Influence of machining parameters on the polymer concrete milling process

Norbert Kepczak¹ · Piotr Zgorniak¹ · Paweł Lajmert¹ · Radosław Rosik¹ · Małgorzata Sikora¹

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Abstract

The paper examines the wear of end mill cutters, the parameters of a workpiece's surface layer and the values of cutting forces during the machining of polymer concrete, which is one of the most difficult-to-cut materials. Increased abrasive wear of the active cutting edges is a result of the heterogeneous structure of this material, and it has a negative effect on the cutting process, the durability of the cutting tools as well as the roughness of the workpiece. It is very important to determine the machining parameters for this material from a tool durability and quality of machining point of view. The research was divided into two stages. In the first stage, the appropriate machining parameters were determined based on the measurement of the components of the cutting force. In the second stage, durability tests of four end mill cutters were carried out. During the tests, the component cutting forces, tool wear and surface roughness were measured. The highest tool durability was recorded for the monolithic cemented carbide cutter with coating NC Mill G9F42120N 4F. Tools made of high-speed steel should not be used for machining polymer concrete, as they exhibited the highest intensity of tool wear. The rapid loss of machinability of these tools leads to a rapid increase in cutting force and the roughness of the machined surface. From an economic point of view, cemented carbide end mill cutters with coatings seem to be the appropriate choice for machining polymer concrete.

Keywords Milling · Polymer concrete · Mineral cast · Wear · Surface roughness · Cutting forces

Nomenclature

v_c cutting speed
 v_f table feed
 a_p axial depth of cut
 a_e radial depth of cut

F_x component cutting force in X direction of the rotating dynamometer
 F_y component cutting force in Y direction of the rotating dynamometer
 F_z component cutting force in axial Z direction of the rotating dynamometer
 F_a resultant active force in the X–Y plane
 L cutting distance
 Ra roughness average
 Rz average maximum height of the profile
 $VB1$ uniform flank wear
 $VB2$ non-uniform flank wear

✉ Norbert Kepczak
norbert.kepczak@p.lodz.pl

Piotr Zgorniak
piotr.zgorniak@p.lodz.pl

Paweł Lajmert
pawel.lajmert@p.lodz.pl

Radosław Rosik
radoslaw.rosik@p.lodz.pl

Małgorzata Sikora
malgorzata.sikora@p.lodz.pl

¹ Institute of Machine Tools and Production Engineering, Faculty of Mechanical Engineering, Lodz University of Technology, Stefanowskiego 1/15, 90-924 Lodz, Poland

1 Introduction

Modern industry is constantly looking for new construction solutions, as well as modern and ecological materials, which thanks to their properties will improve the quality of manufactured products, reduce the costs associated with the production process and increase its flexibility. Such materials include polymer concrete, which also appears under the name

mineral cast. It is a complex material consisting of inorganic aggregates, such as basalt, spodumene ($\text{LiAlSi}_2\text{O}_6$), fly ash, river gravel, sand, chalk, etc., bound with each other by resin [1–3]. The most commonly used resins are epoxy [4], polyester [5] and vinyl ester [6].

Current trends in the development of machine tool construction include the application of mineral casts as substitutes for cast iron. In some cases, polymer concrete is applied to selected components of machine tools, e.g. guides or as filler for the ribs of machine tool bodies [7]. This material is also used to manufacture entire machine tool frames, e.g. precision grinding machine bodies, if the strength requirements allow [8, 9]. What is more, in order to improve the dynamic properties of machine tool, polymer concrete with addition of styrene-butadiene rubber can be used [10].

Due to the significant initial dimensional and shape errors of mineral cast, it is necessary to carry out precise machining in selected surfaces of the material for the correct assembly of machine tool parts. For this purpose, the most widely used method is milling.

The literature offers mostly information on turning [11, 12] or grinding [13–15] mineral casts. The results of these tests, however, have no impact on the milling process due to the variability of the cutting edge loads occurring during this process. Variable cutting edges loads adversely affect tool durability, dimensional and shape accuracy, the quality of the machined surface and the cost of machining. Therefore, it was considered reasonable to determine the durability of tools during the milling of polymer concrete. It was very important to select the appropriate machining conditions and cutting tool, both of which are known to influence considerably the course and effects of the machining process of polymer concrete.

