Evaluation of the Applicability of Fractal Analysis to Describe the Surface of Aluminium Composites after Drilling

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The paper presents the results of the drilling of an aluminum matrix composite reinforced with ceramic fibers. The drilling process was carried out dry and with assistance from oil mist. The 3D surface roughness was measured using the contact method. A number of roughness parameters were analyzed: average, height, and statistical parameters. The box-counting fractal dimension of the hole surfaces was also determined. Correlation coefficients between the fractal dimension and roughness parameters were calculated. The fractal dimension was found to describe the irregularity of the surface. Fractal dimension values are dependent only on the drilling parameters if the process is carried out wet with the processing fluid. The fractal dimension does not correlate with surface roughness parameters such as Sa, Sq, and Sz. Some correlation was observed between it and the Sku parameter, but only after drilling with oil mist. The geometric structure of the surface after drilling does not show clear features of directionality and periodicity.

Keywords: *aluminum composites, surface roughness, geometric structure of the surface, fractal dimension, correlation*

1. INTRODUCTION

Great emphasis on ecology, moving away from fossil fuels, requirements to reduce fuel consumption, green–house gas emissions, and noise mean that modern ma–terials used in the construction of means of transport must have special properties. Therefore, newer and improved materials are being developed. A group of materials of special importance in the automotive and aerospace industries are composites. The main division of these materials is based on the type of matrix. Among metal matrix composites, the most commonly used are those based on aluminum alloys. Aluminum matrix composites (AMC) are used in a variety of engineering applications and are well known for their strength-to-weight ratio. In addition, AMCs are characterized by good stiffness, high corrosion resistance, high specific modulus, and excellent wear resistance properties [1]. The production of elements from composite materials is an important field of technology. The biggest problem in the machining of aluminum matrix composites is the abrasive effect of the reinforcement. This poses a serious threat to cutting tools. They wear much more abrasively than when machining aluminum alloys [2,3]. Therefore, it is recommended that tools be made of sintered carbide and polycrystalline diamond [4].

A separate and important problem is the making of holes in composite materials. The most well-known research issue is the delamination of composite materials. This unfavorable phenomenon occurs mainly during the machining, drilling, or milling of polymer matrix composites [5-7]. In the drilling of metal matrix composites, including aluminum, this problem is much smaller. This is related to the much higher strength of the aluminum matrix than that of the polymer matrix and the good cohesion between the matrix and the reinforcement, which is the result of the technology used to produce these composites [1,8]. Problems in making holes in aluminum composites or composite laminates are the already mentioned tool wear, dimen–sional and shape quality, and surface roughness of the holes [9]. Basically, the main method is still drilling. Dry drilling can be performed, but the life of the tool and the quality are not satisfactory and a machining fluid must be used [10]. Since flood cooling and lubri–cation increase production costs and are environmen–tally unfriendly, it is recommended to supply liquid in the form of oil mist or cryogenic drilling [10,11]. When, despite the use of cutting fluid, drilling is not effective, other supporting methods such as ultrasound can be used [12]. When tool wear is so severe that economic conditions preclude the use of conventional drilling, holes are drilled in aluminum matrix composites using unconventional methods. One of these is electrical dis–charge machining EDM [13]. The selection of electrode material is very important in this method. Copper electrodes allow the highest machining efficiency, while brass electrodes allow the obtaining of holes with the lowest roughness [14]. Small-diameter holes can be produced efficiently using laser techniques [15]. They are undoubtedly the future, but these technologies are still limited by machining efficiency and hole dimen–sions.

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In order to properly design a technological process, the manufacturing method, tools, and process parameters must be selected so that the quality, performance, and often cost requirements of the process are met. This is particularly complicated with heterogeneous materials that are difficult to machine, such as composites. Various methods such as Grey Relational Analysis [16,17] are used to optimize composite machining processes, including drilling. Such analyses are also carried out successfully in the context of drilling holes in sets or material stacks [18]. Wavelet analysis can be used for an advanced analysis of individual machinability indicators, for example, to filter cutting forces [19].

However, the greatest emphasis is placed on the correct analysis of the quality of the machined surface. The formation of the geometric structure of the surface is an extremely important issue in the process of operating machines and devices. The depth, density, and directionality of the machining marks determine the functional properties of the surface. The standard roughness parameters, depending on the direction in which they are defined, are divided into three basic groups: height, distance, and mixed (hybrid). Each parameter characterizes surface roughness in a different way, so it is impossible to get a complete picture of the complexity of the surface structure using only one indicator. The most frequently used in research are *Ra* or *Sa* in 3D measurements - the arithmetic mean of the ordinates of a profile or surface and *Rz* or *Sz* - the greatest height of the profile or surface, giving limited, averaged information. For this reason, additional methods are used to study and describe the surface. One of these is fractal analysis [20]. Fractal analysis is traditionally the characterization of complex objects found in nature by means of self-similarity properties. Mandelbrot [21] was the first to study objects in this way. A fractal is a geometric pattern or object that can be broken into smaller parts, with the individual parts appearing original and self-similar.

The assessment of surface quality is complex and the parameters for assessing surface quality do not describe the irregularity of machined surfaces [22,23]. Geometry and fractal analysis with self-affinity or self-similarity can describe complex and irregular structures, which undoubtedly include surface roughness [24]. Fractal analysis primarily involves calculating a specific dimension, called the fractal dimension, of the object or signal being analyzed [25, 26]. Many methods are known to calculate the fractal dimension. For analyzing images, graphics, and therefore surface roughness, the box method is most commonly used. It is considered the most reliable and produces the most reliable results [27]. Fractal analysis characterizes machined surfaces and distinguishes the level of surface irregularities [28,29], including aluminum composites [30]. The fractal dimension is used as a criterion in studies of thin film surfaces [31], soft layers [32], and the degree of wear of the interacting surface [33]. Interesting applications of fractal analysis include studies of the topography of the fracture surface of an object due to fatigue loading mode [34], evaluation of the fracture surfaces of rocks in mining [35], fracture resistance studies of dental ceramics [36], and roughness analysis of the martian topography [37].

The degree of complexity of machined surface roughness, especially in the case of materials such as composites, combined with the enormous quality requirements placed on such surfaces, makes the use of non–standard methods to describe them a necessity these days. Therefore, it was decided to investigate the possibilities of using fractal analysis and fractal dimension as a quantitative indicator to describe the quality of holes drilled in an aluminum matrix composite.

2. TESTING CONDITIONS

The object of the research was an aluminum matrix composite reinforced with long ceramic fibers. The AlSi9Mg (EN AC-43300), which is the matrix of the composite, belongs to multicomponent aluminium-silicon alloys. It is characterized by good castability and a low tendency to crack. The addition of magnesium causes precipitation hardening, positively influencing the strength properties of the alloy. It can be heat treated to further improve mechanical properties. The AlSi9Mg alloy is used primarily to make large castings with complex shapes and high strength. For example, gearbox casings and transmission housings are cast from them. Moreover, this material is characterized by high resistance to corrosion and seawater, very good weldability, and good machinability.

