Figs 2 and 3. The calculated values of ALLIE, ALLPD and RSE are summarised in Tables 2-4 and graphically analysed in Figs 4-6.

TABLE 2

Total strain energy ALLIE $(\times 10^{-3}\ mJ)$

Friction coefficient μ = 0 (frictionless)								
Yield strength, MPa	Young's modulus, GPa				Young's modulus, GPa			
	160	180	200	220	160	180	200	220
	Diamond protrusion 25 μm				Diamond protrusion 100 μm			
350	126.7	131.4	135.9	139.5	59.2	61.6	63.7	65.6
500	150.9	157.3	162.5	167.6	69.2	72.5	75.4	77.9
650	169.9	177.9	185.1	191.1	76.6	80.5	84.1	86.7
750	180.8	189.2	196.4	204.2	80.0	84.6	88.6	91.6
Friction coefficient μ = 0.4								
350	129.1	133.9	138.2	142.2	61.6	63.9	66.1	68.0
500	154.3	160.7	166.4	171.5	72.4	75.5	78.4	81.0
650	173.9	182.0	189.1	195.4	80.2	84.0	87.7	91.3
750	184.6	193.7	201.8	209.0	84.1	88.2	92.4	96.1
Friction coefficient μ = 0.8								
350	130.0	135.1	139.1	142.9	62.4	64.9	66.9	68.9
500	155.5	161.9	167.6	173.1	73.5	76.8	79.7	82.1
650	175.5	183.6	190.7	197.0	81.6	85.8	89.4	92.7
750	186.4	195.6	203.7	210.8	85.5	89.8	94.5	97.7



MAP OF RESIDUAL STRESS DISTRIBUTION

$E = 160$ GPa, $R_{0,2} = 350$ MPa, $\mu = 0.2$

$E = 160$ GPa, $R_{0,2} = 750$ MPa, $\mu = 0.2$

$E = 220$ GPa, $R_{0,2} = 350$ MPa, $\mu = 0.2$

$E = 220$ GPa, $R_{0,2} = 750$ MPa, $\mu = 0.2$

MAP OF PLASTICALLY DEFORMED ZONE

$E = 160$ GPa, $R_{0,2} = 350$ MPa, $\mu = 0.2$

$E = 160$ GPa, $R_{0,2} = 750$ MPa, $\mu = 0.2$

$E = 220$ GPa, $R_{0,2} = 350$ MPa, $\mu = 0.2$

$E = 220$ GPa, $R_{0,2} = 750$ MPa, $\mu = 0.2$

Fig. 2. Example of stress and strain distribution calculated for diamond protrusion of 25 μm