Modern high-performance tools, which allow high-speed cutting, have had a significant impact on the development of machining. The increase in durability of cutting tools depends on the abrasive resistance of the material from which they are made (high-speed steel, cemented carbide, ceramics or super-hard materials – cubic boron nitride (CBN) or synthetic diamond) [16]. In the case of polymer concrete processing, due to its heterogeneity, durability of the tool can be a parameter determining its application.

Cutting edge wear refers to the geometric change of the tool during operation and is related to material loss, change of deformation, high temperature, etc. Mechanical wear can occur after exceeding the immediate or fatigue strength of the cutting edge. It may have an unexpected character and is often called strength wear, which can be manifested by nicks at the edge of the cutting tool, chipping, breaks or cracks. The vibrations of the tool relative to the workpiece are one of the reasons for strength wear. Abrasive wear is caused by micro-scratching and shearing of micro-tops and irregularities on the surface of the active cutting edge. Typical abrasive wear is characterized by loss, cracks, plastic deformation or oxidation of the material.

The degree of the tool's wear is described by wear indicators, which are determined on the flank and face surfaces. These indicators are described in detail in works [12, 17]. When the cutting properties of the edge are lost due to tool wear, 'dulling' occurs.

Failure to comply with technological criteria may lead to weakening and excessive wear of the cutting tool, resulting in catastrophic tool wear. The recommended values of wear criteria for fine machining are shown in Table 1 [18].

Monitoring the varying conditions of milling tools over time to facilitate the timely detection of tool damage is critical for limiting the indirect effects of tool breakage while maximizing the usable life of milling tools. Thus, tool condition monitoring (TCM) systems have been developed to generate better workpiece surface quality and extend tool life by diagnosing cutting tool deficiencies using appropriate signal processing and pattern recognition techniques. An accurate and reliable TCM system can reduce costs by 10–40% by reducing downtime and maximizing the usable life of milling tools [19, 20]. Monitoring the machining process in real time allows for the uninterrupted monitoring of process conditions during cutting without the need to stop the machine in order to measure tool wear, cutting forces, surface roughness, etc. [21]. Various real-time monitoring instruments exist, such as dynamometers, current sensors, vibrations sensors and acoustic emissions [22–24].

During milling processes, tool wear increases surface roughness and leads to a corresponding increase in cutting force. A number of studies [25–28] have demonstrated that the cutting force is very sensitive to changes in tool condition and can, therefore, accurately estimate the state of the tool. Wang et al. [29] determined that the cutting force signal is the most stable and reliable signal among the commonly employed sensor signals closely related to tool wear. Huang et al. [30] used a piezoelectric dynamometer to monitor the tool state of an end milling operation according to cutting force. Bulent et al. [31] adopted a rotary dynamometer to capture the cutting forces in three dimensions and the torque of the drive moment on a rotating tool. Cutting force sensors, however, are difficult to apply in industrial environments because their physical properties limit the physical size of a workpiece, which is not practical when milling medium and large workpieces [32]. In addition, Koike et al. [33]

Table 1 Recommended values of the wear criteria of milling tools [18]

Material of cutters	Indicator of wear [mm]		
	<i>VB1</i>	<i>VB2</i>	<i>KT</i>
High-speed steel	0.2–1.0	0.35–1.0	0.1–0.7
Cemented carbide	0.3–0.5	0.5–0.7	0.1–0.2
Ceramics	0.15–0.3	–	0.1

established that cutting force monitoring interferes with the motion control of the spindle and stage in a milling machine, thus, reducing its rigidity. Moreover, the expense of commercial dynamometers can increase manufacturing costs prohibitively [34, 35].

This article presents the results of investigations on the polymer concrete milling process. The study has been divided into two stages. In the first stage, convenient processing parameters for polymer concrete were determined on the basis of cutting force. In the second stage, durability tests of four end mill cutters were carried out. In order to obtain a full picture of the cutting process during machining, the values of the components of cutting force were recorded. Then, following machining, tool wear and the roughness of the machined surface were measured. A schematic diagram of the experimental set-up showing the procedures used during the investigation can be found in Fig. 1.