The composite is reinforced with ceramic fibers called Saffil produced by the British company ICI Saffil, consisting of Al_2O_3 (96-97%) and SiO_2 (3-4%). The diameter of the fibers used was 3-4 μm. These fibers are characterized by resistance to high temperatures (melting point 2320^{o}C, maximum working temperature 1600^{o}C), high tensile strength 2000 MPa, and a high coefficient of longitudinal elasticity. Such properties make it a high-strength material and it is commonly used to reinforce aluminium matrix composites. Ceramic reinforcement increases the hardness and tensile strength of the composite compared to the matrix material.

Figure 1. A device for producing oil mist

Drilling tests were carried out on a radial drilling machine, type Csepel RF 50/1250. The stand was also equipped with a device for minimized lubrication MQL - Minibooster by Accu-Lube (Fig. 1).

The cooling and lubricating liquid in the form of an aerosol was supplied externally using two nozzles located close to the drill (Fig. 2). The liquid flow rate was 180ml/h. A 6537 VHM drill with a diameter of 9.9 mm was used to machine the holes. It was a carbide drill coated with TiAlN. Three cutting speeds were used in the drilling tests v_c = 11; 22; 44m/min and 4 feeds f = 0.05; 0.075; 0.112; 0.17 mm/rev.

As part of the research, a 3D measurement of the machined surface was performed. For this purpose, a multifunctional Mitutuyo SURFTEST SV - 3200 profilographometer (Fig. 3) was used.

Figure 2. Composite drilling station with external oil mist supply

Figure 3. SURFTEST SV – 3200 device for measuring surface roughness

The machined surface analyzer was equipped with a measuring tip, a detector that, operating on the differential-inductive measuring principle, measures 2D roughness parameters. The use of additional equipment in the form of a positioning table on the Y axis and the use of 2D roughness measurement data on the X axis allows the obtaining of a high-quality 3D surface topography of the tested element.

The measurement range of the device on the X-axis is 100 mm and the column height is 500 mm. The detector pitch value is set at 800 µm. The measuring tip was made of diamond. The radius of its rounded cone is 2 µm, the angle of the cone is 60° and the contact force is 0.75 mN. The profilographometer is equipped with FORMTRACEPACK software that enables 2D and 3D measurements. Analysis of the measured surfaces, calculation of roughness parameters, and fractal dimension were performed in McCube Ultimate software.

3. TEST RESULTS AND DISCUSSION

During the 3D surface roughness tests, an area of 1 mm by 1 mm was measured. The X-axis measurement step was 5 µm, and the measurement table was also moved every 5 µm. In this way, 40,000 points were recorded. The measured surfaces were subjected to a procedure including extracting a fragment of 0.95 x 0.95 mm from the measured surface (in order to eliminate possible measurement errors at the border of the examined area), leveling the surface using the least squares method, removing the shape outline using a second-degree polynomial and signal filtering (separating the waviness profile from the roughness). Roughness from waviness was separated with a Gaussian filter. The cutoff wavelength λc for the Gaussian filter was 250 µm. Then, the program calculated a number of roughness parameters in accordance with the PN-EN ISO 25178-2:2022 standard. The parameters *Sa*, *Sq*, *Sz*, *Sp*, *Sv*, *Ssk*, *Sku*, and the box fractal dimension *D* were selected for the analyses.

3.1 Fractal dimension measurement results

The dimension commonly used in fractal analysis of surface topography is the box dimension. Measurements can be made for both profiles and three-dimensional spaces. The idea of this method is simple and involves applying a regular grid of fixed sizes to the measured structure. Depending on the dimension examined (2D / 3D), the elements take the form of squares or cubes, boxes, with a constant size ε. The number of elements in which the measured structure N(ε) occurs is then counted. This process is repeated for a smaller size ε and a graph of ln(N(ε))/ ln(ε) is plotted.

The work uses the method of calculating box dimensions called enclosing boxes. The method consists of enclosing each surface area by a cube of side ε and calculating the area Vε of all the boxes enclosing the whole tested surface roughness. This procedure is iterated with boxes of different widths to build a graph ln(Vε)/ln(ε). The fractal dimension is calculated from the slope of the regression line. The accuracy of the calculations has been set to exactly. The ε value varied in the range of 25-235 µm. This is the largest range that can be set in the McCube Ultimate software. The step in which the ε value was changed in subsequent iterations was 10 µm for boxes with a side of ε of 25-135 µm and 20 µm for boxes with a side of ε of 135-235 µm. This setting determines the number of iterations and therefore the computation time.

Table 1 shows the values of the measured and calcu–lated fractal dimensions for the surfaces of the holes drilled in the tested composite. Figures 4 and 5 show graphs of changes in the value of fractal dimension depending on the feed and cutting speed.

Table 1. Fractal dimension D of the surface after drilling composite

Cutting speed v_c m/min	Feed f mm/rev	Cooling and lubrication conditions	Fractal Dimension D
11	0.05	DRY	2.51
11	0.075		2.56
11	0.112		2.33
11	0.17		2.39
22	0.05		2.48
22	0.075		2.56
22	0.112		2.49
22	0.17		2.24
44	0.05		2.48
44	0.075		2.48
44	0.112		2.4
44	0.17		2.51
11	0.05	MQL	2.66
11	0.075		2.63
11	0.112		2.56
11	0.17		2.43
22	0.05		2.58
22	0.075		2.57
22	0.112		2.55
22	0.17		2.48
44	0.05		2.51
44	0.075		2.53
44	0.112		2.57
44	0.17		2.55

Analysing Figures 4 and 5, the effect of the use of oil mist on the dependence of the fractal dimension on the cutting parameters can be clearly seen. In the case of dry drilling, the influence of cutting parameters on the value of the fractal dimension of the surface is ambiguous, while when drilling with oil mist, such an influence can be observed. After drilling with MQL, the fractal dimension and therefore the irregularity of the surface decreases with increasing drilling feed. The degree of this reduction depends on the cutting speed. At the lowest value used, the D value decreases from 2.66 for a feed of 0.05 mm/rev to 2.43 for a feed of 0.17 mm/rev and respectively, from 2.58 to 2.48 for a speed twice as high. By doubling the cutting speed again, this dependence of the fractal dimension on the feed disappears. These results partially coincide with the results of turning the tested composite. Also, after this machining, a clear decrease in the value of the fractal dimension was observed with increasing feed, especially after turning with polycrystalline diamond blades [30]. When turning, it was observed that the value of the fractal dimension is lower for the surface obtained by turning with oil mist. The surface after dry turning is more irregular, with more sudden and sharp changes in the geometric structure of the surface [30]. This effect of oil mist was not observed on the surface after drilling. This can be explained by the fact that external mist application is less effective for drilling than for turning. Oil mist fed externally close to the entrance of the drill into the hole cannot operate perfectly on the cutting edges, as occurs during turning.

