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MACHINABILITY ASSESSMENT OF ALUMINIUM ALLOY EN AW-7075 T651 UNDER VARYING MACHINING CONDITIONS

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Abstract: This paper presents the experimental results of a study investigating the milling process of aluminium alloy EN AW-7075 T651. The main objective of the study was to establish the relationship between machining conditions, such as cutting parameters and cutting tool type, and selected machinability indicators, i.e. cutting force components and surface roughness parameters. The milling process was conducted using two different tools: a solid carbide cutter and a cutter with PCD (polycrystalline diamond) inserts. Obtained results showed that the use of the PCD tool led to a significant improvement of surface quality. In particular, the surface roughness parameter Ra was reduced, but changes are also visible for the other roughness parameters. Despite a similar trend of variations in surface roughness parameters observed for both tools, the values of these parameters obtained with the PCD tool were significantly lower. Similar values of the cutting force components were obtained with both cutting tools, these values being lower only in some cases for the carbide cutter. The effect of varying the cutting speed and feed per tooth on these indicators was also determined. The obtained results indicate that the selection of cutting parameters depends primarily on the expected results. Considering the surface roughness, it is better to use high cutting speeds, while in terms of cutting force, low speeds are more beneficial. In both cases, it is recommended to use the lowest possible feed.

Key words: milling, aluminium alloy, surface roughness, cutting force, cutting tools

1. INTRODUCTION

Aluminium alloys are widely used in the aerospace and automotive industries, among others [1,2]. This is primarily owing to their low density, high corrosion resistance and good strength properties. However, the peculiarities of these industries require high quality of manufactured components, which implies a need for continuous improvement of machining processes. The selection of appropriate cutting conditions is therefore crucial for ensuring optimum machining results, and hence research must be conducted in this area [3–5].

The machining result depends on numerous factors such as the machine tool, cutting tool and cutting parameters. The dynamics of this process, which is significantly related to the cutting force, is of importance, too. The selection of optimum machining conditions has been of interest to researchers from all over the world. By varying technological parameters, it is possible to exert a significant impact on the cutting process and its effects. The machining of alloy EN-AW 7075 conducted with variable cutting parameters was investigated in [6]. The study showed that the spindle speed and feed rate had the primary impact on surface roughness. Increasing the values of these parameters resulted in improved surface quality. The depth of cut, on the other hand, showed no specific effect on surface condition. Similar conclusions were included in the paper [7], also concerning EN-AW 7075 alloy. It was shown that cutting speed had an approx. 85% effect on surface roughness and chip segmentation. However, this applied to high speed machining, because when standard cutting speeds were used, the significance of cutting speed decreased, while the influence of feed and depth of cut increased. A study [8] investigated the milling process of pure EN-AW 7075 alloy, EN-AW 7075 alloy with Sc and Li additives, as well as of EN-AW 7075 after different heat treatments. The applied feed rate was found to have the greatest effect on cutting forces. A reduction in the feed value had a positive effect on the cutting force. This observation was especially important when machining high-hardness alloys, for which it was recommended using a cutting fluid in order to reduce the cutting force. It was also more advantageous to use higher cutting speeds. A study investigating the machining of EN-AW 7050 conducted by Ping et al. [9] showed that the cutting force components remained constant despite an increase in the cutting speed and a higher cutting temperature. The depth of cut was found to have the greatest effect on the cutting force, as increasing the depth of cut value resulted in a several-fold increase in the components of this force. The effect of tool geometry was also investigated. It was observed that as the rake angle was increased, the cutting force components and the cutting temperature decreased. In contrast, an increase in the tool tip radius produced the opposite effect. This implies that the cutting tool geometry, too, has impact on the machining process.

The effect of rake angle and clearance angle was investigated in [10] for the EN-AW 7075 alloy. It was shown that the “sharper” cutting edge caused the cutting temperature to decrease and the cutting force to increase at the same time. Other tools caused the cutting temperature to increase, which probably led to plasticization of the material and a decrease in the cutting force. The study [11] focused on rake angle and nose radius. Choosing the right rake angle proved to be a difficult task, as increasing the rake angle results in a reduction of the infeed force, while at the same time the crossfeed and thrust forces increase intensively. However, by increasing the nose radius, the cutting forces were reduced by up to several times. A study [12] showed that the cutting tool's helix angle had a significant impact on the cutting process. The cutting temperature was reduced when using a small helix angle tool. This angle had a greater effect on the cutting temperature than the spindle speed and feed. The use of a large helix angle, on the other hand, had a positive effect on surface roughness and was more significant than a variable feed. Ikhries et al. [13] compared the results of a machining process conducted with a flat and a ball tool. The use of the flat tool resulted in enhanced surface quality and a higher material removal rate. In the machining process conducted with the flat tool, the feed rate had the dominant effect on surface roughness, while for the ball tool – the depth of cut had the greatest effect on surface roughness.

Not only does the overall geometry of the tool matter, but the cutting edge microgeometry is of significance too, as demonstrated in [14]. The results showed the margin width to be of the greatest significance, as any increase in this parameter led to reduced surface quality. The corner radius was found to have a nonlinear impact, as the best effect was obtained using intermediate radius values. In contrast, the relief angle did not have any significant effect on surface roughness. Schönecker et al. [15] developed HSS end mills with structure elements on the flank face. The research showed that the proposed tool geometry reduced the cutting force and the susceptibility to chatter vibration, which, in turn, allowed the depth of cut to be increased. This effect became more powerful with increasing the size of structure elements.