2 Materials and methods

The material used for the tests was polymer concrete offered by RAMPF, available on the market under the name EPUCRET 140/5 [36]. This is a material used for casting small parts of machines, for example, guideways, tables or beds, with a weight not exceeding 500 kg. It consists of aggregates with dimensions ranging from a few micrometres up to 5 mm. A series of cuboidal samples were prepared for the tests with the following dimensions: cross-section 40×40 mm

and height 60 mm. The samples were prepared according to the following composition:

- 10% weight of the resin with the hardener
- 50% weight of grains, with grain diameter not exceeding 2 mm
- 40% weight of grains, with grain diameter greater than 2 mm

Figure 2 shows a view of a sample prepared for testing, mounted on a machine vice.

The purpose of the first part of the study was to determine the appropriate cutting parameters by performing milling tests with variable machining parameters: cutting speed (v_c), table feed (v_f) and axial depth of cut (a_p), and analysing the cutting force components. In the scientific literature, there is no information on the machining parameters during the milling of mineral casts. Therefore, the intention of these experiments was to determine the most convenient cutting parameters in order to obtain the smallest values for the cutting force components. For this research, monolithic cemented carbide end mill cutter NC Mill G9F42120N with coating, with a diameter of 12 mm, was used (Fig. 3c). During each test, a new cutter was mounted on the machine. The cutting distance during the machining of polymer concrete was $L = 60$ mm. Milling tests were repeated three times. The research was conducted on a Haas Mini Mill CNC milling machine with a spindle power of 7.5 kW. Based on the machine tool capabilities, the tests were carried out for three cutting speed values v_c , three table feed

Fig. 1 Schematic diagram of experimental setup showing the procedures used during the investigation

Fig. 2 Machined sample with NC Mill G9F42120N 4F end mill cutter

values v_f and three cutting axial depth values a_p (Table 2). The value of radial depth of cut a_e was constant and set at 8 mm. A Kistler type 9123C rotary dynamometer was used for the tests, which was connected to a Kistler 5223 type amplifier. Data from the dynamometer was registered by Keithley KUSB-3102 data acquisition card and quickDAQ measuring software.

In the second part of the study, experiments on the wear of four end mill cutters with a diameter of 12 mm of various construction materials were carried out (Fig. 3):

- a) Monolithic cutter HSS Fenes 844 A 12 K-N; $z = 4$; helix angle $\lambda = 30^\circ$; rake angle $= 8^\circ$

Fig. 3 Tools used in the experiments: (a) HSS Fenes 844 A 12K-N, (b) Dolfamex A12 K-M-N HSS-E, (c) NC Mill G9F42120N 4F, (d) Sandvik Coromant 2F341–1200-100-SC 1710

- b) Monolithic cutter with addition of cobalt Dolfamex DIN844A 12 K-M-N HSS-E; $z = 4$; helix angle $\lambda = 30^\circ$; rake angle $= 8^\circ$
- c) Monolithic cemented carbide cutter with coating YG-1 Group; Nc Mill G9F42120N 4F; $z = 4$; helix angle $\lambda = 30^\circ$; micrograin, X-Coating
- d) Monolithic cemented carbide cutter with protective coating Sandvik 2F341-1200-100-SC 1710; $z = 5$; helix angle $\lambda = 42^\circ$; grade, 1710; coating, PVD TiAlN+TiSiN; corner radius = 1 mm; axial rake angle $= 10.5^\circ$

In order to obtain reliable cutting test results, each milling test presented in Table 2 was repeated three times. For the final evaluation of the influence of individual cutting parameters and the type of cutting tool, the results were developed using mathematical statistics. In addition, for each test, the parameters describing the microgeometry of the machined surface were measured using the Mitutoyo SJ-210 surface roughness gauge. The arithmetic mean of three measurements of R_a and R_z surface roughness parameters was calculated for each sample in strictly defined places in order to define the influence of the wear of cutters on surface quality.