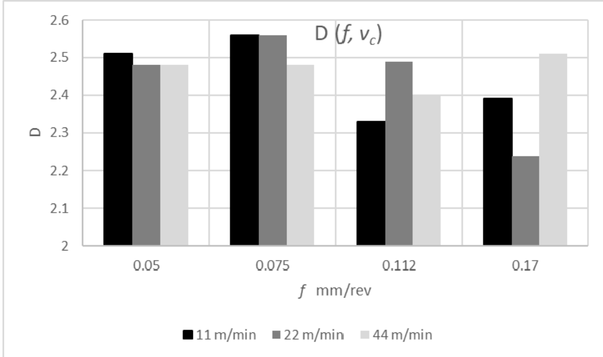


Figure 4. Influence of drilling parameters on box fractal dimension values for surfaces after composite dry drilling

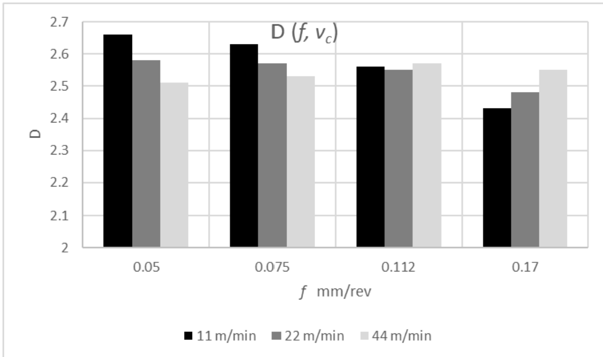


Figure 5. Influence of drilling parameters on box fractal dimension values for surfaces after composite MQL drilling

The surface after drilling is believed to not have a clearly defined geometric structure. This is due to the fact that drilling is often only preliminary processing. Only reaming gives the final quality of the holes and a unidirectional parallel structure. Drilling carried out precisely, e.g. with a low feed, also makes it possible to obtain such a structure. Figures 6-8 show the surface after dry drilling of the composite. A directional parallel structure with visible blade marks can be seen in Figures 6a and b (v_c 11m/min with f 0.05 and 0.075 mm/rev). At higher drill rotational speeds, this structure appears for feeds of 0.075 and 0.17mm/rev (Figs. 7b and d), and at the highest cutting speed for feeds of 0.112 and 0.17mm/rev (Figs. 8c and d). The surface with the smallest fractal dimension of 2.24 has the most visible directional structure, i.e. it is the most regular. However, surface images after dry drilling show nume–rous surface defects and irregularities. Unfortunately, they are not reflected in the fractal dimension values. For example, you can notice the sticking and pulling of the machined material on the surface after drilling at the lowest speed and highest feed (Fig. 6d) or after drilling at the highest speed and lowest feed (Fig. 8a). The fractal dimensions for these surfaces are 2.39 and 2.48, respectively, and these are not the highest values. The highest D values were obtained for the surfaces in Figures 6b and 7b. Only on the second of these surfaces are its defects and unevenness visible.

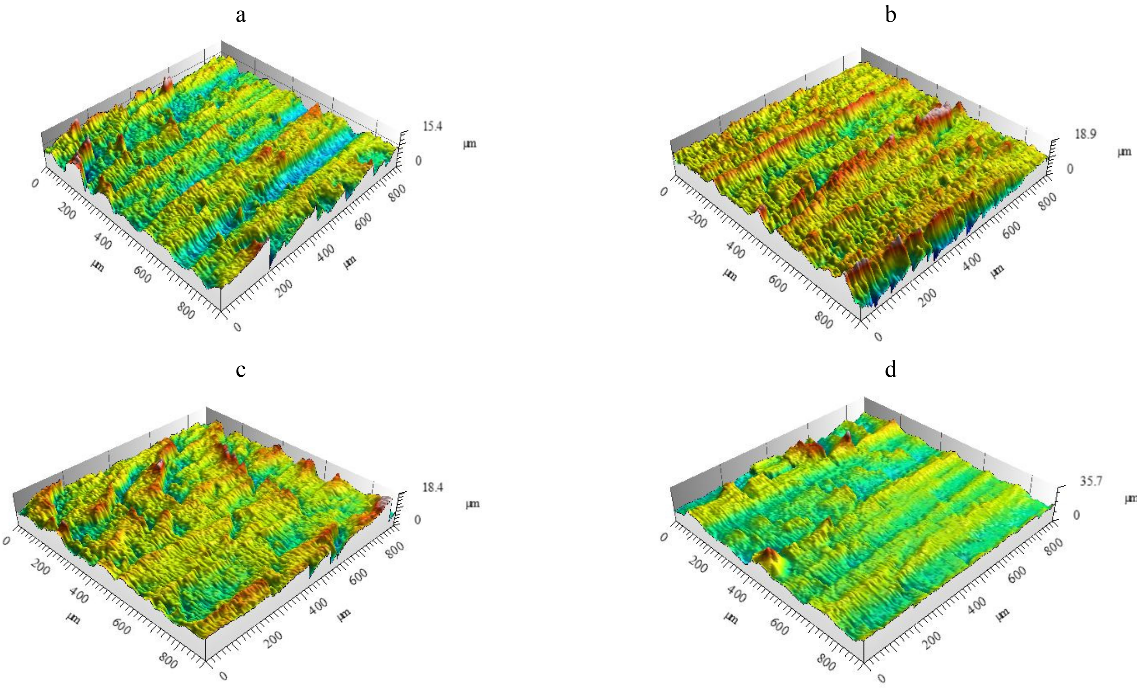


Figure 6. Surfaces of aluminum matrix composite after dry drilling at a cutting speed of 11m/min: a) *f* = 0.05mm/rev; b) *f* = 0.075mm/rev; c) *f* = 0.112 mm/rev; d) *f* = 0.17mm/rev