The material of a cutting tool is of vital importance, too. Kuczmaszewski et al. [16] conducted a comparative analysis of the results of an HSM (High Speed Milling) process for EN-AW 2024 that was conducted using a carbide and a PCD tool. Lower values of the roughness parameter Ra over the entire length of the machined surface were obtained with the PCD tool, regardless of the rolling direction. However, the differences were relatively small. The use of the diamond tool resulted in lower deflection along the longitudinal rolling direction. A comparison of carbide and PCD tools was also undertaken in [17]. The use of the PCD tool for milling EN-AW 5754 and EN-AW 6082 alloys resulted in several-fold lower values of the surface roughness parameter Ra. The tool was also found to be less sensitive to changes in cutting parameters. The dependence of high surface quality on the use of diamond tools was also confirmed in [18]. The best results were obtained using low cutting speeds, feeds and cutting depths. The diamond tool also had a positive effect on the shape of formed chips, which promoted improved surface quality. O'Toole et al. [19] compared the use of a PCD tool and a CBN (Cubic Boron Nitride) tool in the micromilling of pure aluminium. The PCD tool produced better surface quality and several-fold lower cutting force components. The tool also exhibited lower wear. Similar results were obtained in the simulation of a milling process for the EN-AW 7075-0 alloy [20]. The use of the PCD tool resulted in lower cutting forces and feed forces than those obtained in the milling process conducted with a tool made of carbide K10. This also meant lower cutting temperatures. The favourable properties of polycrystalline diamond were also found to promote reduced burr formation [21]. The benefits of using diamond tools were confirmed not only by research on milling, but also by studies devoted to turning [22–26].

The machining effect can also be enhanced via tool coatings. The benefits of using coatings in micromilling were confirmed in a study [27]. It was demonstrated that compared to an uncoated tool, the use of DLC (Diamond-Like Carbon) and NCD (Nano-Crystalline Diamond) coatings reduced the cutting forces by up to 20-30%. The use of the DLC-coated tool also produced the best surface quality. Similar observations were made in a study [28] which investigated the machining process of EN-AW 6082-T6. The use of the DLC-coated tool produced significantly better results than when using uncoated and AlCrN-coated tools. The obtained surfaces had higher quality and better properties. The DLC-coated tool also generated lower vibration. It should be emphasized that the coating material selection depends on the specific application, as the use of a wrong coating can even deteriorate the machining process and its results [29].

The selection of a suitable machining strategy is also important. In [30], conventional and plunge milling strategies were considered. Plunge milling was shown to improve productivity and reduce tool wear, but at the same time generated more vibration and poorer surface quality. This machining strategy can therefore be an interesting option for rough machining. The type of milling can also affect the machining effect. Burhanudin et al. [31] compared climb and conventional milling using an HSS end mill. The results showed that climb milling produced better surface quality, with significantly greater differences obtained for EW-AW 5052 than for EN-AW 7075. The study also demonstrated that increasing the cutting allowance promoted improved surface roughness. A similar investigation of the EN-AW 7075-T6 alloy was made in [32]. In this study, however, no clear differences were observed between the two types of treatment. This could be due to the fact that the carbide tool had a different geometry or that the aluminium alloy was subjected to a different heat treatment condition.

Sivalingam et al. [33] showed that the machining effects for aluminium alloy EN-AW 7075 can also be improved by using lubricants. They investigated several cooling methods: MQL (Minimum Quantity Lubrication), cryogenic, and a combination of MQL and cryogenic. The use of lubrication led to reduced friction, which resulted in lower cutting forces and tool wear. Surface quality was also improved, with fewer defects occurring. The most benefits were achieved using a combination of MQL and cryogenic. The positive effect of cooling on surface roughness was also confirmed in a study [34]. The use of cooling led to a more than half reduction in the surface roughness parameter Ra. Nevertheless, the spindle speed was found to have a much greater effect on surface roughness. Yapan et al. [35] conducted a study on EN-AW 6082 using MQL with graphene nanoparticles. The use of nanofluid resulted in significant improvements in cutting force, surface roughness, temperature and carbon emission. A study [36] compared dry machining and SQL (Small Quantity Lubrication) with sunflower oil. The application of SQL reduced the cutting force by up to 35% and the surface roughness by even up to 45%. The effect of using SQL in milling was much better than that achieved in turning. Innovative solutions were also proposed for cutting force reduction, such as vibration assisted milling [37,38], which could additionally be implemented over helical paths [39].