3 Experimental results

3.1 Selection of appropriate cutting parameters

The initial examination concerned F_x , F_y and F_z component forces acquired with 1000 Hz frequency. The influence of depth of cut a_p , table feed v_f and cutting speed v_c on cutting forces during the polymer concrete milling process was investigated. The values of component forces F_x and F_y have been located approximately symmetrically in accordance with level zero [37]. For better evaluation results, the F_a resultant active force in the X–Y plane has been calculated as the root of the sum of component squares F_x and F_y (1).

$$F_a = \sqrt{F_x^2 + F_y^2} \quad (1)$$

A representative resultant active force profile obtained in test 1 (Table 2) is presented in Fig. 4.

For cutting test 7, where the fastest table feed $v_f = 300 \text{ mm/min}$ was set, the total number of samples acquired was 13,632. This test determined the evaluating range of 10,001 samples for all cutting tests, which gives approximately 10 s of evaluated time. On the basis of the described procedure, the influence of different cutting parameters on resultant active force F_a has been investigated. The results of the influence of depth of cut a_p , table feed v_f and cutting speed v_c on F_a have been presented in Fig. 5.

Table 2 Machining parameters

Test	Cutting speed v_c [m/min]	Table feed v_f [mm/min]	Axial depth of cut a_p [mm]	Radial depth of cut a_e [mm]
1	25	100	1	8
2	25	100	2	
3	25	100	3	
4	50	200	1	1
5	25	200	1	
6	15	200	1	
7	25	300	1	

In each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points that are not considered outliers (lower and upper adjacent), while the outliers are plotted individually using the ‘+’ symbol. The detailed results of F_a forces presented in Fig. 5 have been tabulated in Table 3.

On the basis of the obtained results presented in Fig. 5 and Table 3, an increase of the F_a force alongside the increase of depth of cut a_p was observed. F_a force also increased alongside table feed v_f . When cutting speed v_c increased, however, F_a values initially decreased and raised their minimum at 25 m/min. Then, the values of F_a increased again.

The same procedure was employed for the F_z component cutting force. Evaluation took place on the same number of samples as for the resultant active force F_a . The influence of different cutting parameters on F_z component forces was presented in Fig. 6.

The detailed results of F_z forces presented in Fig. 6 have been tabulated in Table 4.

The obtained data of component cutting force F_z have similar character to resultant active force F_a , which confirms the authors’ selection of cutting parameters for the following tests.

Although the data presented on the basis of raw signals shows correctly the influence of different types of cutting parameters, the authors decided to use a special script created in MATLAB taking into consideration the moving average (movmean) and also a function called “findpeaks”. By means of this script, it was possible to analyse the influence of different values of parameters, such as window size in the moving average and also the distance between peaks in the course of forces. Peaks in the signal seem to appear at regular intervals. Some of the peaks, however, are very close to each other. The MinPeakProminence property was used to filter out these peaks. For better clarity, Fig. 7 presents the results of filtering the F_z signal by moving average, with a window parameter equal to 100 and the MinPeakProminence parameter set to 4. In order to identify the maximum force values recorded during the milling process, the mean of maximum values for F_a and F_z was employed (Figs. 11 and 12) and a longer time interval was taken into consideration during tool wear investigation (Chapter 4.2.2).

Based on the analyses carried out for the milling tests, it can be observed that minimum values of component forces were obtained in tests 1, 6 and 7. Conversely, maximum values were obtained in test 3 (Table 2). As is well known, extensive levels

Fig. 4 Raw signal of resultant active force F_a obtained for test number 1 presented in Table 2

Fig. 5 Boxplots of the influence of cutting parameters on resultant active force F_a

of cutting force during removal processes cause accelerated wear in cutting tools and tool-in-use systems of machine tools.

On the basis of the obtained results, the authors concluded that for tool-life tests, the following parameters should be established: $a_p = 1$ mm, $v_f = 100$ mm/min and $v_c = 25$ m/min.