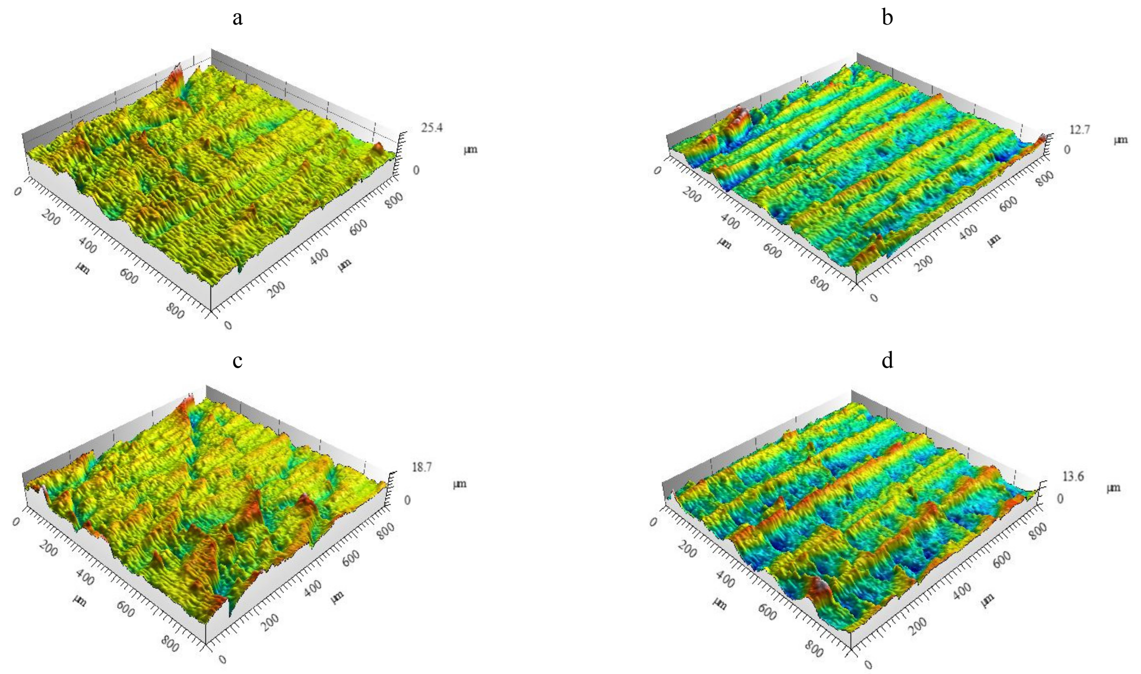
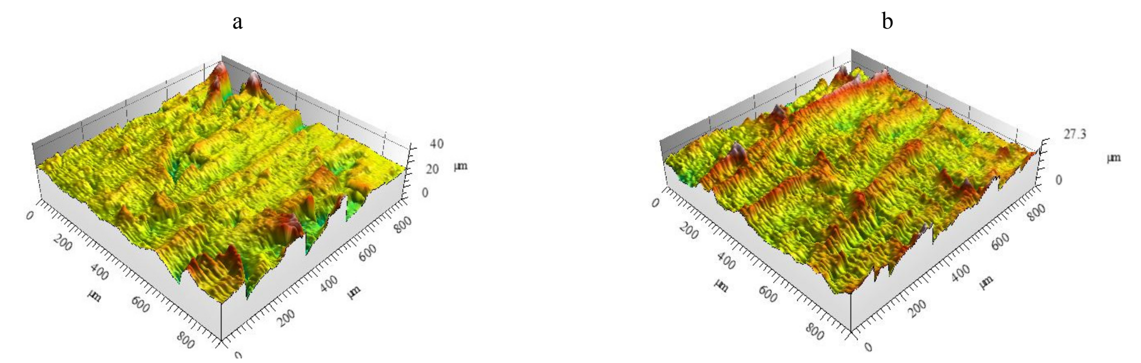
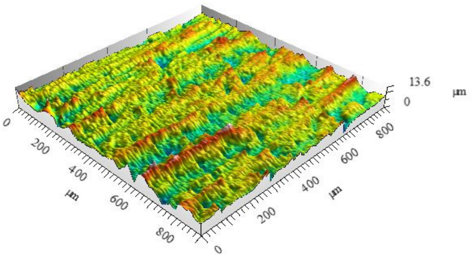


Figure 7. Surfaces of aluminum matrix composite after dry drilling at a cutting speed of 22m/min: a) *f* = 0.05mm/rev; b) *f* = 0.075mm/rev; c) *f* = 0.112 mm/rev; d) *f* = 0.17mm/rev



c



d

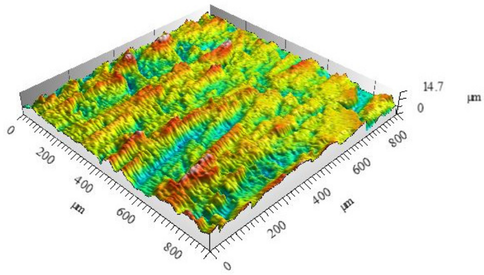
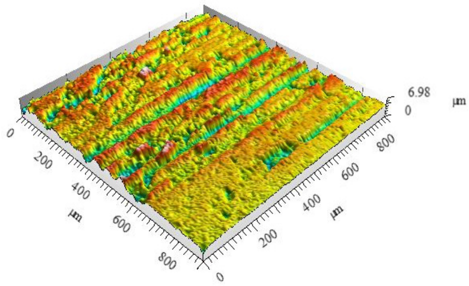
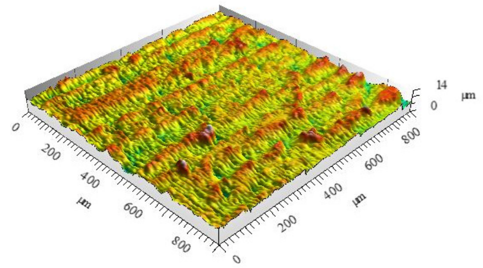


Figure 8. Surfaces of aluminum matrix composite after dry drilling at a cutting speed of 44m/min: a) *f* = 0.05mm/rev; b) *f* = 0.075mm/rev; c) *f* = 0.112 mm/rev; d) *f* = 0.17mm/rev

a



b



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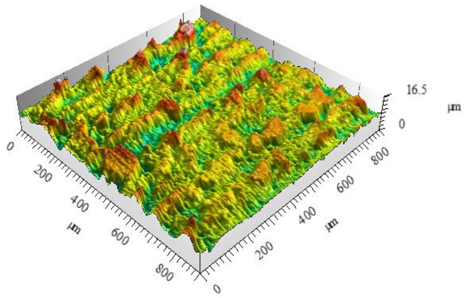

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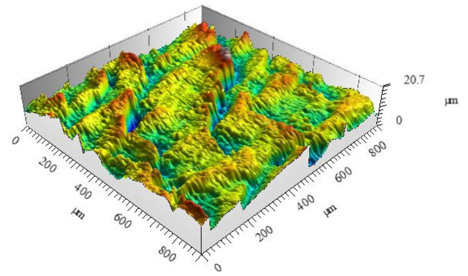
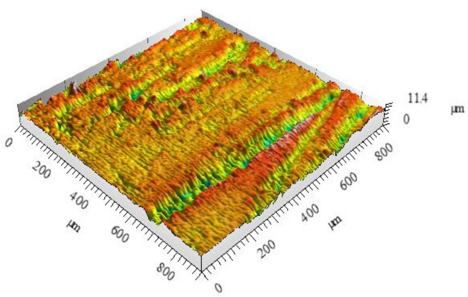


