Abrasive Machining Of Metal Matrix Composites

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Abstract: *The current technologies of Metal Matrix Composites abrasive machining for aviation and automotive industries were described. The results of carried out cut-off tests of aluminium composites reinforced with Al2O3 and Si3N4 particulates were discussed. The machine tools employed for this purpose were given. The characteristic of the diamond grinding wheels, made in the Institute of Advanced Manufacturing Technology for this task, were given.*

Key words: *abrasive machining, diamond grinding wheel, cutting-off, grinding machine*

1. Introduction

Contemporary materials for, especially, aviation and automotive industries include metal-ceramic composites with matrices of aluminium, magnesium, titanium and their alloys and superalloys – which presents problems with the shaping of products' external and internal surfaces. In recent years there have been numerous applications for the metal composite materials (MMC's) in manufacturing the aviation components such as: the frames and casings, turbofan rotors and compressor blades [1, 9, 12] and in producing the automotive parts – the brake discs, internal combustion engine pistons, drive shafts in some sport cars, and various light trucks, pump and differential housings, brake callipers, and pulleys [2, 4, 8, 9, 12]. One of the major barriers to the use of MMC's in the motorization industry is the high cost of final machining the castings, e.g. of the brake rotors.

Semi-production techniques can involve casting, forging, rolling, sintering, Rapid Prototyping, Rapid Tooling, abrasive machining, deburring with abrasive brushes [11, 12], ultrasonic-abrasive machining, machining with tools possessing defined edge geometry, erosion machining, electrochemical machining, grinding with tools with and without a bond, water-jet, abrasive water-jet and other hybrid machining methods have also been used. For cutting hard-to-work materials, cut-off machines were used and, for materials conducting electrical current, electro-chemical abrasive cut off grinding (e.g. employing machines from Chevalier and Everite companies) [11]. The cutting of composite materials by circular, straight and band saws is uneconomic because of very short cutting edge lives. The difficult machining characteristics of MMC's are the result of the two phase microstructure consisting of the relatively soft and ductile continuous aluminium alloy matrix reinforced by hard ceramic particles (e.g. B, SiC, SiC-TiAl) of the average size from 8-25 microns up to 45 microns or larger [8]. The machining of these materials is related to a discontinuous cutting process. Then the edge contacts alternatively soft and hard phases, which makes impossible use of high abrasive resistant tool materials, because of their embrittlement. Tool materials with a good ductility are sensitive to abrasive wear, being worn by hard silicon crystals.

Cemented carbides have a good ductility and good resistance to abrasive wear, but aluminium [11] covers theirs surfaces, which induces deterioration of the cutting process. Machining of aluminium, titanium and magnesium alIoys and high-alIoy steels is facilitated by tools coated by films with very low friction coefficient and low tendencies to cover workpiece materials and to edge attack of the surface.

The basic problems of machining metal composite materials (MMC's) is intensive edge's wear [5-9, 11, 12], induced by hard ceramic phases with high abrasive properties. Additionally to edge's wear, other very important factors relate to avoiding stresses, cracking and other damage of the matrix phase in the product surface. For machining aluminium composites and aluminium alloys, only use of tools with diamond edges has resulted in long edges lives and short machining times [5-9, 11, 12]. According to Teti [6], future altemative for PCD edges would be tools with edges coated by thick diamond films using the CVD method. Hardness of polycrystalline diamond films (PCD) with bond phase (6,000 HV) is smaller than the CVD diamond film hardness, because of lack of a bond phase. Investigation of the turning and milling of AlSi9Cu3 / 20% SiC (aluminium alloy composite with 20 vol % SiC particles) confirmed higher wear resistance of the edge with CVD diamond film than of the PCD edge [6].

2. Purpose and range of research

Research works regarding the metal matrix composite machining were undertaken in Poland for the first time. The aim was selection of tools, machine tools, conditions and parameters of machining aluminium composite castings AlSi7Mg with 20 vol. % SiC particles, suitable for brake discs, and ceramic preforms of Al_2O_3 in AlSi9Mg alloy, formed by pressure squeeze infiltration, which imitates the piston head of internal combustion engine [3].

The important role at the cast composite machining were run with cut-off processes (the castings gating system cutting-off, cutting-out and slicing the samples for investigation, grinding the final samples for the tensile tests, cutting-through of the worn parts at the recycling processes).