3.2 Tool-life testing

The method for measuring wear indicators in the case of end mill cutters is more complicated than in the case of the turning process [38]. Various designations for these indicators can be found in the literature [12, 17, 39]. During the machining of polymer concrete, the most common wear type observed is abrasive wear on the tool flank of the end mill cutter. In order to evaluate the intensity of abrasive wear of different types of end mill cutters (Fig. 3), two categories of wear indicators have been chosen [39]:

- VB1 – uniform flank wear
- VB2 – non-uniform flank wear

Machining tests of cuboid samples with cutting speed $v_c = 25$ m/min, table feed $v_f = 100$ mm/min, axial depth of cut $a_p = 1$ mm and radial depth of cut $a_e = 8$ mm were carried out. The total milling distance for each tool depended on its degree of wear. If extensive tool wear was observed, exceeding the recommended values, or if chipping had occurred, the experiment was interrupted because the tool was unable to continue with the machining operation. In this article, the non-uniform flank wear indicator VB2 was determined from the flank and concerned the maximum value detected after each cutting test. The uniform flank wear indicator VB1 was determined from the cylindrical flank as an average of three measurements from a relatively uniform abrasive wear area. An indicative way of measuring the described indicators is presented in Fig. 8. The values of indicators presented in the subsequent plots are the arithmetic mean of wear measured on all teeth of the milling cutters tested.

Table 3 Detailed results of F_a forces

	a_p [mm]			v_f [mm/min]			v_c [m/min]		
	<u>1</u>	<u>2</u>	<u>3</u>	<u>100</u>	<u>200</u>	<u>300</u>	<u>15</u>	<u>25</u>	<u>50</u>
Min.	0.174	10.519	7.554	0.1740	0.0738	0.440	1.415	0.074	0.266
Lower adjacent	0.174	10.519	7.554	0.1740	0.0738	0.440	1.415	0.074	0.266
25th percentile	24.183	126.510	236.024	24.183	34.438	40.259	47.526	34.438	51.257
Median	43.785	169.759	310.262	43.785	58.794	65.707	72.095	58.794	85.355
75th percentile	72.470	227.573	399.096	72.471	92.285	101.756	105.605	92.285	134.208
Upper adjacent	144.856	379.040	643.487	144.857	178.809	193.718	192.080	178.809	258.555
Max.	214.326	452.626	699.221	214.326	239.981	282.184	251.054	239.981	397.530
Outliers	156	83	15	156	79	179	68	79	117

Fig. 6 Boxplots of the influence of cutting parameters on the F_z component cutting force

3.2.1 Wear of end mill cutters

Figure 9 shows wear indicators $VB1$ and $VB2$ as a function of cutting distance L , measured in compliance with the procedure described in the previous chapter and illustrated in Fig. 8. The highest wear after the shortest cutting distance was obtained for HSS cutters made of high-speed steel, i.e. 844 A 12 K-N and A 12 K-M-N HSS-E. At the very beginning of the experiment, these mill cutters were heavily worn and were not suitable for further machining. The smallest wear and the longest cutting distance L were obtained for a cemented carbide milling cutter, NC Mill G9F42120N 4F, with protective coating. In this case, a cutting distance of $L = 3550$ mm was obtained with the abrasive wear criterion of $VB1 = 0.5$ mm. The fastest wear was observed at the corners of the tool.

In the initial cutting trials (up to $L = 1120$ mm), the least wear was obtained for the Sandvick Coromant 2F341-1200-100-SC 1710 end mill cutter with protective coating. During the tool-life experiment, however, it transpired that the applied coating was not resistant to impact strength, which caused it to

break off at a rapid rate and intensive wear. Upon exceeding the cutting distance of $L = 1120$ mm, considerable nicks appeared on the cutting edges. These tests confirmed that when machining polymer concrete samples, intensive abrasion is observed at the corners and on the cylindrical and front flanks (Fig. 8), making it highly difficult to machine. A very important factor that has a direct impact on the durability of cutting tools is the amount of heat generated in the machining zone. This aspect has been widely studied [40–42]. Based on the literature review, it was found that not only the cutting parameters should be selected in such a way as to obtain the highest efficiency, but also that the temperature values generated in the machining zone should be taken into account. As heat generated during the machining process has a significant impact on the durability of cutting tools, maximum temperature values should be investigated and measured. This is especially important in the case of dry cutting or cutting with a minimum quantity of lubrication (MQL). In the research presented in this article, the flooding method of delivering a cooling-lubricant liquid into the cutting zone was employed.