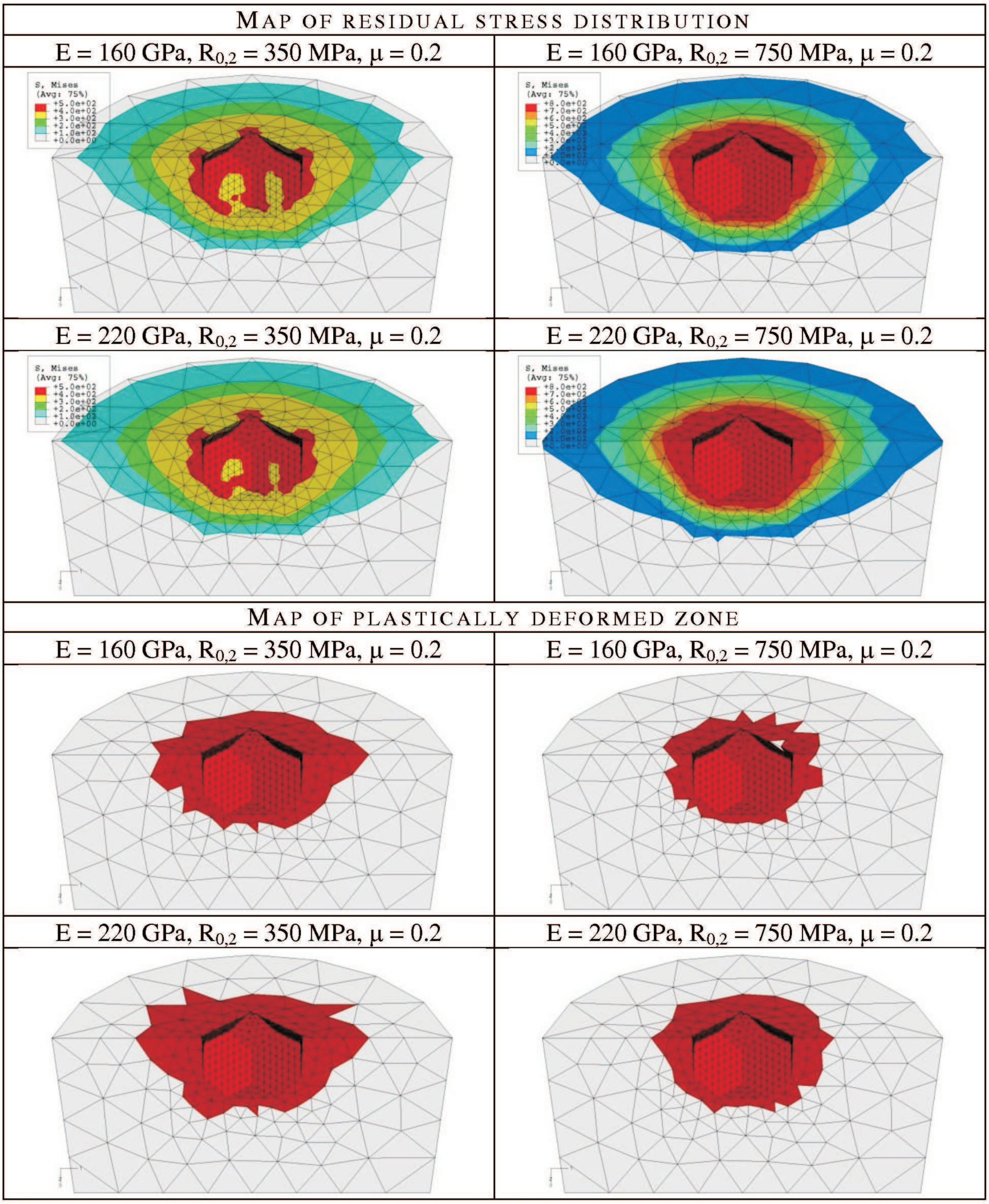


Fig. 3. Example of stress and strain distribution calculated for diamond protrusion of 100 μm

TABLE 3

Energy of plastic deformation – ALLPD $(\times 10^{-3}\ mJ)$

Friction coefficient μ = 0 (frictionless)								
Yield strength, MPa	Young's modulus, GPa				Young's modulus, GPa			
	160	180	200	220	160	180	00	220
	Diamond protrusion 25 μm				Diamond protrusion 100 μm			
350	81.9	86.9	91.5	95.3	36.1	38.6	40.8	42.7
500	90.3	97.0	102.5	107.8	37.8	41.5	44.6	47.4
650	93.9	102.4	109.8	116.5	36.8	41.2	45.4	48.6
750	94.1	103.7	111.5	119.8	35.0	39.9	44.4	48.2
Friction coefficient μ = 0.4								
350	83.9	89.0	93.5	97.6	38.0	40.4	42.7	44.8
500	92.9	99.6	105.7	111.1	40.0	43.6	46.9	49.7
650	97.1	105.6	113.1	119.7	38.8	43.2	47.5	51.6
750	97.3	107.3	115.9	123.4	37.0	41.6	46.4	50.8
Friction coefficient μ = 0.8								
350	84.6	89.8	94.2	98.1	38.6	41.2	43.4	45.4
500	93.9	100.6	106.6	112.3	40.9	44.6	47.9	50.6
650	98.5	106.9	114.4	121.0	39.9	44.7	48.9	52.7
750	98.9	108.9	117.4	124.9	38.0	42.8	48.1	52.1