The choice of cut-off technology, grinding machine and tools depended on overall dimensions of cast and cast mass , kind of composite materials, geometrical accuracy requirement and quality of surface area after cut-off process.

3. Research process

3.1. Methodics of investigations

To cut-off the castings of MMC's, manufactured at the Foundry Institute, were employed at the Institute of Advanced Manufacturing Technology (IAMT) the diamond grinding wheels with resinous and metals bonds. Taken into account were the following characteristics of wheels: type of body material, size of abrasive layer, grain size, concentration of grains, bond wheels hardness, wheel speed and type of the cutting fluid. Type and grade of diamond grains for the wheels were selected on the basis of knowledge and experience of the research team.

The investigation of cut-off process of sample of ceramic preforms of Al_2O_3 in AlSi9Mg were undertaken on the universal tool grinding machine (3E642 type)with manual feed and on the semi-automatic diamond cut-off machine PDPB 250 type using different diamond wheels for comparison of the cut-off process efficiency, wear volume of wheels and surface quality of the machined workpieces (Fig 1). The plates being cut-off from the aluminium composite castings were assigned for preparing the samples for strength properties testing on a tensile machine at the Foundry Institute.

The cut-off process on the 3E642 grinding machine was carried out using a diamond wheel with resinous bond of the 1A1R 150x1,3x5xx32 D126 C100 B designation with constant speed of grinding v_s = 23,5 m/s, constant speed of feed v_f = 23,4 mm/min and depth of infeed a_p = 1; 2,5; 5; 10 mm. The cut-off tests were performed using oil emulsion as a grinding lubricant.

The cut-off process on the diamond cut-off grinding machine PDPB 250 type (designed and manufactured in IAMT) was performed using diamond wheels with resinous bond of the 1A1R 150x1.0x5x32 D151 C100 B designation with grinding speed v_s = 19.9 m/s, feed speed v_f = 25 mm/min, infeed speed a = 3 mm/per pass. The cut-off tests were carried out with intensive cooling (with 2 % solution of Synkon PGA concentrate in a tap water).

Measured were: power *N,* mass of a material to be ground *m,* dimension of wheels *D* and the time of the cut-off process, t_m. Calculated were: volume of grinding material V_w, wear volume of wheels V_s, radial volume of wheels Δr_s, diamond mass wear *A*, wear rate of wheels Q_s, grinding ratio *G*, diamond relative wear rate q_p, material removal rate Q_w and the average cutting cost of wheels during the process, PLN/cm^2. The results are given in Tables 1 and 2 and shown on diagrams (Fig2).

To measure the topography of the workpiece surface and the analysis of roughness and waviness profile the profilometer TOPO 01 vP of IZTW was employed. Metallographic investigations of superficial surface (structure analysis, X-ray microanalysis) were conducted using a new generation JOEL scanning microscope JSM-6460LV with an EDS system. To determine microhardness, the FM-7 Future Tech digital microhardness tester was used.

3.2. Research process

Preparation process of samples of Al_2O_3 based and Si_3N_4 based ceramic preforms of different porosities, infiltrated with Al, AlSi9Mg alloy (AK9) and AlSi12CuNi Mg (AK12), were shown in Fig. 1. Castings pressed together with ceramic preforms on Al_2O_3 base of diameters ∅66mm x 16 mm were turned from the frontal side with the cemented carbide tipped knife, until the ceramic perform is revealed and on the sample circumferences of 80 mm diameter, to obtain cylindrical_surface on the length of 30-35mm approx. The pressed castings with ceramic performs of VII, VIII and IX (Fig 6a-c) batch were turned in the same way (Fig 6f).

Turning was performed at the following parameters: cutting speed v_c = 112 m/min, feed v_f = 0.6 mm/rev., depth of cut a_p = 0.5 mm/per pass.