Table 4 Detailed results of F_z forces

	a_p [mm]			v_f [mm/min]			v_c [m/min]		
	<u>1</u>	<u>2</u>	<u>3</u>	<u>100</u>	<u>200</u>	<u>300</u>	<u>15</u>	<u>25</u>	<u>50</u>
Min.	−10.693	−11.035	−19.238	−10.693	−13.672	−14.648	−11.182	−13.672	0.195
Lower adjacent	−10.693	−11.035	−19.238	−10.693	−13.672	−14.648	−11.182	−13.672	0.195
25th percentile	11.279	10.986	11.035	11.279	11.231	15.820	11.279	11.231	33.594
Median	17.822	18.311	21.240	17.822	18.750	25.244	23.047	18.750	46.875
75th percentile	29.394	30.518	34.277	29.394	34.668	43.274	41.272	34.668	68.897
Upper adjacent	56.543	59.766	69.141	56.543	69.824	84.424	85.938	69.824	121.777
Max.	74.072	81.641	102.734	74.072	102.979	138.477	108.301	102.979	185.938
Outliers	70	52	114	70	150	325	65	150	361

Fig. 7 Filtering results of F_z component cutting force for test 1

3.2.2 Cutting forces

Among many methods of online tool wear monitoring [21–23], the cutting forces measurements have been taken into consideration. Experiments on machining performed to determine the durability of cutting tools for uniform cutting parameters: $v_c = 25 \text{ m/min}$; $f = 100 \text{ m/min}$; $a_p = 1 \text{ mm}$ and $a_e = 8 \text{ mm}$ were analysed in detail taking into account the amplitude of the components of cutting force. The following figures show a comparison of the amplitude of components of cutting force for cutting distance $L = 40 \text{ mm}$, corresponding to the end mill cutter in sharpened state, and for cutting distance $L = 3550 \text{ mm}$, corresponding to the tool in which the VB1 indicator was detected at the value of 0.5 mm . Cutting tests

were recorded at a frequency of 10,000 Hz. One series of data from a cutting experiment included approximately 585,000 samples from three measurement channels (F_x , F_y , F_z), corresponding to 58.5 s of data acquisition time. Due to the readability of the presented data, only the time interval corresponding to 1 s is shown in the diagrams in Fig. 10.

On the basis of the presented waveforms, it can be stated that the character of the waveforms of the F_x and F_y forces is similar, while it is shifted relative to each other in the phase. In the case of the F_z component, the course corresponding to the sharp tool is approximately repeated from zero to maximum value (Fig. 10c). For the dulled tool, the minimum value does not return to zero but remains at around 300 N. Therefore, components F_x and F_y were compared in terms of the

Fig. 8 Wear of HSS Fenex 844 A 12 K-N end mill cutter: (a) general view, (b) uniform flank wear VB1, (c) face wear (crater and cutting edge loss), (d) non-uniform flank wear VB2

Fig. 9 Relationship between tool wear and cutting distance L : (a) VB1 abrasive wear indicator, (b) VB2 abrasive wear indicator

amplitude of the forces, while component F_z was compared in terms of maximum values. The results of the comparison are presented in Fig. 10d. The waveforms presented in Fig. 10 show that from the commencement of work to reaching the VB1 criterion value at 0.5 mm, the amplitude of the F_x component force increased by 564%, that of the F_y component force by 351%, and the maximum value of the F_z component force increased by 1691%. Thus, the increase in the F_z component force was the largest, which suggests much greater intensive wear at the corners and cutting edges on the face flank of the cutter than on the cylindrical flank surface.

In relation to the tool-life analysis, the F_z component cutting force and the F_a resultant active cutting force in the X–Y plane were determined.

Compared to the initial cutting tests carried out, it was also determined that the cutting force measurements are characterized by considerable arbitrariness in subsequent tool-life tests. The variable and random nature of the loads acting on the tool

result from the different amounts and size of the aggregate grains contained in different areas of the machined sample. In order to analyse these forces reliably and reduce the impact of material inhomogeneity, special software has been developed to calculate the average values of recorded signals.