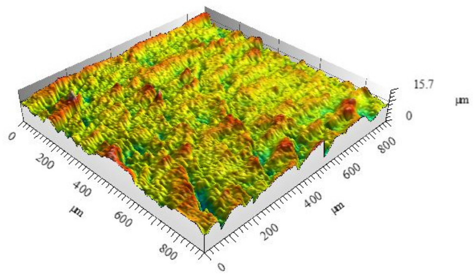
Figure 9. Surfaces of aluminum matrix composite after drilling with MQL at a cutting speed of 11m/min: a) *f* = 0.05mm/rev; b) *f* = 0.075mm/rev; c) *f* = 0.112 mm/rev; d) *f* = 0.17mm/rev

The surfaces after oil mist-assisted drilling (Figs. 9-11) do not show a clear, directional, periodic geometric structure. It is also impossible to clearly mark traces on the surface that would reflect the kinematic-geometric path of the cutting blade. Compared to dry drilled hole surfaces, fewer surface defects and defects are also visible. The exceptions are the surfaces obtained after drilling with the lowest speed and highest feed (Fig. 9d) and the lowest feed and speed of 22 m/min (Fig. 10a). In the first case, deep valleys and high peaks of roughness are visible on the surface. They are very irregular. Unfortunately, this irregularity is not in any way indicated by the box fractal dimension, whose value is only 2.43. This is definitely inconsistent with the theory. This may be the result of the fact that the machined material is a composite with a heterogeneous structure. In the second case (Fig. 10a), a deep scratch is visible on the smooth surface. The fractal dimension for this surface is larger and amounts to 2.58. It seems that even such a single scratch is the main reason for the increase in the value of this parameter. The surface with the largest fractal dimension of 2.66 (Fig. 9a) is characterized by several deep parallel scratches. Taking into account this surface and the surface from Figure 10a, it can be concluded that the appearance of deep cracks and valleys causes the fractal dimension *D* to increase. This conclusion can be confirmed after analyzing the roughness parameters *Sp*, *Sv,* and *Ssk*.

a



b



c d

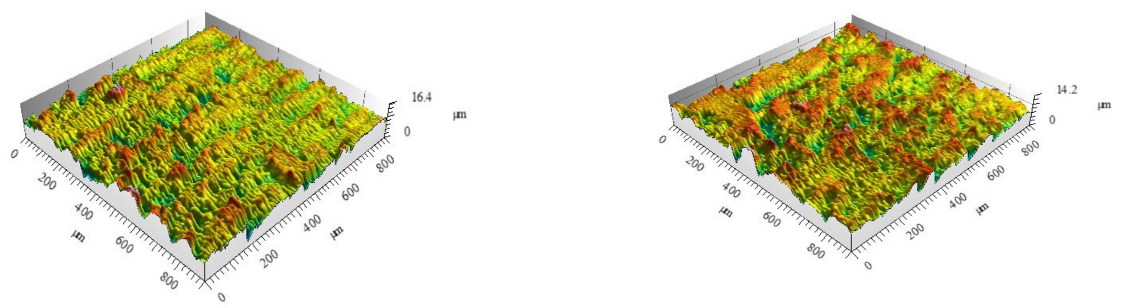


Figure 10. Surfaces of aluminum matrix composite after drilling with MQL at a cutting speed of 22m/min: a) *f* = 0.05mm/rev; b) *f* = 0.075mm/rev; c) *f* = 0.112 mm/rev; d) *f* = 0.17mm/rev

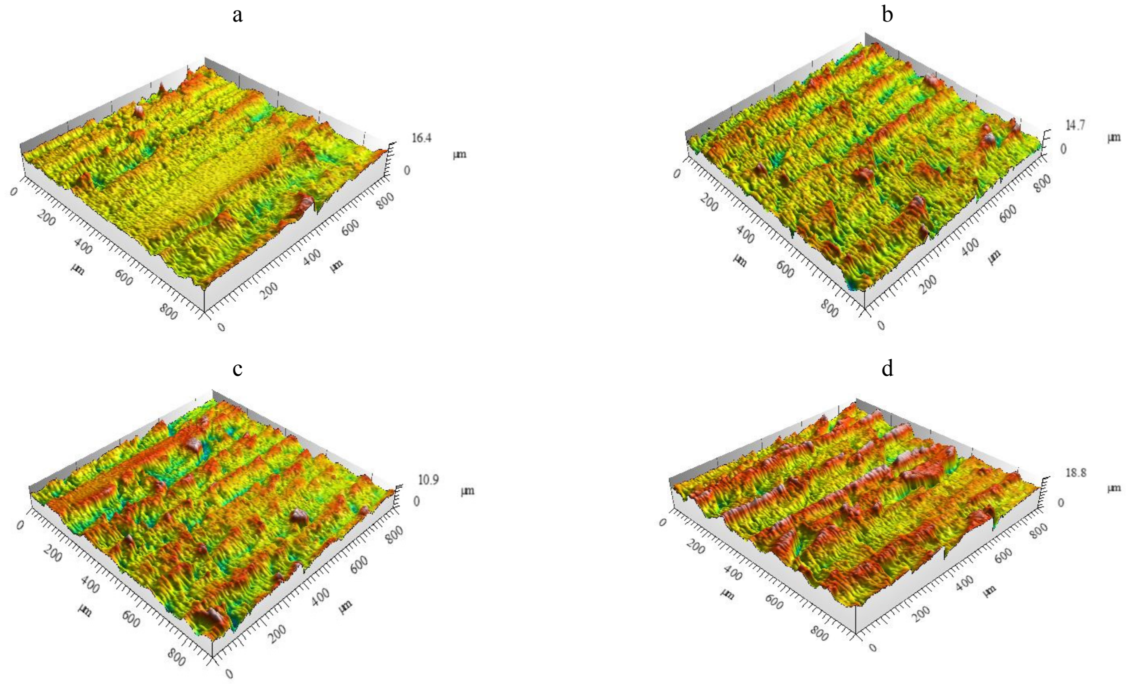


Figure 11 Surfaces of aluminum matrix composite after drilling with MQL at a cutting speed of 44m/min: a) *f* = 0.05mm/rev; b) *f* = 0.075mm/rev; c) *f* = 0.112 mm/rev; d) *f* = 0.17mm/rev

3.2 Correlation of fractal dimension and mean roughness parameters

The next stage of the analysis was to calculate the correlation coefficient between the fractal dimension and the selected roughness parameters for the constant cutting speed and feed. The fractal dimension is gene–rally treated as an additional parameter that describes the geometric structure of the surface because there is very rarely a correlation between it and standard roughness parameters.