The ∅78 x 28 mm discs of Al and Al alloys (AlSi9Mg) were cut-off from the high conical shaped castings in the perpendicular plane to the casting axis (Fig1a). The sample plates of 5mm width, were cut-off from the discs using two types of the grinding machines, for comparison: the universal grinding-sharpening machine (3E642 type) with manual feed, which was equipped with stepless grinding wheel drive, (parameters: v_c = 23.5m/s, v_t = 23.4 mm/min, a = 10mm/per pass) and on semi-automatic diamond grinding-cutting off machine (PDPB type) with hydraulic feed (Fig. 1e). The cut-off process was performed using diamond wheels with resinous and metal bonds. These grinding wheels have been manufactured in the Institute of Advanced Manufacturing Technology under the own technological descriptions, specially for this investigation.

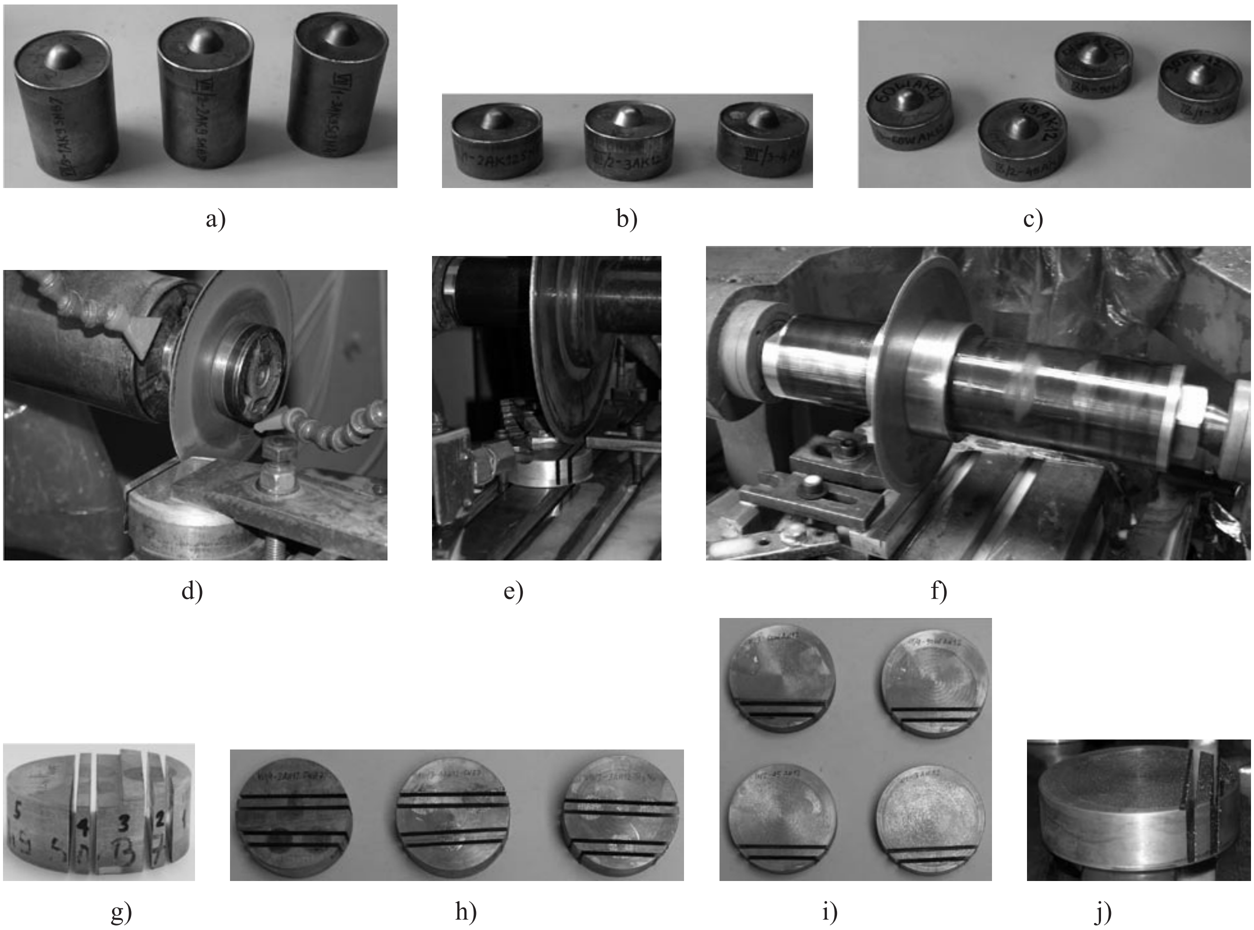

Figure 1 The method of samples preparation to the tests from the castings of a conical shape made of AlSi9Mg (AK9) and AlSi12CuNiMg (AK12) alloys with the ceramic performs ∅66 x 16 mm, based on Al_2O_3 and with the Si_3N_4 based ceramic preforms (with outside diameters of 18; 19; 22 mm):
a – the castings of VII batch with Si_3N_4 preforms being impregnated with AlSi9Mg alloy; b – the castings of VIII batch with Si_3N_4 preforms being impregnated with AlSi12CuNiMg alloy; c – the castings of IX batch with Al_2O_3 preforms being infiltrated with AlSi12CuNiMg alloy; d – the specimen with thickness of 5 mm from a disc sample cut-off operation on the 3E642 grinding machine using diamond cut-off wheel of ∅150 mm diameter with resinous bond; e – the specimen with thickness of 5 mm from a disc sample cut-off operation on the semi-automatic diamond cutting off machine PDPB 250 using diamond cut-off wheels of ∅250 mm diameter with metal bond; f – the plate with thickness of 3.2 mm from a centre bar (I batch) cut-off operation on the PDPB 250 cutting-off machine using diamond cut-off wheels of ∅150 mm diameter with resinous bond; g – the casting No. VII/3-AK9 SNB7 with three preforms made in IAMT after cutting-off operation into 5 slices; h – the castings of VIII batch with three Si_3N_4 preforms made in IAMT after cut-off operation; i – the castings with Al_2O_3 preforms after cut-off process on the PDPB machine using diamond metal bonded cut-off wheels; j – the disc from IX batch of castings after cut-off process on the PDPB 250 grinding machine using diamond metal bonded cut-off wheels.