Based on the literature review, it can be seen that the milling process depends on many factors. In order to obtain an optimal machining effect, it is necessary to determine the influence of individual machining conditions. The objective of this study is to determine the effect of variable cutting parameters and different cutting

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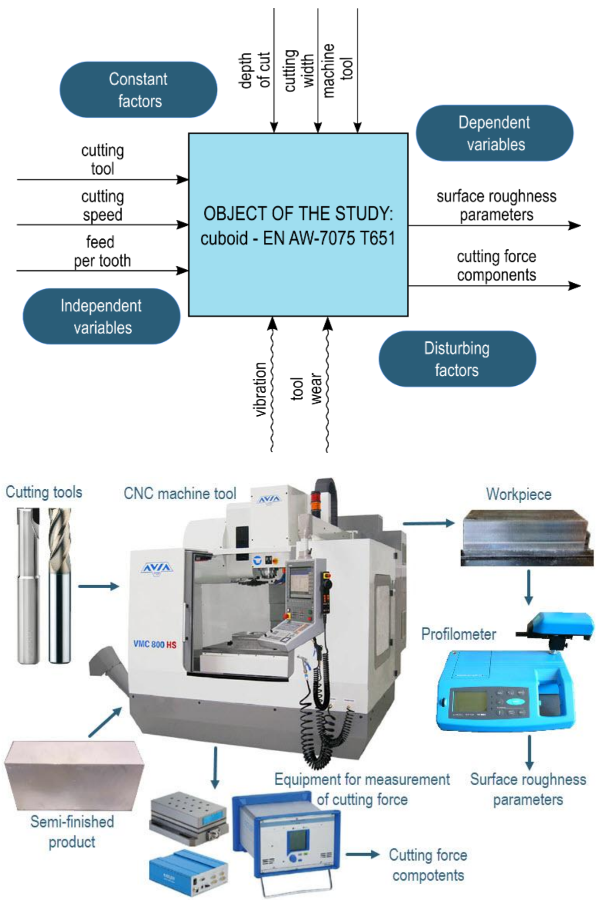
tool types on surface quality and cutting force. For improving surface quality, one of the first steps to be taken is to change the cutting parameters, as this does not require additional tooling and equipment. Therefore, an attempt is made to determine the extent to which varying the machining conditions will affect the milling effect. The impact of the cutting tool is also considered, since the end mills used in this study are made of different materials and have different geometries.

The novelty of the research consists in a comprehensive analysis of the influence of various cutting parameters on the machinability of the EN AW-7075 T651 aluminum alloy, considering two different cutting tools. This provides new information on the optimization of the milling process of this aluminum alloy, which can contribute to improving the quality and efficiency of manufactured parts. A wide range of cutting parameters corresponding to conventional and High Speed Cutting allows for better representation of real manufacturing conditions.

2. MATERIALS AND METHODS

The study involved investigating the stability and effects of a milling process for aluminium alloy EN AW-7075 T651. Owing to its high strength and corrosion resistance combined with low specific weight, this material is widely used in the aerospace and automotive industries. Test specimens came in the form of cuboids with the dimensions of 160x70x33 mm. The milling process was performed on an AVIA VMC 800HS milling centre – Figure 1.

a)



b)

Fig. 1. Experimental setup: a) schematic diagram; b) experimental procedure

The milling process was conducted using variable cutting parameters, as shown in Table 1. The variable parameters were the cutting speed v_c and the feed per tooth f_z, while the constant parameters were the depth of cut equal to 1 mm and the width of cut equal to 12 mm.

Tab. 1. Parameters of milling process

v_c (m/min)	f_z (mm/tooth)	n (rpm)	v_f (mm/min)
100		2 654	796
300		7 962	2 389
500	0.100	13 270	3 981
700		18 577	5 573
900		23 885	7 166
	0.050		1 194
	0.075		1 791
300	0.100	7 962	2 389
	0.125		2 986
	0.150		3 583
	0.050		3 583
	0.075		5 374
900	0.100	23 885	7 166
	0.125		8 957
	0.150		10 748

The selection of technological parameters was based on the recommendations of the cutting tool manufacturers, as well as the authors' experience in machining aluminium alloys. The tests were carried out on the basis of one pass for one configuration of technological parameters for two tools.The milling process was carried out using two 12 mm diameter milling cutters:
– a cutter with three PCD inserts (Bryk D10.1210), each having a length of 25 mm, with an overall length of 82 mm and a tooth angle of 0°;
– a four-teeth solid carbide cutter (Engram 4HCEG 120 260 S12), with a tooth length of 26 mm, having an overall length of 75 mm and a tooth angle of 35°, provided with Nano-X coating.

During the tests, no significant wear on the cutting tools was found to affect the results.

Cutting forces were measured during the milling process using a Kistler 9257B piezoelectric force gauge connected to a 5070A amplifier, from which the signal was sent to a DAQ 5697A module. The maximum values of the cutting force components F_x, F_y and F_z were analysed.

The study also included an evaluation of surface roughness parameters *Ra*, *Rz* and *RSm*. The measurements were made using a Hommel Tester T1000 contact profilometer in accordance with the PN-EN ISO 4287 standard.

3. RESULTS

3.1. Surface roughness

Results of the investigated surface roughness parameters are given in Figures 2-4.

Regardless of the cutting tool type, a similar trend of changes in the values of all surface roughness parameters can be observed for the milling process conducted with a variable cutting speed. However, significantly lower values of all parameters were obtained for the PCD tool. The differences are as high as 0.79 µm for the *Ra* parameter, 1.3 µm for *Rz* and 0.045 mm for *RSm*. Comparing the results obtained for both tools, the greatest differences in the values of the surface roughness parameters can be observed for the milling process conducted with the lowest cutting speed. These differences decrease as the cutting speed is increased.