The procedure employed for determining the mean values of analysed component force signals consists of detecting the maximum values recorded during one revolution of the end mill cutter in the assumed interval of time and calculating the average value from the detected maxima. A fixed time interval was assumed for all machining tests equal to 25 s. An example of the course of the component cutting force F_z ($L = 2920$ mm) with the analysed range was shown in Fig. 11. Figure 12 shows the course of the maximum values of component F_z (in red) and the determined mean value (in green) for the set range.

The cutting forces obtained in this way are characterized by a smaller spread of the force values, which greatly facilitates their subsequent analysis and prediction of the wear rate of the end

Fig. 10 Amplitude of component cutting force: (a) F_x , (b) F_y , (c) F_z , (d) the effect of end mill cutter wear based on a comparison of the amplitudes F_x and F_y and the maximum values of the component cutting force F_z

mill cutters. Figures 13 and 14 show the courses of the resultant cutting force F_a and the component cutting force F_z , respectively.

The highest values of cutting force occurred for end mill cutters made of high-speed steel (844 A 12 K-N and A 12 K-M-N HSS-E). The lowest cutting force values, however, were obtained for a cemented carbide cutter NC Mill G9F42120N 4F with protective coating. The lower cutting force for the cemented carbide tools is the result of protective coatings. Both tools have different types of protective coatings and different geometries, mainly the sharp corner and rounded corner. It can be said that sharp geometry is better for milling polymer concrete compared to a tool with a rounding radius.

Further, faster wear of the cutting edges results in increased tool vibrations [43] and variations in the cutting force, which translates into deterioration of the geometrical parameters of the machined surface. For this reason, in addition to measuring the components of the cutting force, the cutting force variations were also determined. There are many statistical features that

can describe the variability or non-stationarity of the cutting force [21, 23, 44]. The standard deviation of the F_z component signal and the resultant F_a milling force was used for this purpose. The standard deviation describes how widely the signal values are scattered around its mean. This parameter is described by the following relationship:

$$\sigma(F) = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (F_i - \bar{F})^2} \quad (2)$$

where:

n – the number of elements in the registered time series

$\bar{F}$ – the mean value of force calculated for the analysed time interval

Figures 15 and 16 show changes in the standard deviation for the F_a force and F_z component, respectively. As before, the largest increase in standard deviation was registered for end mill cutters made of high-speed steel, i.e. 844 A 12 K-N and A

Fig. 11 The course of component force F_z changes of the cutting force with the analysed time interval

Fig. 12 The signal of the component cutting force F_z in the analysed time interval and the determined mean line (in green) of the instantaneous maximum force values (in red) per one revolution of the milling cutter

Fig. 13 Changes of resultant cutting force F_a for individual end mill cutters

Fig. 14 Changes of component cutting force F_z for individual end mill cutters

Fig. 15 Relationship between the standard deviation of resultant cutting force F_a for individual end mill cutters and cutting distance L

12 K-M-N HSS-E. The smallest increase in standard deviation, however, was recorded for 2F341-1200-100-SC 1710 with coating and for the cemented carbide end mill cutter NC Mill G9F42120N 4F with coating.

3.2.3 Polymer concrete surface roughness

The surface roughness is influenced by many factors, including the material, manufacturing quality, the geometry of the cutting tool, the properties of the workpiece and the technological parameters used. Among the technological parameters, the most influential for surface quality is table feed rate v_f and to a lesser extent cutting speed v_c [45].

Surface roughness parameters Ra and Rz were measured during the tests. The relationship between Ra and Rz and cutting distance L for individual end mill cutters is presented in Fig. 17a, b, respectively. The quality of the surface, as expected, deteriorates with the increase of abrasive wear of end mill cutters. The worst surface quality was obtained for high-speed steel cutters (844 A 12 K-N and A 12 K-M-N HSS-E).