TABLE 4

Recoverable strain energy – RSE $(\times 10^{-3}\ mJ)$

Friction coefficient μ = 0 (frictionless)								
Yield strength, MPa	Young's modulus, GPa				Young's modulus, GPa			
	160	180	200	220	160	180	200	220
	Diamond protrusion 25 μm				Diamond protrusion 100 μm			
350	6.7	7.2	7.7	8.1	4.0	4.3	4.6	4.9
500	9.7	10.5	11.2	11.8	5.9	6.3	6.7	7.1
650	12.7	13.7	14.7	15.6	7.8	8.4	8.9	9.4
750	14.8	15.9	17.1	18.2	9.0	9.7	10.4	11.0
Friction coefficient μ = 0.4								
350	6.7	7.2	7.7	8.1	4.2	4.5	4.8	5.0
500	9.8	10.5	11.2	11.9	6.2	6.6	7.0	7.4
650	12.9	13.9	14.9	15.8	8.3	8.9	9.5	10.0
750	15.1	16.2	17.4	18.5	9.7	10.4	11.1	11.8
Friction coefficient μ = 0.8								
350	6.8	7.3	7.7	8.2	4.2	4.5	4.8	5.1
500	9.9	10.6	11.3	12.0	6.3	6.7	7.1	7.5
650	13.0	14.1	15.0	15.9	8.4	9.0	9.6	10.1
750	15.2	16.4	17.5	18.6	9.8	10.5	11.2	11.8