Surfaces of samples of the aluminium castings with ceramic preforms after cutting were subjected to initial testing to determine the machined surface quality. The samples surface roughness measurements were carried out using the TOPO 01vP profilometer made in IZTW. Surface measurements were performed with the use of the BS1000 measuring head without a slide, of the tip roundness radius of 2 μm and 90° angle. Surface geometrical structure parameters were determined according to the PN-EN ISO 4287 Standard – primary profile parameters: *Pz*, *Pt*, *Pa*, roughness parameters: *Rz*, *Rt*, *Ra*, – for filtered profile (Lc = 0.8 mm filter) and waviness parameters: *Wt* – to determine the surface shape. Samples mass measurements have been performed every time prior to and after machining using the Radwag WPT 5 laboratory electronic balance of 2 g measurement accuracy. Grinding wheel diameter measurements have been done before and after cut-off process of each sample using electronic calipers of 0.01mm measurement accuracy.

The metallographic investigation of samples after cutting-off (structural analysis, surface analysis, microphotography) were performed with use of the JSM 6460 LV scanning electron microscope. The 20 kV acceleration voltage was applied and specimens were tested with the use of a high vacuum technique (H.V.).

4. Results of research

The results of cutting-off the aluminium composites locally reinforced with Al_2O_3 based preforms (Fig. 1d) using diamond cut-off wheel of designation 1A1R 150x1.3x5x32 D126 C100B being manufactured in IAMT were given in Table 1 and shown on diagrams in Fig. 2.

Table 1. The statement of results of composites with the preform samples on Al_2O_3 base, infiltrated with AlSi9Mg aluminium alloy, cutting-off with resinous diamond grinding wheel 1A1R 150x1.3x5x32 D126 C100 B, with cutting speed v_c = 23.5 m/s.

