

Surface Quality of a Groove after Trochoidal Milling with a Monolithic Ceramic Milling Cutter

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Hard-to-machine materials conclude a variety of materials. In this group of materials are high-strength, hardness-resistant steels, such as austenitic steels, but also non-ferrous alloys with high corrosion, heat resistance and strength based on nickel, titanium or cobalt, etc. For machining of these materials, it is necessary to choose suitable tools. The improper cutting tool can cause an increase in geometric inaccuracies, rapid wear, etc. Cutting material is an important factor during designing of cutting tools. A combination of a proper cutting tool with the trochoidal milling can reduce machining time, extend tool lifetime and reduce production costs.

Keywords: Surface Quality, Trochoidal Milling, Ceramics

1 Introduction

Machining difficult-to-machine materials requires more effort in selecting the machine, cutting tool, machining strategy, and cutting conditions than conventional materials [1], [2]. Due to the constant progress in the aviation, automotive or aerospace industries, where the demand for the mechanical properties of materials is constantly increasing, more and more difficult - to - machine materials are being used [3], [4].

Hard-to-machine materials are a wide range of materials. In this group of materials we find high-strength, hardness-resistant steels, such as austenitic steels, but also non-ferrous alloys with high corrosion, heat resistance and strength based on nickel, titanium or cobalt [5], [6], [7].

By using suitable cutting materials, we can effectively increase productivity. One such new material is a material called Cerazur. Due to its good mechanical and physical properties, Cerazur has good conditions for the production of machine tools [8]. These tools are, for example, a ceramic finishing cutter.

Cutting ceramics are also suitable due to their high hardness. One of its disadvantages is the high brittleness and susceptibility to breakage, especially if the cutting tool is used during interrupted cutting. This is partially reduced by the use of an improved zirconia-based ceramic material. It has improved weak properties of cutting ceramics, such as increased flexural strength, modulus of elasticity, impact resistance, etc.

When using conventional tools, it is necessary to reduce the heat generated to maintain tool life. This means that the cutting speed is limited to approximately 70 m.min⁻¹. However, ceramic end mills can

achieve cutting speeds of 500 m.min⁻¹ and higher. This causes the heat that is generated to soften the material [9].

Usually, in the case of ceramic cutting tools, it is recommended to use high cutting speeds to generate heat, which can soften the material. It is not recommended to use process fluid (to avoid the risk of thermal cracks) in the cutting process [10], [11].

There are many different types of ceramics, but two types are particularly important: alumina (Al₂O₃) and silicon nitride (Si₃N₄). Compared to Al₂O₃, Si₃N₄ is chemically inert against atomic impurities and diffusion. A considerable amount of research has been done in machining with cutting inserts [4], but only a few machining experiments with finishing milling tools [12]. Due to the high cutting temperatures, high adhesive wear of the workpiece material was found. It was investigated the composition of this adhesive layer [13]. In addition, determined tool wear and cutting performance of nickel-based alloys. In this way, he has found that ceramic milling tools can perform comparable metal machining in less time, but the tool life is halved compared to coated finishing milling tools [14], [15].

When machining difficult-to-machine materials, there is high mechanical and thermal wear of the cutting tool. There is high friction on the cutting edge due to the contact between the cutting tool and the material being machined. Plastic deformation of the cutting edge and the periodic formation and separation of the growth during machining are common [2], [7], [16].

2 Procedure of Experiment

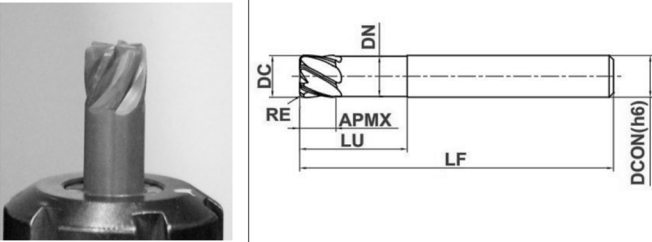
The experiments are based on the principles of

"Design of Experiment" DoE. It is a method of surface response. The determination of the cutting conditions was based on the recommendations of the tool manufacturer, the machine parameters and the rules of factorial arrangement of the experiment.

During the experiment, 5 factors changed (a total of 28 variants):

- cutting speed v_c ,
- feed per tooth f_z ,
- depth of cut a_p ,
- step trochoids s ,
- angle of engagement α_{eng} .