First, the correlation between the fractal dimension and the average height parameters was examined, i.e. Sa arithmetic mean roughness height (Tables 3 and 5) and Sq mean square roughness height (Tables 4 and 6). Table 2 shows the values of the *Sa* and *Sq* parameters after drilling the tested composite.

Comparing the values of the *Sa* and *Sq* parameters after dry drilling and with MQL, the differences are clearly visible after machining with the lowest feed of 0.05 mm/rev. For each cutting speed, significantly lower values of these parameters were obtained after drilling assisted with oil mist. This can be caused by the lateral flow of material or the formation of built-up edges, which disappear when the friction between the drill and the hole surfaces is reduced under the influence of oil mist. It is worth noting that, apart from one case where efficiency drilling parameters were used, the roughness of *Sa* and *Sq* is lower after drilling with MQL. This one case may be related to the fact that at such a high drill speed and feed, the externally supplied oil mist is not delivered in the appropriate amount to the cutting zone and its positive effect disappears. Similar relationships were obtained during 2D roughness measurements [11].

Table 2. Surface roughness *Sa* and *Sq* after drilling aluminum composite

Cutting speed v_c m/min	Feed *f* mm/rev	Cooling and lubrication conditions	*Sa* µm	*Sq* µm
11	0.05	DRY	1.29	1.64
11	0.075		1.37	1.87
11	0.112		1.49	1.94
11	0.17		1.98	2.69
22	0.05		1.25	1.71
22	0.075		1.13	1.46
22	0.112		1.3	1.73
22	0.17		1.61	1.97

44	0.05		2.2	3.38
44	0.075		1.87	2.47
44	0.112		1.18	1.54
44	0.17		1.42	1.79
11	0.05	MQL	0.621	0.805
11	0.075		0.962	1.23
11	0.112		1.37	1.75
11	0.17		2.07	2.59
22	0.05		0.753	1.01
22	0.075		1.07	1.43
22	0.112		1.2	1.59
22	0.17		1.28	1.6
44	0.05		0.925	1.28
44	0.075		1.16	1.51
44	0.112		1.06	1.31
44	0.17		1.61	2.02

Table 3. Values of the correlation coefficient of the fractal dimension *D* and the roughness parameter *Sa* after drilling composite, for constant values of cutting speed v_c

Machining conditions	Cutting speed v_c [m/min]	Correlation coefficient
Dry	11	-0.55
	22	-0.99
	44	0.5
MQL	11	-0.99
	22	-0.77
	44	0.37

Table 4. Values of the correlation coefficient of the fractal dimension *D* and the roughness parameter *Sq* after dril– ling composite, for constant values of cutting speed v_c

Machining conditions	Cutting speed v_c [m/min]	Correlation coefficient
Dry	11	-0.48
	22	-0.93
	44	0.39
MQL	11	-0.99
	22	0.67
	44	0.23

Table 5. Values of the correlation coefficient of the fractal dimension *D* and the roughness parameter *Sa* after drilling composite, for constant values of feed *f*

Machining conditions	Feed *f* [mm/rev]	Correlation coefficient
Dry	0.05	-0.47
	0.075	-0.95
	0.112	-0.55
	0.17	-0.27
MQL	0.05	-0.99
	0.075	-1
	0.112	-0.45
	0.17	-0.5

Table 6. Values of the correlation coefficient of the fractal dimension *D* and the roughness parameter *Sq* after drilling composite, for constant values of feed *f*

Machining conditions	Feed *f* [mm/rev]	Correlation coefficient
dry	0.05	-0.53
	0.075	-0.91
	0.112	-0.46
	0.17	-0.13
MQL	0.05	-0.99
	0.075	-0.99
	0.112	-0.63
	0.17	-0.49

Upon turning the tested composite [30], it was noticed that there is an inverse correlation between the Sa parameter and the fractal dimension *D* for the surface obtained by dry machining with a carbide blade at a constant cutting speed. The argument was that these surfaces become rougher as the feed increases, but they also become more regular to some extent and the disturbances associated with the lateral flow of the material disappear [30]. In the case of dry drilling, no correlation was found between the *Sa* or *Sq* parameter and the fractal dimension, both for the constant feed and the cutting speed. An inverse correlation of -0.99 appears, but only for, for example, one cutting speed. The lack of correlation between the average surface roughness parameters and the fractal dimension after dry drilling may be caused by two factors. First, the roughness *of Sa* and *Sq* does not increase either linearly or quadratically with the increase in feed, and secondly, the surface after drilling does not have a directional, periodic geometric structure like after turning.

In [30] it was also found that the correlation after turning with MQL is lower because the use of oil mist allowed a significant reduction of the *Sa* parameter for the smallest feeds and the increase in *Sa* with an increase in feed is faster than the reduction in irre– gularities and box dimension fractal parameter [30]. The inverse relationship was observed after drilling. The correlation between the average parameters and the fractal dimension after drilling with MQL is higher than after dry drilling. It can be assumed to be full and inverse for low cutting speed (11m/min) and small feeds (0.05 and 0.075mm/rev). This is due, first of all, to the fact that it is possible to determine the relationship between *D* and cutting parameters and because the surfaces after drilling with oil mist support have fewer defects, nicks, or burrs that may be rem– nants of build-up. This greater regularity and predic– tability in surface roughness of composite holes after drilling is very valuable when technological processes plan the machining of composite holes.

3.3 Correlation of fractal dimension and height roughness parameters

The height parameters, i.e. the maximum roughness height *Sz*, the maximum height of the peak *Sp*, and the maximum height of the valley *Sv* for 3D measurements, are characterized by high sensitivity to single upper or lower peaks. Despite performing 3 measurements and calculating the average values from them, significant deviations in the values of these parameters are visible. Therefore, in the described research, the quadratic relationship between the increase in roughness and the increase in feed, known from theory, was not observed. The influence of using MQL on the value of the *Sz* parameter is similar to that of average parameters. The greatest positive effect of MQL is visible for the feed of 0.05 mm/rev. As the feed increases, this influence of oil mist decreases. The results of 3D measurements of the *Sz* parameter are consistent with 2D measurements *Rz* parameter [11].