Similar relationships can also observed for the milling process conducted with variable feed per tooth. Lower values of the surface roughness parameters were again obtained for the tool with PCD inserts, and the trend of changes is similar for all roughness parameters regardless of the tool; this time, however, the values increase with increasing the feed per tooth. At the same time, the tool with PCD inserts was more sensitive to the variations in feed, because the values of the roughness parameters increase faster with increasing the feed value. This is particularly true for the parameters *Rz* and *RSm*, for which the differences between the results obtained with both tools gradually decrease as the feed is increased. On the other hand, for the lowest feed value, the differences in the values of *Ra*, *Rz* and *RSm* obtained with the two tools are 1.16 µm, 2.1 µm and 0.09 mm, respectively.

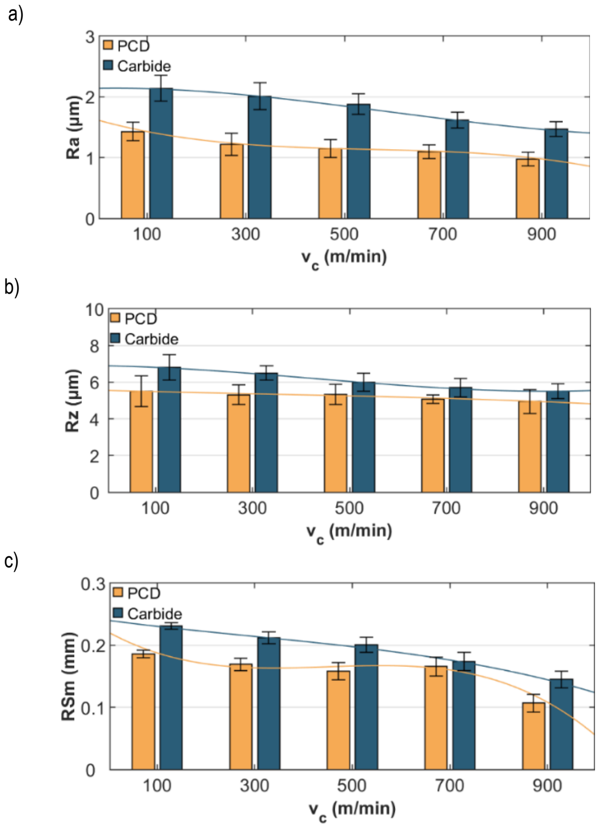


Fig. 2. Cutting speed vs surface roughness parameters: a) *Ra*; b) *Rz*; c) *RSm* (f_z = 0.1 mm/tooth)

Tab. 2. Regression equations for surface roughness parameters

Parameter	PCD	Carbide
	v_c	
Ra	$y = -2.2396 \times 10^{-9}x^3 + 3.7195 \times 10^{-6}x^2 - 0.0022461x + 1.6193$	$y = 1.1458 \times 10^{-9}x^3 - 2.0223 \times 10^{-6}x^2 + 0.00014211x + 2.1396$
	$R^2 = 0.99992$	$R^2 = 0.99358$
Rz	$y = -5.2083 \times 10^{-10}x^3 + 5.1339 \times 10^{-7}x^2 - 0.00072693x + 5.555$	$y = 3.125 \times 10^{-9}x^3 - 3.9732 \times 10^{-6}x^2 - 0.00049554x + 6.8933$
	$R^2 = 0.93879$	$R^2 = 0.99697$
RSm	$y = -7.5521 \times 10^{-10}x^3 + 1.0158 \times 10^{-6}x^2 - 0.00042798x + 0.22112$	$y = -1.0417 \times 10^{-10}x^3 + 9.1964 \times 10^{-8}x^2 - 0.00010467x + 0.24011$
	$R^2 = 0.96237$	$R^2 = 0.99545$
	f_z (v_c = 300 m/min)	
Ra	$y = 8.8889x^3 - 43.2381x^2 + 16.6754x + 0.001$	$y = 1493.3333x^3 - 416x^2 + 44.2667x + 0.39$
	$R^2 = 0.99686$	$R^2 = 1$
Rz	$y = -4800x^3 + 1228.5714x^2 - 73.7143x + 5.23$	$y = 533.3333x^3 - 148.5714x^2 + 23.381x + 5.24$
	$R^2 = 0.99256$	$R^2 = 0.99824$
RSm	$y = -57.7778x^3 + 9.1619x^2 + 1.4737x + 0.0045667$	$y = 5.3333x^3 - 2.0571x^2 + 0.8481x + 0.15$
	$R^2 = 0.97841$	$R^2 = 0.99985$
	f_z (v_c = 900 m/min)	
Ra	$y = -1395.5556x^3 + 396.381x^2 - 23.104x + 0.88433$	$y = -320x^3 + 137.1429x^2 - 8.8286x + 1.42$
	$R^2 = 0.93968$	$R^2 = 0.97975$
Rz	$y = -1244.4444x^3 + 161.9048x^2 + 38.0635x + 0.73333$	$y = 1.1446 \times 10^{-11}x^3 + 11.4286x^2 + 11.7143x + 4.4$
	$R^2 = 0.99764$	$R^2 = 0.98848$
RSm	$y = -268.4444x^3 + 88.0571x^2 - 7.6403x + 0.28237$	$y = 21.3333x^3 - 5.8286x^2 + 1.1324x + 0.077$
	$R^2 = 0.9568$	$R^2 = 0.99786$