For both cemented carbide end mill cutters, the quality of the machined surface of the workpiece was similar. When the Sandvick Coromant 2F341-1200-100-SC 1710 end mill cutter begins to crumble, the surface quality deteriorates significantly. It should be emphasized that despite the significant level of wear of the tool's cutting edges, defined by the $VB1$ and $VB2$ indicators, the surface roughness parameters

Fig. 16 Relationship between the standard deviation of component cutting force F_z for individual end mill cutters and cutting distance L

Fig. 17 Relationship between surface roughness parameters and cutting distance for individual end mill cutters: (a) Ra , (b) Rz

Fig. 18 Dependence of cutting force components F_z and F_a on the tool wear parameters VB

Fig. 19 Dependence of part surface roughness parameters R_a and R_z on the tool wear parameters VB

observed at cutting distance $L = 1750 \text{ mm}$ for the NC Mill G9F42120N 4F end mill cutter changes slightly. These changes are at the level of $1 \mu\text{m}$. At a later stage, surface roughness deteriorates significantly.

The relationships between the tool wear parameters VB and the resulting cutting force components F_z and F_a , as well as part surface roughness parameters R_a and R_z , are shown in Figs. 18 and 19, respectively. In all cases, the coefficient of determination R^2 between tool wear and cutting force components, as well as part surface roughness parameters, is greater than 0.8 which confirms the possibility of diagnosing tool wear based on measurements of these force components. It confirms that use of these force components for the assessment of tool wear during preliminary test presented in Chapter 4.1.

In addition, it should be noted that the standard deviation waveforms (Figs. 15 and 16) are well correlated with changes in the R_a and R_z parameters of the machined surface. Therefore, the standard deviation of the resultant cutting force can also be used to predict surface quality as part of the cutting process diagnostics system.

Comparative photos of end mill cutters wear are shown in Fig. 20.

It should be noted that end mill cutter NC Mill G9F42120N 4F (Fig. 20c) cut the longest distance $L = 3550 \text{ mm}$ with the smallest wear. Sandvick Coromant 2F341-1200-100-SC 1710 (Fig. 20d) had cut a distance of $L = 1750 \text{ mm}$ when the values of wear indicators $VB1$ and $VB2$ exceeded the wear limit. End mill cutters HSS Fenes 844 A12K-N (Fig. 20a) and Dolfamex A12 K-M-N HSS-E (Fig. 20b) exceeded the wear limit after a cutting distance of $L = 40 \text{ mm}$.

Fig. 20 Comparison of end mill cutters wear: (a) HSS Fenes 844 A12K-N, (b) Dolfamex A12 K-M-N HSS-E, (c) NC Mill G9F42120N 4F, (d) Sandvick Coromant 2F341-1200-100-SC 1710

4 Conclusions

The paper presented the results of investigations in the machinability of a mineral cast material during milling. The impact of four types of end mill cutters and different machining conditions on cutting force, tool-life and selected surface roughness parameters were tested. The research allowed the formulation of the following conclusions:

1. Tools made of high-speed steel should not be used for machining mineral casts, as they exhibited the highest intensity of tool wear. The rapid loss of machinability of these tools leads to a rapid increase in cutting force and the roughness of the machined surface. In addition, the high values and variance of the cutting force during machining may adversely affect the durability of the machine components.
2. The machining parameters have a significant impact on the values of cutting force components F_x , F_y and F_z . As a result of the experimental tests carried out, the following convenient milling parameters for polymer concrete were determined:
 - Cutting speed $v_c = 25 \text{ m/min}$.
 - Table feed $v_f = 100 \text{ mm/min}$.
 - Axial depth of cut $a_p = 1 \text{ mm}$.
 - Radial depth of cut $a_e = 8 \text{ mm}$.
3. The highest durability for a tool was obtained for the monolithic cemented carbide cutter with coating NC Mill G9F42120N 4F. In this case, the cutting distance reached $L = 3550 \text{ mm}$.
4. The values of surface roughness parameters are comparable for both cemented carbide end mill cutters.
5. Despite the wear of cemented carbide cutters, changes in the surface roughness parameters are relatively small between the beginning and end of the machining process.

In conclusion, from an economic point of view, cemented carbide end mill cutters with coatings seem to be the most appropriate choice for the machining of mineral cast materials.

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