Quantity	**Designation, unit**	**No. of batch / No. of sample**					
		I / 1	**I / 2**	**I / 3**	**I / 4**	**I / 5**	**I / 6**
Infeed (depth of material layer being ground during one pass of the grinding wheel)	a_p, mm	1; 2.5	2.5	2.5	5; 10	10	10
Input power (input power mean value by the grinding wheel one pass)	*N*, kW	0.88	1.236	1.182	1.10	1.007	1.033
Mass of the ground (removed) material	*m*, g	13.0	12.6	11.4	11.4	12.0	12.4
Volume of the ground material (Material removal)	V_w, mm³ (cm³)	4,790 (4.79)	4,790 (4.79)	4,170 (4.17)	4,200 (4.20)	4,400 (4.40)	4,570 (4.57)
Volumetric grinding wheel wear	V_s, mm³	220.20	228.11	238.85	154.59	171.89	247.90
Grinding wheel radial wear	Δr_s, mm	0.73	0.76	0.80	0.52	0.58	0.84
Diamond mass wear rate	*A*, mg	193.60	200.64	210.14	136.05	151.27	218.15
Time of cutting-off (without se tup times ts)	t_m, min	15.84	15.66	12.0	7.17	13.85	8.5
Grinding wheel wear rate	$Q_s = V_s / t$, mm³ / min	27.78	29.12	19.90	21.61	12.41	29.16
Grinding ratio	$G = V_w / V_s$, mm³/ mm³	21.77	20.29	17.38	27.17	25.59	18.43
Diamond relative wear rate	q_p, mg / g	14.89	15.92	18.43	11.93	12.61	17.59
Material removal rate	$Q_w = V_w / t$, mm³ / min	302.65	295.60	347.08	585.77	317.55	537.41
Diamond cut-off wheel wear cost mean value	PLN/cm²	1.24	1.27	1.48	0.96	1.06	1.46
Surface roughness measurement results (on sampling length 4 mm)	*Ra*, μm *Rz*, μm *Rt*, μm	0.1173 0.8883 1.7303	0.229 1.8435 3.1311	0.2748 1.678 2.3241	0.367 1.8595 2.3129	0.1472 1.017 1.6496	0.090 0.7755 1.3485

Table 2. The statement of results of composites with the preform samples on Al_2O_3 base, infiltrated with AlSi9Mg aluminium alloy, cutting-off with resinous diamond grinding wheel 1A1R 150x1.0x5x32 D151 C100 B, with cutting speed v_c = 19.9 m/s.

Quantity	Designation, unit	No. of batch / No. of sample					
		I / 1	I / 2	I / 3	I / 4	I / 5	I / 6
Infeed (depth of material layer being ground during one pass of the grinding wheel)	a_p, mm					3,8	3,8
Input power (input power mean value by the grinding wheel one pass)	N, kW	0.48	0.48	0.48	0.48	0.48	0.48
Surface cross-section being cut-off (L x H) L = 78 mm; H = 15 mm	F, cm^2 (mm^2)	1.17 1,170	1.17 1,170	1.17 1,170	1.17 1,170	1.17 1,170	1.17 1,170
Mass of the ground (removed) material	m, g	16.14	16.17	16.,23	16.06	16.20	15.,98
Volume of the ground material (Material removal)	V_w, cm^3	5.96	5.95	5.95	5.92	5.93	5.90
Volumetric grinding wheel wear	V_s, mm^3	103.67	129.20	128.76	128.34	153.44	203.61
Grinding wheel radial wear	Δr_s, mm	0.2	0.25	0.25	0.3	0.3	0.4
Diamond mass wear rate	A, mg	91.2	113.70	113.31	112.90	134.99	179.17
Time of cutting-off (without se tup times t_s)	t_m, min	57	58	69	50	62	48
Grinding wheel wear rate	$Q_s = V_s / t$, mm^3 / min	1.82	2.23	1.87	2.57	2.47	4.24
Grinding ratio	$G = V_w / V_s$, mm^3/ mm^3	57.45	46.01	46.16	46.16	38.67	28.96
Diamond relative wear rate	q_p, mg / g	5.65	7.03	6.98	7.03	8.33	11.21
Material removal rate	$Q_w = V_w / t$, mm^3 / min	104.49	102.48	86.14	118.48	95.68	122.83
Diamond cut-off wheel wear cost mean value	PLN/cm^2	0.37	0.47	0.47	0.56	0.56	0.74

The comparison of individual values of the abrasive cutting-off parameters of six samples (Table 1) indicated that the diamond mass wear rate values A were between 218.15 mg and 136.05 mg, grinding ratios G were included in the range of values from 17.38 mm^3/mm^3 up to 27.17 mm^3/mm^3, diamond relative wear q_p from 11.93 mg/g up to 18.43 mg/g, grinding wheel wear rate Q_s from 12.41 mm^3/min to 29.16 mm^3/min. Material removal rate Q_w was in the range 295.60 mm^3/min to 585.77 mm^3/min, and the mean values of unit costs of the diamond cut-off wheel wear were between 0.96 PLN/cm^2 and 1.48 PLN/cm^2. During the cutting-off a material layer of 1 – 10 mm depth was ground in one pass, and the power consumption of the grinding wheel drive motor was 0.88 – 1.24 kW.