Tab. 1 Ceramic monolithic milling cutter

|  | DC | RE | APMX | LU | DN | LF | DCON |
|---|----|-----|------|----|------|----|------|
| | 10 | 1,0 | 7,5 | 20 | 9,70 | 65 | 10 |

An Alicona InfiniteFocus 3D scanning microscope was used to detect groove deformation. Samples were prepared on a Hurco VMX-30 t machine. Grooves' length was 65 mm and width 20 mm and they

Using the trochoidal milling, the parameters step of trochoid and engagement angle define the trochoidal path. The engagement angle α_{eng} is the angle of stroke occurring between the two directions, at the contact point of a tool and material.

During the experiment, the basic components of the cutting force were monitored using a three-component dynamometer Kistler 9255A and evaluated by DASYLab software.

The experiments used ceramic monolithic milling cutters with 6 teeth, CERAMIC END MILL series from Mitsubishi.

were made by trochoidal milling. The cutting conditions of the experiments are given in the following table:

Tab. 2 Values of cutting parameters in experiments

| cutting parameters | value | value | value |
|--|-------|-------|-------|
| cutting speed v_c (m.min ⁻¹) | 300 | 450 | 600 |
| feed per tooth f_z (mm) | 0,02 | 0,04 | 0,06 |
| depth of cut a_p (mm) | 1 | 3 | 5 |
| step of trochoid s (mm) | 0,2 | 0,6 | 1 |
| engagement angle α_{eng} (°) | 10 | 30 | 60 |

3 Results of the Experiment

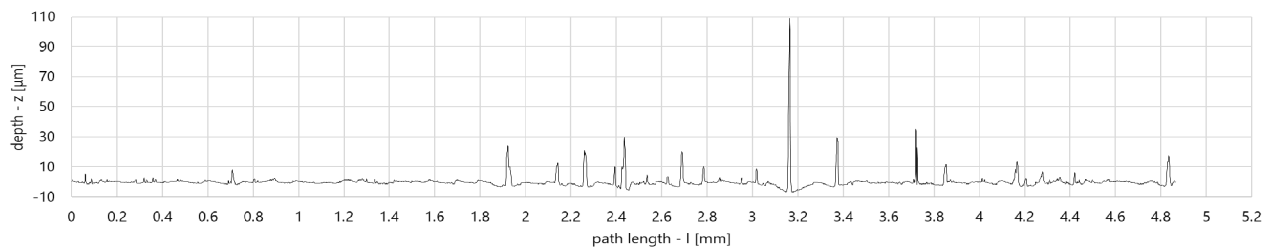
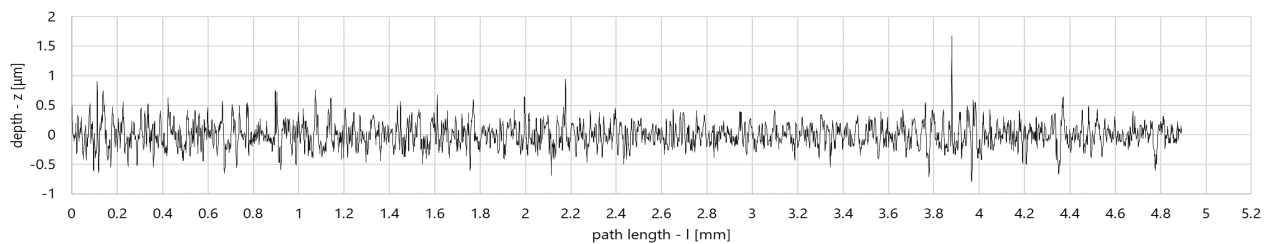
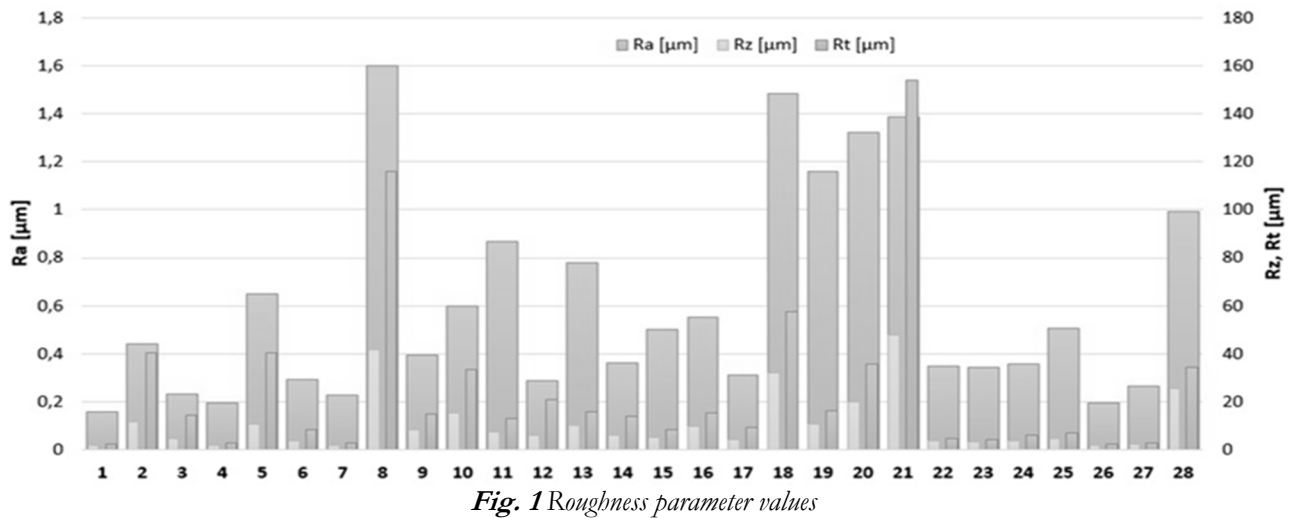
After the experiments, the surface roughness parameters were evaluated:

- roughness R_a , R_t , R_z measured in the middle of the groove according to ISO 4287 and ISO 4288,
- surface roughness S_a , S_q , S_z measured on the entire surface of the groove according to the ISO 25178.
- cutting forces (not in the first place).

The measured values are shown in the graphs.

As the graph shows, the largest values of roughness were reached by the parameters R_a and R_t .

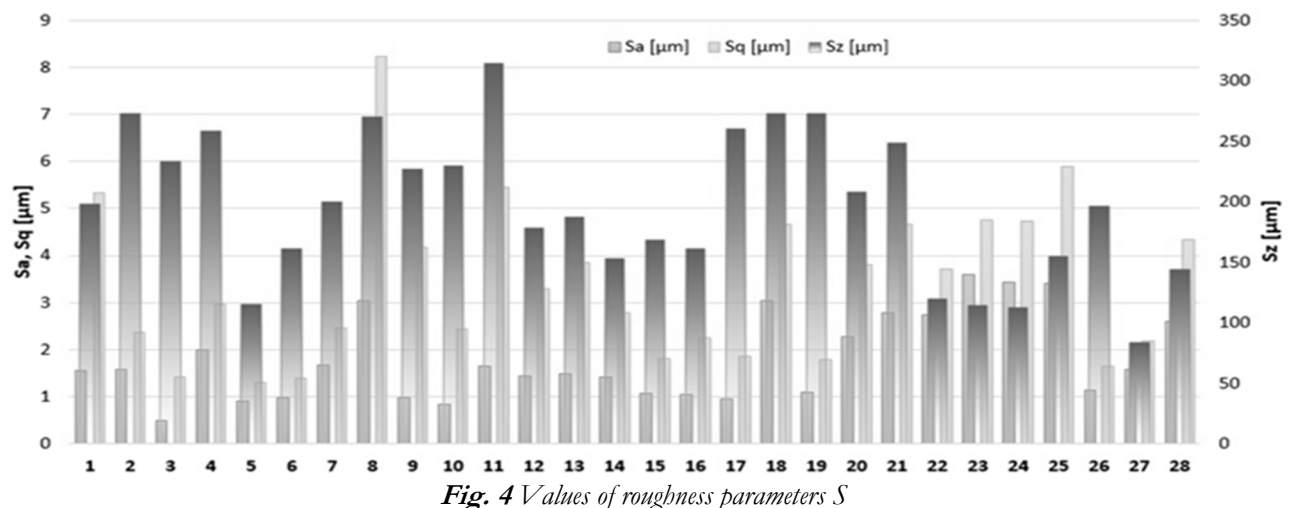
The measured length is shorter than the grooves' length due to the measuring errors caused by an entry and a run-out of the tool to and from the material. The fact that it is R_z , resp. R_t several times higher than R_a is due to the high differences between the protrusions and depressions. According to the definition of the parameter R_t , it follows that it describes the maximum difference between the depressions and the vertices of the inequalities, the parameter R_a - arithmetic average roughness - dependent on it also increased. The lowest value of roughness was reached by samples no. 1, no. 4 and no. 26. On sample No. 1, low roughness values R_a 0.16 μm , roughness R_z 1.67 μm and roughness R_t 2.47 μm at $v_c = 300$ m.min⁻¹ were achieved during milling, $f = 0.06$ mm, $s = 0.2$ mm, $a_p = 1$ mm and $\alpha_{eng} = 10^\circ$.