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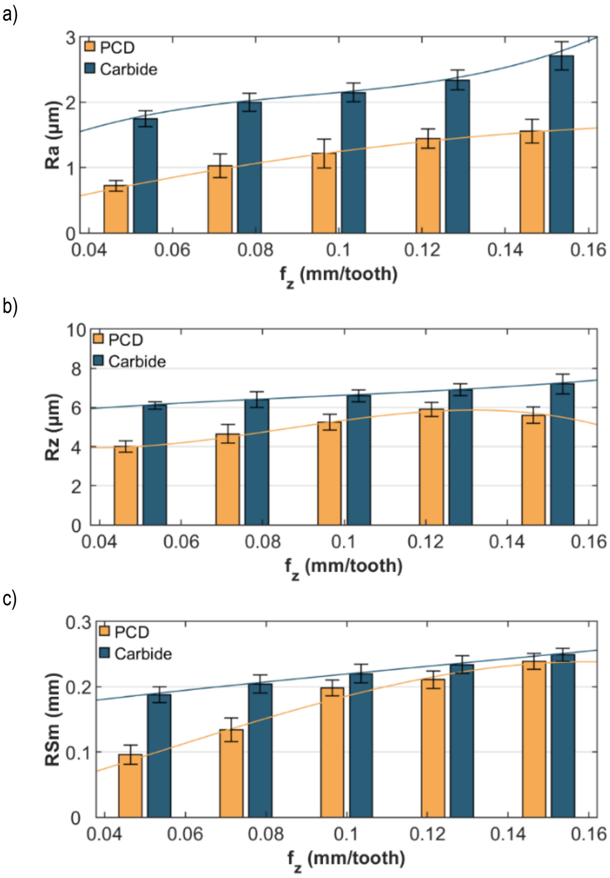

Fig. 3. Feed per tooth vs surface roughness parameters: a) *Ra*; b) *Rz*; c) *RSm* (v_c = 300 m/min)

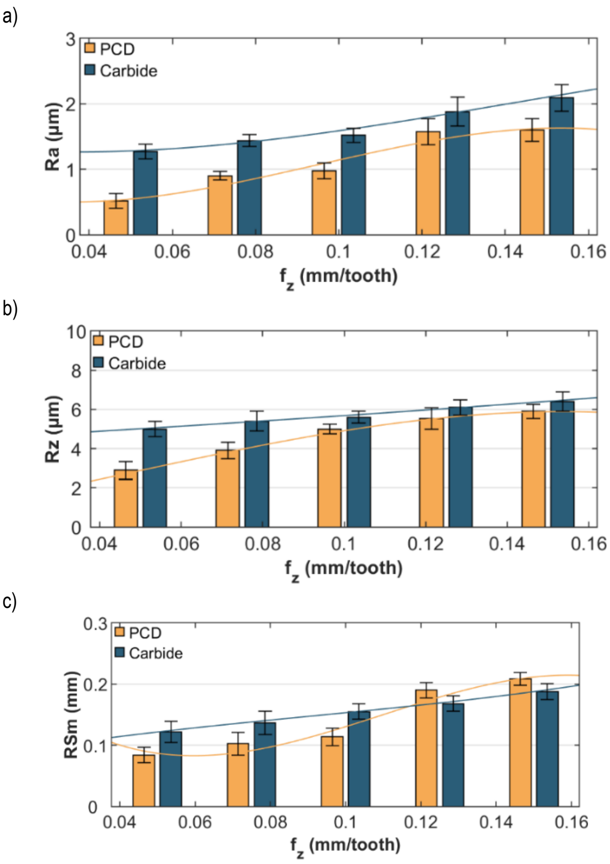

Fig. 4. Variable feed per tooth vs surface roughness parameters: a) *Ra*; b) *Rz*; c) *RSm* (v_c = 900 m/min)

In a milling process conducted with the cutting speed v_c = 900 m/min similar relationships can be observed as in that conducted with v_c = 300 m/min. The surface roughness parameters increase with increasing the feed per tooth and they are lower by as much as 0.75 µm for *Ra*, 2.1 µm for *Rz* and 0.038 mm for *RSm* for the milling process performed using the tool with PCD inserts. The use of the highest feed values, however, resulted in a significant increase in the *RSm* value, exceeding that obtained with the carbide tool.

In addition, the use of higher cutting speeds resulted in lower values of the surface roughness parameters than those obtained with v_c = 300 m/min. For the tool with PCD inserts, the differences are 0.24 µm for *Ra*, 1.1 µm for *Rz* and 0.084 mm for *RSm*. At the highest feed per tooth, however, the parameters are comparable for both cutting speeds. For the carbide tool, an increase in the cutting speed is beneficial over the entire tested feed per tooth range as the differences are as high as 0.62 µm for *Ra*, 1.1 µm for *Rz* and 0.067 mm for *RSm*.

Regression equations were also determined for the obtained surface roughness parameters – Table 2.

3.2. Cutting force

The study also involved measuring the cutting force components during machining. Figures 5-7 give examples of signals of the cutting force component F_x for the extreme values of the analysed cutting parameters. The signals are characterized by high stability, with no sudden jumps in their values, which indicates that the milling process proceeded in a stable manner. On the other hand, their characteristics change with varying the machining parameters.