Much more interesting is the analysis of the components of the *Sz* parameter, i.e. *Sp* and *Sv*. The use of MQL makes single high peaks of roughness disappear. Within the entire range of drilling parameters, only in two cases did the *Sp* value exceed *Sv*. This happened much more often after dry drilling. Moreover, for example. After drilling at a speed of 22 m/min and feeds of 0.075 and 0.17 mm/rev, *Sp* is greater than *Sv* by 30%. These differences are visible in the surface images (Figs. 7b and d). On the basis of these data, it can be concluded that oil mist support makes material de-cohesion more effective. Less of the processed material sticks to the hole surface and makes a built-up edge.

Table 7. Surface roughness *Sz, Sp*, and *Sv* after drilling composite

Cutting speed v_c m/min	Feed f mm/rev	Cooling and lubrication conditions	*Sz* µm	Sp µm	*Sv* µm
11	0.05	DRY	15.4	8.31	7.14
11	0.075		18.9	8.29	10.6
11	0.112		18.4	8.83	9.56
11	0.17		35.7	19.7	16.0
22	0.05		25.4	11.9	13.5
22	0.075		12.7	7.24	5.5
22	0.112		18.7	8.65	10.0
22	0.17		13.6	7.76	5.83
44	0.05		44.9	19.0	25.9
44	0.075		27.3	11.0	16.3
44	0.112		19.1	12.0	7.06
44	0.17		14.7	6.96	7.74
11	0.05	MQL	6.98	2.87	4.11
11	0.075		14.0	5.64	8.36
11	0.112		16.5	7.64	8.84
11	0.17		20.7	10.4	10.2
22	0.05		11.4	3.97	7.41
22	0.075		8.2	9.29	8.94
22	0.112		16.4	7.34	9.06
22	0.17		14.2	5.97	8.23
44	0.05		16.4	6.8	9.56
44	0.075		14.7	6.28	8.46
44	0.112		10.9	4.42	6.44
44	0.17		18.8	6.41	12.4

Table 8. Values of the correlation coefficient of the fractal dimension *D* and the roughness parameter *Sz* after drilling composite, for constant values of cutting speed v_c

Machining conditions	Cutting speed v_c [m/min]	Correlation coefficient
Dry	11	-0.39
	22	0.23
	44	0.13
MQL	11	0.9
	22	0.03
	44	-0.48

Table 9. Values of the correlation coefficient of the fractal dimension *D* and the roughness parameter *Sp* after drilling composite, for constant values of cutting speed v_c

Machining conditions	Cutting speed v_c [m/min]	Correlation coefficient
Dry	11	-0.4
	22	0.16
	44	-0.2
MQL	11	-0.96
	22	0.07
	44	-0.85

Table 10. Values of the correlation coefficient of the fractal dimension *D* and the roughness parameter *Sv* after drilling composite, for constant values of cutting speed v_c

Machining conditions	Cutting speed v_c [m/min]	Correlation coefficient
Dry	11	-0.34
	22	0.28
	44	0.3
MQL	11	-0.8
	22	-0.07
	44	-0.28

No correlation was observed between the height parameters and the fractal dimension *D* (Tabs. 8-13). This is due to the fact that the height parameters are calculated from individual peaks and valleys on the entire measured surface, and the fractal dimension is an average of the entire surface. Taking into account that fewer high roughness peaks were observed after dril–ling with MQL, the correlation between *Sp* and *D* for this type of machining is higher. This difference is insignificant. The single correlation appearing above 0.9 is mostly inverse. However, this does not change the overall conclusion that there is no correlation between these roughness parameters and the fractal dimension.

Table 11. Values of the correlation coefficient of the fractal dimension *D* and the roughness parameter *Sz* after drilling composite, for constant values of feed *f*

Machining conditions	Feed f [mm/rev]	Correlation coefficient
dry	0.05	-0.76
	0.075	-0.9
	0.112	0.36
	0.17	0.11
MQL	0.05	-1
	0.075	-0.27
	0.112	-0.86
	0.17	-0.19

Table 12. Values of the correlation coefficient of the fractal dimension *D* and the roughness parameter *Sp* after drilling composite, for constant values of feed *f*

Machining conditions	Feed f [mm/rev]	Correlation coefficient
dry	0.05	-0.76
	0.075	-0.96
	0.112	-0.2
	0.17	0.01
MQL	0.05	-0.96
	0.075	-0.28
	0.112	-0.82
	0.17	-0.76

Table 13. Values of the correlation coefficient of the fractal dimension *D* and the roughness parameter *Sv* after drilling composite, for constant values of feed *f*

Machining conditions	Feed f [mm/rev]	Correlation coefficient
dry	0.05	-0.76
	0.075	-0.88
	0.112	0.21
	0.17	0.24
MQL	0.05	-1
	0.075	-0.27
	0.112	-0.9
	0.17	0.6

3.4 Correlation of fractal dimension and statistic roughness parameters

The next analyzed parameters are *Ssk* and *Sku*. On the one hand, they are classified as height parameters. On the other hand, they are dimensionless and can be classified as statistical parameters. They are characterized by very high sensitivity to single changes in the profile, so it is much better to analyze them from measured surfaces. *Ssk* is the surface asymmetry coefficient, or in other words, it determines the skewness of the ordinate distribution. It has an averaging character and may take positive values in the case of structures characterized by numerous hills, or negative values for surfaces dominated by depressions. The further this parameter moves away from zero, the more nonuniform the material distribution is. As noted above, after drilling with MQL, *Sv* values are greater than *Sp*. If these are not just single valleys larger than the peaks, the value of the *Ssk* parameter should be negative. As can be seen in Table 14 this is the case. This shows the general dominance of depressions over hills on these surfaces. When the surfaces are analyzed after dry drilling, such a conclusion cannot be drawn. The values of the *Ssk* parameter are very different, and their dependence on the drilling parameters cannot be assumed. For the surfaces for which the *Sp* ratio was greater than *Sv*, the *Ssk* parameter takes positive values, which confirms the dominance of roughness peaks over depressions. The values of the Ssk parameter after drilling an aluminum matrix composite are completely different from the values of this parameter after turning this material. This undoubtedly proves a completely different geometric structure of the hole surface, dominated by valleys.

Table 14. Surface roughness *Ssk* and *Sku* after drilling composite

Cutting speed v_c m/min	Feed *f* mm/rev	Cooling and lubrication conditions	*Ssk* [-]	*Sku* [-]
11	0.05	DRY	0.195	3.79
11	0.075		-0.157	5.14
11	0.112		-0.182	3.99
11	0.17		0.397	6.25
22	0.05		-0.606	6.63
22	0.075		0.282	3.94
22	0.112		-0.337	4.56
22	0.17		0.177	2.64
44	0.05		-0.931	11.2
44	0.075		0.083	5.0
44	0.112		0.236	5.34
44	0.17		0.056	3.18
11	0.05	MQL	-0.594	3.68
11	0.075		-0.139	3.79
11	0.112		0.06	3.45
11	0.17		-0.281	3.31
22	0.05		-0.905	4.96
22	0.075		0.221	5.6
22	0.112		-0.75	5.16
22	0.17		-0.483	3.34
44	0.05		-0.67	7.31
44	0.075		-0.11	4.21
44	0.112		-0.291	3.25
44	0.17		-0.128	3.24

The *Sku* parameter is a measure of the sharpness of the amplitude density curve, which can also be referred to as the flattening factor. When it takes values below the limit value of 3, the irregularities have a longer length and the vertices of roughness are more filled with material, while above it they become shorter and sometimes sharper. Analyzing the data from Table 14, it can be noticed that *Sku* has a value below 3 only for one surface. Similarly to the *Ssk* parameter, the results for *Sku* after drilling are different than after turning. After turning, a larger amount of material fills the vertices, while after drilling there are fewer of them, and they are more sharp and short.