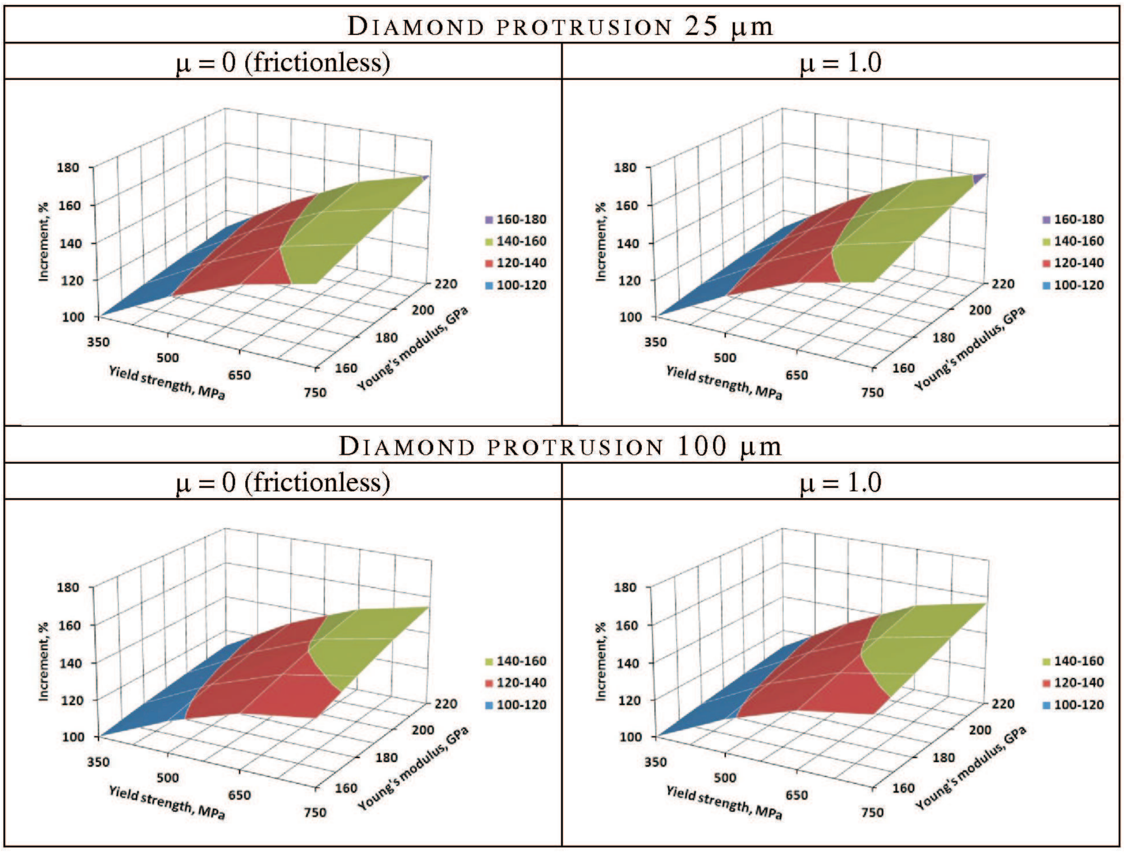


Fig. 4. The effect of friction and diamond protrusion on ALLIE

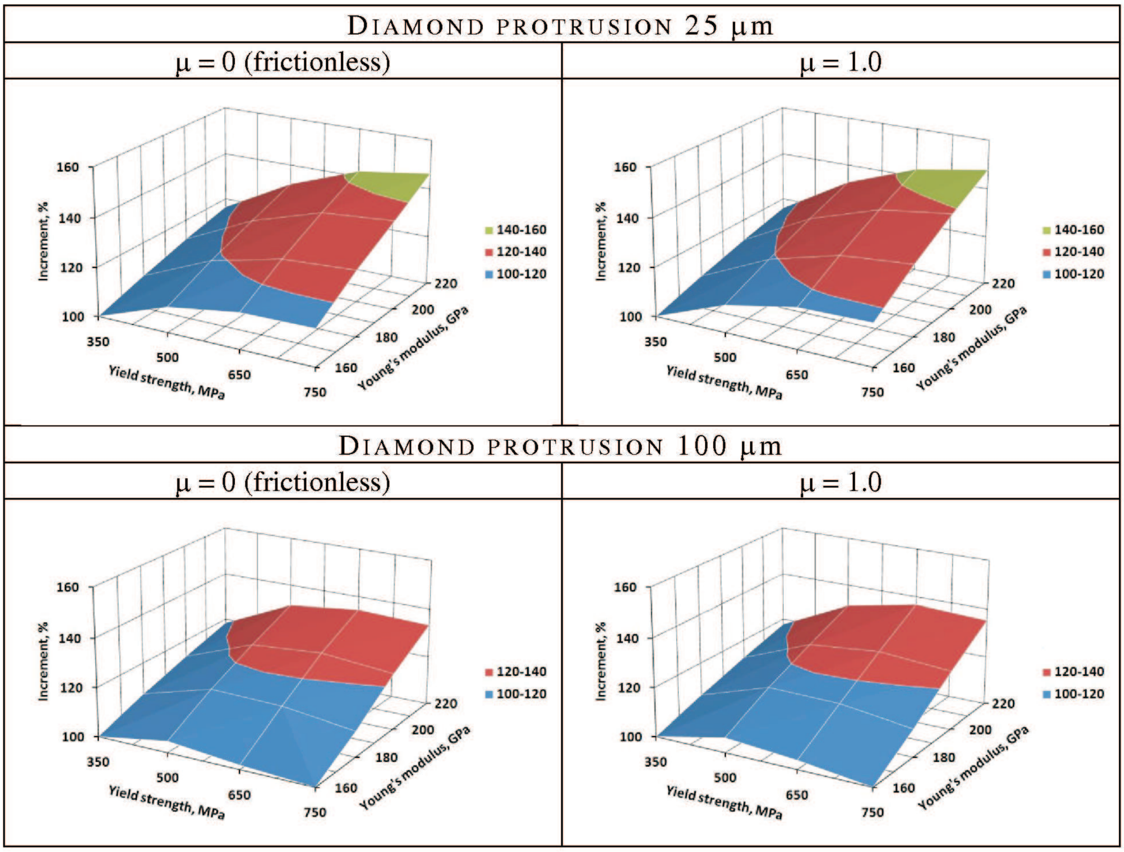


Fig. 5. The effect of friction and diamond protrusion on ALLPD

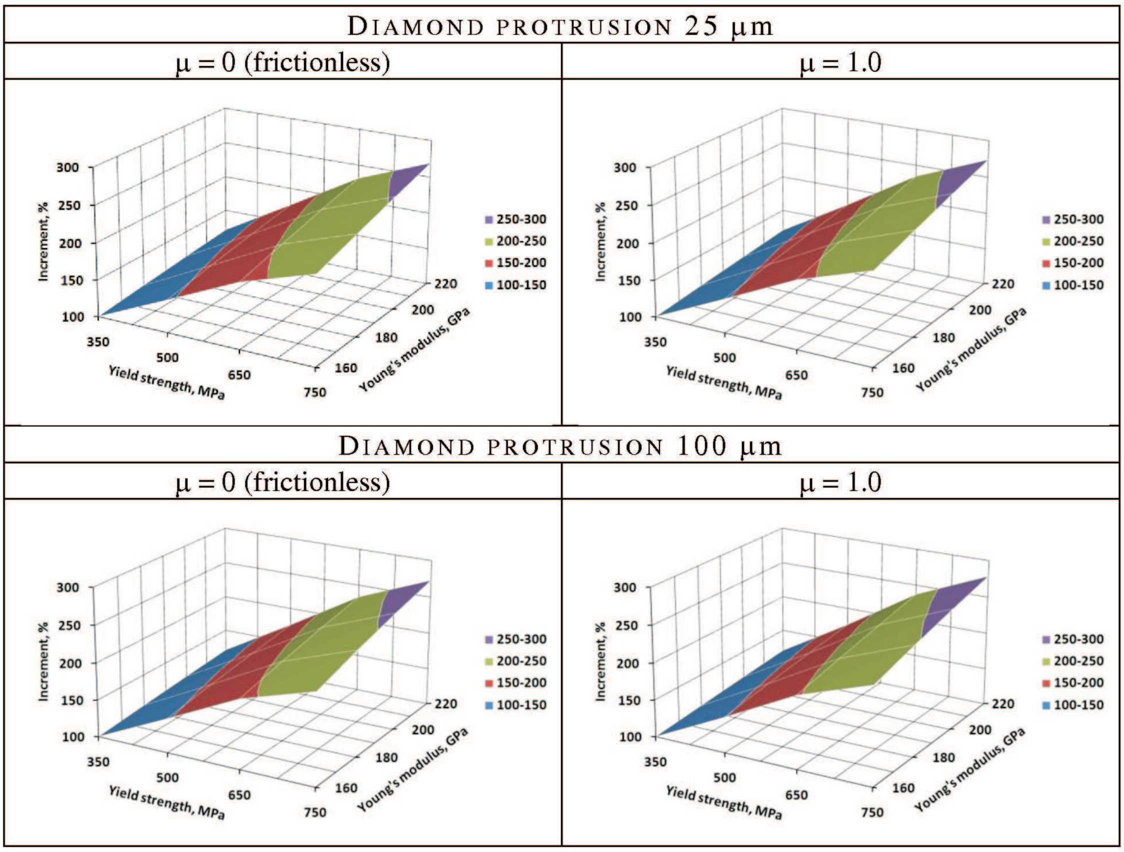


Fig. 6. The effect of friction and diamond protrusion on RSE

3. Discussion and concluding remarks

As seen in Figs 2 and 3 the local stress is proportional to the yield strength of the matrix, whereas the size of plastically deformed zone shows the inverse trend.

From Tables 2-4 it is evident that ALLIE markedly increases with the yield strength and Young's modulus while the effect of friction can be neglected. The effect of yield strength on ALLIE is more pronounced for lower diamond protrusion and the opposite situation is seen for Young's modulus. Interestingly, the effect of the coefficient of friction increases by a factor of ~2.5 as the height of diamond protrusion rises from 25 to 100μm.

Contrary to ALLIE, ALLPD is mainly affected by Young's modulus, and its dependence on yield strength is markedly weaker.

It is noteworthy that RSE strongly depends on the yield strength of the matrix whereas the other two factors are of secondary importance.

All in all, the generated data indicate that ALLPD and RSE are mainly influenced by Young's modulus and yield strength, respectively, whereas both these properties equally affect ALLIE. The variation of friction coefficient between 0÷1 has negligible effect on the calculated energies, especially for low diamond protrusion. It should be noted, however, that coated diamonds are chemically bonded to the matrix and the friction coefficient may attain values markedly higher than analyzed in this work. In such a case the role of friction must not be ignored.

The calculated energies apparently depend on the height of diamond protrusion (Tables 2-4). It seems reasonable to assume that the working height of diamond protrusion is above 100μm [13] and, therefore, the results obtained for this value suggest that the factors which contribute to improved diamond retention can be ranked in order of decreasing importance as follows:

1. yield strength of the matrix – which markedly affects RSE thus enhancing the hold on unloaded diamond crystals
2. Young's modulus of the matrix – which markedly affects ALLPD and may potentially constrain plastic deformation of the matrix around loaded diamonds
3. friction coefficient at the matrix/diamond interface – which has a minor effect on the calculated energies within the range from μ=0 to 1.

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