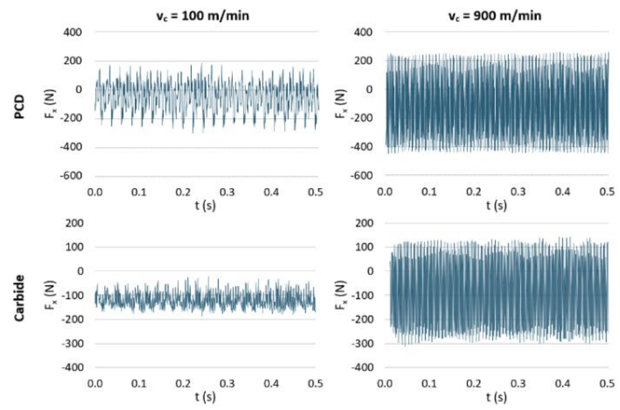

Fig. 5. Variations in the cutting force component F_x during a milling process conducted with variable v_c

Based on the obtained signals, the maximum values of the cutting force components were determined and analysed. A similar trend of changes in the values of these components can be observed in the milling process conducted with a variable cutting speed, for both cutting tools – Figures 8-10. The F_z component values increase with the cutting speed, while the values of F_x and F_y decrease first and then begin to increase again when the process is conducted with the high cutting speed values. The exception is milling conducted using the diamond tool and v_c = 300 m/min where all cutting force components increase. The highest values were obtained for the F_x, F_y and F_z components,

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respectively for both tools. Significantly higher values were obtained using a diamond tool, which is due to its geometry. No correlation is observed between the changes in the values of the cutting force components and the surface roughness parameters, as the latter decrease steadily with increasing the cutting speed.

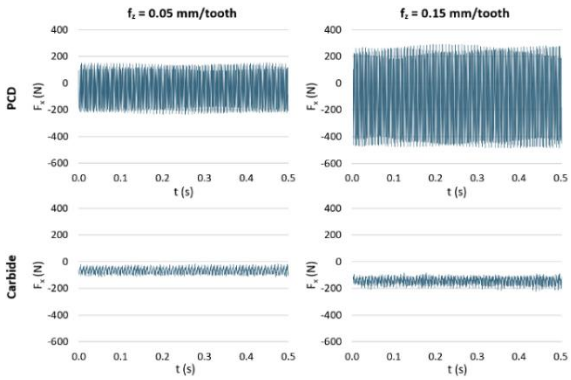

Fig. 6. Variations in the cutting force component F_x during a milling process conducted with variable f_z (v_c = 300 m/min)

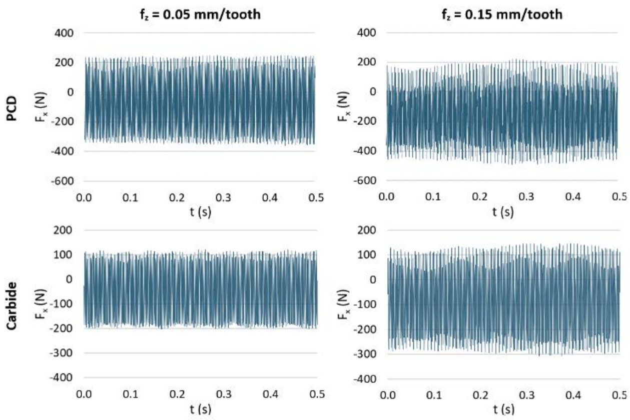

Fig. 7. Variations in the cutting force component F_x during a milling process conducted with variable f_z (v_c = 900 m/min)

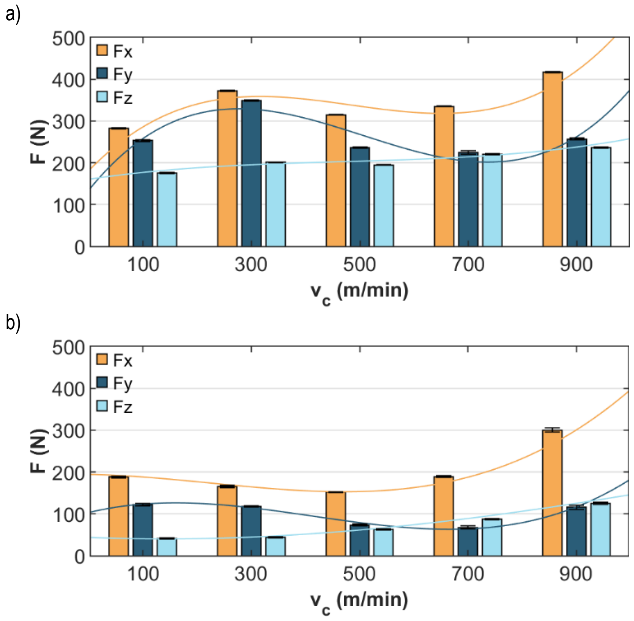

Fig. 8. Variable cutting speed vs cutting force for: a) PCD; b) carbide tool (f_z = 0.1 mm/tooth)

The relationship between a variable feed and the cutting force components is rather unambiguous for the milling process conducted using the diamond tool. All components successively increase their value over the entire feed range. The highest values are observed for the F_x component. The F_y component values are lower, with an increasing difference between them. In contrast, the values of the F_z component are about half lower than those of the F_x component. This trend of changes in the cutting force components corresponds to the changes observed for the surface texture, where the values of the surface roughness parameters would gradually increase with increasing the feed per tooth.