The most encouraging results were on cutting specimen No. 4 (Table 1) on account of the lowest diamond mass wear rate A = 136.05 mg, highest grinding ratio G = 27.17 mm^3/mm^3, highest ground material removal rate Q_w = 585.77 mm^3/min, the lowest cutting-off time t_m = 7.17 min, as well as the lowest unit cost of diamond cut-off wheel wear (0.96 PLN/cm^2) relating to the cut-off surface. This can be interpreted as resulting from favourable and uniform distribution of the reinforcing phase Al_2O_3 in the specimen. It was observed that increase in the ceramic phase content favourably affects the cutting process, because gumming up of the wheel, i.e. deposition of the cut material on the wheel's cutting surface, is avoided, which process took place when cutting unreinforced aluminium.

The results of roughness measurements on castings with ceramic preforms after cutting-off, are presented in Table 1. It should be noted that *Ra, Rz, Rt* are mean values of 4 (specimen No. 2) or 5 measurements (the remaining samples) on 4 mm length. Original profile measurements carried out over a length of 35 mm showed the surface to be uneven as much as by 0.035 µm (specimen No. 2). Roughness was in the range *Ra* = 0.09 µm (specimen No. 6) to *Ra* = 0.367 µm (specimen No. 4), for the same cutting parameters. For specimen No. 6, with ceramic insert with the lowest porosity, used to reinforce the piston head, cutting resulted in the highest wheel wear, Q_s = 29.16 mm^3/min; and radial wear $\Delta r_s = 0.84$ mm.

The research works showed that during cut-off process on the PDPB 250 grinding cutting-off machine (Table 2) grinding wheel relative wear rate was smaller (for No. I/1 sample – 15.3 times, No. I/6 sample – 6.9 times) and average unit cost wheels was smaller (for No. I/1 sample – 3.35 times, for No. I/6 sample – 1.97 times, the smaller was relative power of process (for No. I/1 sample – 1.83 times, for No. I/6 sample – 2.1 times), but the time of cut-off process was longer (No. I/1 sample – 3.7 times, No. I/6 sample – 4.4 times) and the relative mass effectiveness of cut-off process Q_w was smaller (No. I/1 sample – 3 times, No. I/6 sample – 4.4 times) comparing to 3E642 grinding machine.

The results of cut-off process (Tables 1 and 2, Fig. 2) showed that grinding process was more stable with hydraulic feed (PDPB250 grinding cutting-off machine) and the grinding wheels of 1mm width of working layer with the bigger size of abrasive grain (D151) than with manual feed (3E642 grinding machine) with the grinding wheels with thickness of 1.3 mm of working layer, but with smaller abrasive grain size (D126).

5. Conclusions

Initial machining tests of aluminium composite castings, dispersive reinforced with SiC particles and locally reinforced with Al_2O_3 based ceramic preforms , were successful. Research works regarding metal matrix composite machining were undertaken in Poland for the first time. The removal and abrasive machining of MMC's can be performed effectively using diamond cutting and abrasive tools, only. The machining investigation of aluminium composites, dispersive reinforced with SiC particles or locally reinforced with Al_2O_3 and Si_3N_4 ceramic performs, showed the necessity of manufacturing special diamond cut-off wheels with resinous and metal bond. The grinding wheel characteristics must be suitable for the workpiece material properties. The microscopic (SEM, HV0.1) and microgeometric surface measurement of cut-off samples (*Pa*, *Ra*, *Wa*) confirmed it.

Wear of resin bonded diamond wheels was large, with good finish of the cut-off surfaces. In contrast, in the case of metal bonds, the wheel wear was insignificant, but there was a tendency to gumming up of the grinding wheel active surface, especially when cutting monolithic (unreinforced) layer of AlSi9Mg alloy.