Analyzing the correlation coefficients between the statistical parameters and the fractal dimension, one can notice a relatively large relationship between the *Sku* parameter and the *D* dimension for the surface of holes after drilling with MQL (Tables 16 and 18). It can be assumed that the fractal dimension, in a sense, also describes the degree of surface load-bearing capacity, which is related to the *Sku* parameter. Interestingly, no such correlation was observed in [30]. This shows that when the roughness peaks are filled with the workpiece material, the fractal dimension is not affected. When the vertices are sharp, the fractal dimension notices them. In the case of the *Ssk* parameter, no correlation was observed between it and the fractal dimension, both after dry drilling and with MQL. This is again the opposite result of turning, where it was found that there is a strong correlation between *Ssk* and *D*, but only in the case of constant cutting speed. For the surface obtained after dry diamond turning, the correlation coefficient for each constant cutting speed takes the value -1 [30].

Table 15. Values of the correlation coefficient of the fractal dimension *D* and the roughness parameter *Ssk* after drilling composite, for constant values of cutting speed v_c

Machining conditions	Cutting speed v_c [m/min]	Correlation coefficient
Dry	11	-0.08
	22	-0.23
	44	-0.32
MQL	11	-0.27
	22	0.02
	44	0.56

Table 16. Values of the correlation coefficient of the fractal dimension *D* and the roughness parameter *Sku* after drilling composite, for constant values of cutting speed v_c

Machining conditions	Cutting speed v_c [m/min]	Correlation coefficient
Dry	11	-0.05
	22	0.56
	44	-0.04
MQL	11	0.91
	22	0.92
	44	-0.88

Table 17. Values of the correlation coefficient of the fractal dimension *D* and the roughness parameter *Ssk* after drilling composite, for constant values of feed *f*

Machining conditions	Feed *f* [mm/rev]	Correlation coefficient
Dry	0.05	0.96
	0.075	-0.05

	0.112	-0.33
	0.17	-0.29
MQL	0.05	0.27
	0.075	-0.19
	0.112	0.57
	0.17	0.51

Table 18. Values of the correlation coefficient of the fractal dimension *D* and the roughness parameter *Sku* after drilling composite, for constant values of feed *f*

Machining conditions	Feed *f* [mm/rev]	Correlation coefficient
dry	0.05	-0.79
	0.075	-0.4
	0.112	0.35
	0.17	0.2
MQL	0.05	-0.98
	0.075	-0.33
	0.112	-0.91
	0.17	-0.75

4. CONCLUSIONS

The results of drilling aluminium matrix composite reinforced with ceramic fibres presented in this paper show that it is possible to obtain good quality hole surfaces without the need for additional reaming. Both dry drilling and oil mist assisted drilling can obtain a surface with a roughness *Sa* below 1 μm. The relationships between the parameters *Sa* and *Sz* and the drilling parameters are consistent with the relationships between the parameters *Ra* and *Rz* and the drilling parameters [11]. The geometric structure of the hole surfaces does not show any directionality or perio–dicity. The box fractal dimension *D* can be used to describe it. The values of this dimension are more pre–dictable and depend on the drilling parameters when the process is supported by oil mist. Assuming that the fractal dimension describes the irregularity of the sur–face, predicting the regularity of traces on the surface and its functional characteristics is much more possible when the machining fluid is administered in the form of mist than when the machining is carried out dry. The box fractal dimension does not show any significant correlation with the roughness parameters most com–monly used to describe surfaces. Only in the case of the *Sku* parameter and the *Sa* and *Sq* parameters, the correlation coefficients between them and the fractal dimension approach 1. This only applies to drilling with MQL. These results regarding the drilling of the composite are different from the correlation of the rou–ghness parameters and the fractal dimension after turning [30]. This is due to the different geometric structures of the surfaces created after drilling and tur–ning the composite.

Regardless of the type of geometric structure of the surface, there is no universal parameter that could be used alone to fully describe such a surface. In addition, changing the type of structure affects the usefulness of individual roughness parameters for its description. The fractal dimension is a universal parameter that describes the irregularity of the surface, but its degree of correlation with other roughness parameters will not always be sufficient to use it interchangeably for each of the roughness parameters. In the presented study, most of the results confirmed its usefulness as an alter–native to traditional profile parameters, but it should be remembered that eliminating one of these parameters in favor of the fractal dimension will not always be justified. A good solution in some cases will be to use it as a supplement to the information on the surface structure, alongside parameters such as *Sq*, *Sz*, or *Ssk*.

The data presented in this paper complement the research presented in our earlier research [30]. The next step of the research should be to check the possibility of using fractal analysis to describe the surface of milled composites. When examining the quality of holes, the drilled holes should be subjected to additional reaming processing, and the usefulness of fractal analysis describing the surface after reaming should be assessed.

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ПРОЦЕНА ПРИМЕНЉИВОСТИ ФРАКТАЛНЕ АНАЛИЗЕ ЗА ОПИСИВАЊЕ ПОВРШИНЕ АЛУМИНИЈУМСКИХ КОМПОЗИТА НАКОН БУШЕЊА

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У раду су приказани резултати бушења алуминијумског матричног композита ојачаног керамичким влакнима. Процес бушења је изведен на суво и уз помоћ уљне магле. 3Д храпавост површине је мерена контактним методом. Анализиран је већи број параметара храпавости: просек, висина и статистички параметри. Одређена је и фрактална димензија површина рупа која броји кутије. Израчунати су коефицијенти корелације између фракталне димензије и параметара храпавости. Утврђено је да фрактална димензија описује неправилност површине. Вредности фракталних димензија зависе само од параметара бушења ако се процес изводи мокар са течностима за обраду. Фрактална димензија није у корелацији са параметрима храпавости површине као што су Са, Ск и Сз. Уочена је извесна корелација између њега и параметра Ску, али тек након бушења уљном маглом. Геометријска структура површине након бушења не показује јасне карактеристике усмерености и периодичности.