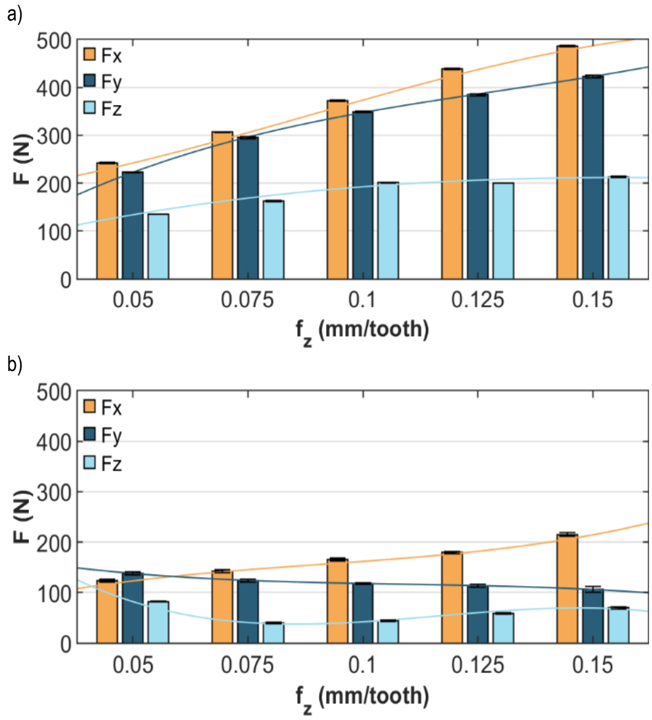

Fig. 9. Feed per tooth vs cutting force for: a) PCD; b) carbide tool (v_c = 300 m/min)

Regarding the carbide tool, each cutting force component shows a different trend. The F_x component increases over the entire tested feed range, while the F_y component decreases. The F_z component decreases first and then increases starting from f_z = 0.75 mm/tooth. The distribution of the cutting force components is similar to that obtained for the diamond tool, i.e. the highest values are achieved by the F_x component whereas the lowest by the F_z component.

Significant differences can be observed in the values of the cutting force components depending on the type of tool. In addition, these differences increase with increasing the feed per tooth. In a milling process conducted with the carbide tool, the values are lower by as much as 271 N for the F_x component, by 316 N for the F_y component and by 143 N for the F_z component. These significant differences may be due to a larger helix angle, leading to a reduction in the generated cutting force. The increase in the cutting force components is accompanied by higher surface roughness parameters.

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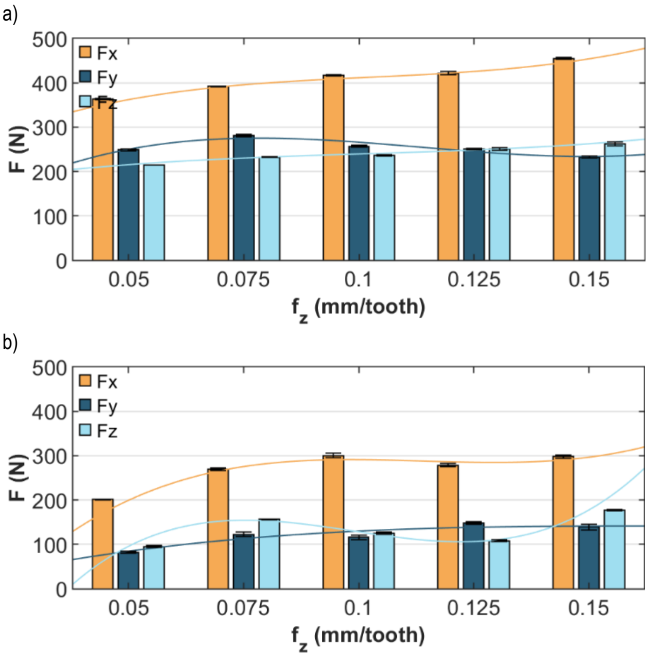

Fig. 10. Feed per tooth vs cutting force for: a) PCD; b) carbide tool (v_c = 900 m/min)

Completely different results were obtained from a milling process conducted with a variable feed per tooth and the cutting speed vc = 900 m/min. When using the diamond tool, the values of the Fx and Fz components increase with increasing the feed per tooth, which – to some extent – is due to changes in the surface texture and reduced surface quality with the feed increase. In contrast, the value of the Fy component begins to decrease starting from fz = 0.75 mm/tooth. For the carbide tool, on the other hand, the values of the cutting force components vary in a non-linear manner, as they fluctuate when the feed per tooth is changed. The values of the cutting force components are again lower for the carbide tool. The highest values are again achieved by the Fx component, while the values of Fy and Fz are about half as high.