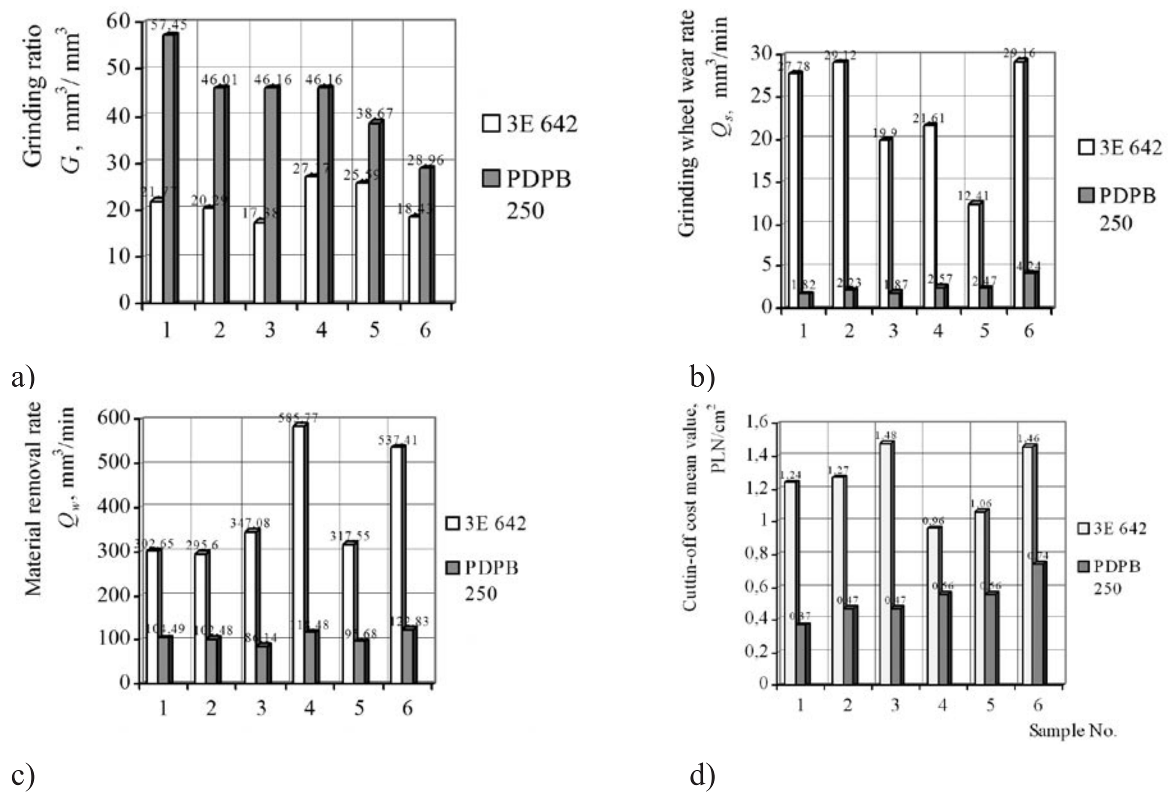

Figure 2. The comparison of wear rate of diamond cut-off wheels during cut-off process of samples with Al_2O_3 – based preform infiltrated with AlSi9Mg alloy (batch I, operation 3) on the 3E642 grinding machine with diamond wheel 1A1R 150x1.3x5x32 D126 C100 B (v_s = 23,5 m/s) and on the PDPB250 semi-automatic diamond cutting-off machine with diamond wheel type1A1R 150x1.0x5x32 D151 C100 B (v_s = 19,9 m/s).
Diagrams: a – grinding ratio *G* mm^3/mm^3; b – grinding wheel relative wear rate Q_s mm^3/min; c – material removal rate Q_w mm^3/g; d – average unit cost of the cut-off process per cm^2, PLN/cm^2 .

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Acknowledgments:

The research was conducted as part of the project PBZ-KBN-114/T08/2004, financed by the Ministry of Science and High Education of Poland: Part II.5.5: Advanced materials and mechanical working of castings, including metal-ceramic composites. The authors wish to acknowledge the assistance of Bogna Królicka, M.Sc. in performing SEM metallographic investigations and of Tatiana Miller, M.Sc. for conducting topographic measurements on specimens after machining and cutting and also of Aleksander Kowalczyk, M.Sc. in assisting in analysing the results.