The milling process conducted using the diamond tool and the cutting speed vc = 900 m/min had no clear impact on the cutting force components when compared to the milling process conducted with vc = 300 m/min. Mainly higher values of the Fx and Fz components were obtained, while the values for the Fy component were lower. The values differ by 121 N for Fx, 190 N for Fy and 79 N for Fz. As for the carbide tool, the high cutting speed has proved to be undesirable because the cutting force increases with the cutting speed. The obtained maximum values are higher by 134 N for Fx, by 34 N for Fy and by 117 N for Fz compared to the machining process conducted with vc = 300 m/min.

Regression equations were also determined for the obtained results – Table 3.

Tab. 3. Regression equations for the cutting force components

Component	PCD	Carbide
	v_c	
F_x	$y = 2.1734 \times 10^{-6}x^3 - 0.0031486x^2 + 1.3387x - 181.5044$	$y = 6.8696 \times 10^{-7}x^3 - 0.00046211x^2 - 0.022684x + 194.5068$
	$R^2 = 0.92574$	$R^2 = 0.99967$
F_y	$y = 2.6357 \times 10^{-6}x^3 - 0.0040011x^2 + 1.6079x - 134.8438$	$y = 9.7847 \times 10^{-7}x^3 - 0.0012124x^2 + 0.31351x + 103.4101$
	$R^2 = 0.80254$	$R^2 = 0.97897$
F_z	$y = 2.3882 \times 10^{-7}x^3 - 0.00033649x^2 + 0.19507x - 160.758$	$y = -4.3391 \times 10^{-8}x^3 + 0.00019882x^2 - 0.053533x + 44.2173$
	$R^2 = 0.92635$	$R^2 = 0.9991$
	f_z (v_c = 300 m/min)	
F_x	$y = -96682.6667x^3 + 25468.1943x^2 + 496.6658x + 165.8101$	$y = 97571.7333x^3 - 26474.3086x^2 + 3036.7114x + 25.412$
	$R^2 = 0.99988$	$R^2 = 0.99437$
F_y	$y = 109699.2x^3 - 42818.3886x^2 + 6999.1857x - 33.956$	$y = -58838.9333x^3 + 19257.8057x^2 - 2257.4428x + 210.1391$
	$R^2 = 0.99976$	$R^2 = 0.99969$
F_z	$y = 15057.0667x^3 - 12366.2514x^2 + 2759.5016x + 25.1968$	$y = -275146.5067x^3 + 96013.5394x^2 - 10386.9419x + 395.9015$
	$R^2 = 0.96265$	$R^2 = 0.99571$
	f_z (v_c = 900 m/min)	
F_x	$y = 170491.7333x^3 - 52457.1543x^2 + 5869.7915x + 178.4637$	$y = 413898.1333x^3 - 141383.1543x^2 + 15794.7885x - 288.4818$
	$R^2 = 0.98706$	$R^2 = 0.9745$
F_y	$y = 232014.1333x^3 - 79230.3303x^2 + 8143.1002x + 12.1011$	$y = 29947.2x^3 - 15807.84x^2 + 2755.607x - 17.3301$
	$R^2 = 0.87723$	$R^2 = 0.84802$
F_z	$y = 57291.3067x^3 - 17403.6217x^2 + 2089.9487x + 147.4216$	$y = 947917.8133x^3 - 281117.8789x^2 + 26232.8967x - 631.465$
	$R^2 = 0.98346$	$R^2 = 0.99651$

4. CONCLUSIONS

Based on the obtained results, the following conclusions were drawn:

- The use of a diamond tool led to a significant improvement in surface quality. Although the greatest differences were observed for the roughness parameter Ra, the results of the parameters Rz and RSm clearly differed as well.
- For both tested tools, the use of variable cutting parameters had a similar effect on the surface roughness results yet with different intensity. Although the diamond tool was more susceptible to changes in the machining conditions, its use allowed to control the machining effect to a greater extent.
- Regardless of the cutting tool type, lower surface roughness parameters were obtained when the milling process was conducted with the highest cutting speed and the lowest feed per tooth.
- The use of variable cutting speed had a similar effect on the changes in the cutting force components for both tested cutting tools. The exception was the milling process conducted with the diamond tool and vc = 300 m/min where an increase in the values of these components was observed.

– The impact of variable feed per tooth depended significantly on the cutting speed. When the milling process was conducted with a cutting speed of 300 m/min, the cutting force components increased linearly as a result of the feed per tooth increase, while the use of a cutting speed of 900 m/min caused the changes to occur in a non-linear manner. Nevertheless, regardless of the cutting tool and cutting speed applied, the lowest values of the cutting force components were obtained when the milling process was conducted with low feed values.
– Regardless of the machining conditions, the highest values were obtained for the Fx component, i.e. in the direction perpendicular to the movement of the cutting tool. While the values of Fy and Fz depended on the cutting parameters.
– No clear relationship was observed between the obtained surface roughness parameters and the cutting force. This makes it difficult to optimize machining both in terms of process stability and workpiece quality. The correlation between the two indicators became evident mainly when the milling process was conducted with the cutting speed vc = 300 m/min, where the cutting force components and the surface roughness parameters increased linearly with increasing the feed per tooth.

In future works, it is planned to extend the research conducted so far with additional indicators, such as: tool wear (especially at high speed cutting), vibrations, cutting temperature or tool deflection. These are phenomena that also have a significant impact on the course of machining and its effects. Analysis of additional parameters will allow for a better understanding of the processes occurring during milling of this group of materials. The research will also be continued for other aluminum alloys.

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