On the contrary, the worst surface quality was in sample no. 8 roughness values $R_a 1.60 \mu\text{m}$, roughness $R_z 41.9 \mu\text{m}$ and roughness $R_t 115.88 \mu\text{m}$ at $v_c = 300 \text{ m.min}^{-1}$, $f = 0.06 \text{ mm}$, $s = 1 \text{ mm}$, $a_p = 1 \text{ mm}$ and $\alpha_{eng} = 60^\circ$. The cutter had a radius of 1 mm, which was on the verge of its use. The higher the cutting angle at low

cutting speed, the worse the surface quality and in practice it would have to be adjusted by another operation.

Another measured parameter was the surface roughness S and its parameters S_a , S_q , S_z . The values are shown in the graph:



According to the graph, the highest values of surface roughness are shown in parameters Sq and Sz. Parameter Sq is the average mean square diameter of the surface roughness profiles and its value has an effect on the average surface roughness Sz.

The parameters S give a comprehensive view of the surface roughness in the whole measured range and thus provide an overall overview of the roughness on the machined surface.

After scanning with a microscope, the best surface on sample no. 3, with values for individual parameters $Sa = 0,49 \mu\text{m}$, $Sq = 1,42 \mu\text{m}$, $Sz = 233.60 \mu\text{m}$ at cutting conditions $v_c = 300 \text{ m}\cdot\text{min}^{-1}$, $f = 0.02 \text{ mm}$, $s = 0.2 \text{ mm}$, $a_p = 1 \text{ mm}$ and $\alpha_{\text{eng}} = 60^\circ$.

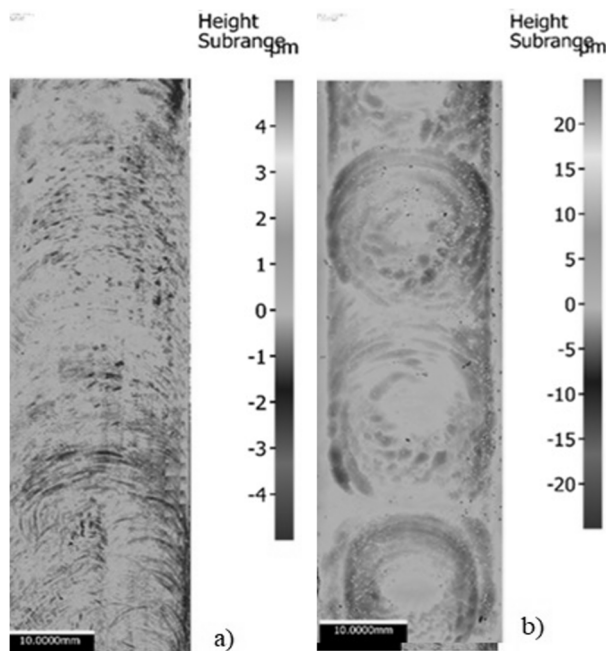


Fig. 5 Surface roughness of sample nr. 3 (a) and nr. 20 (b)

After evaluating the surface roughness, various surface defects, such as opals, were recorded for some samples. Their formation could be caused by poor chip evacuation from under the tool. For example, in sample no. 20 for cutting parameters $v_c = 300 \text{ m}\cdot\text{min}^{-1}$, $f = 0.02 \text{ mm}$, $s = 0.2 \text{ mm}$, $a_p = 5 \text{ mm}$, $\alpha_{\text{eng}} = 10^\circ$. At

$$Ra = -2.18 + 0.01425 \cdot v_c + 27.4f + 0.402 \cdot a_p - 1.87 \cdot s - 0.0653 \cdot \alpha - 0.000017 \cdot v_c^2 - 629 \cdot f^2 - 0.0450 \cdot a_p^2 + 1.23 \cdot s^2 + 0.000821 \cdot \alpha^2 + 0.0196 \cdot v_c \cdot f + 0.000354 \cdot v_c \cdot a_p - 0.00080 \cdot v_c \cdot s - 0.000015 \cdot v_c \cdot \alpha + 0.14 \cdot f \cdot a_p + 15.97 \cdot f \cdot s + 0.285f \cdot \alpha - 0.1979 \cdot a_p \cdot s - 0.00381 \cdot a_p \cdot \alpha + 0.02447s \cdot \alpha$$

$$R^2 = 88,49\%$$

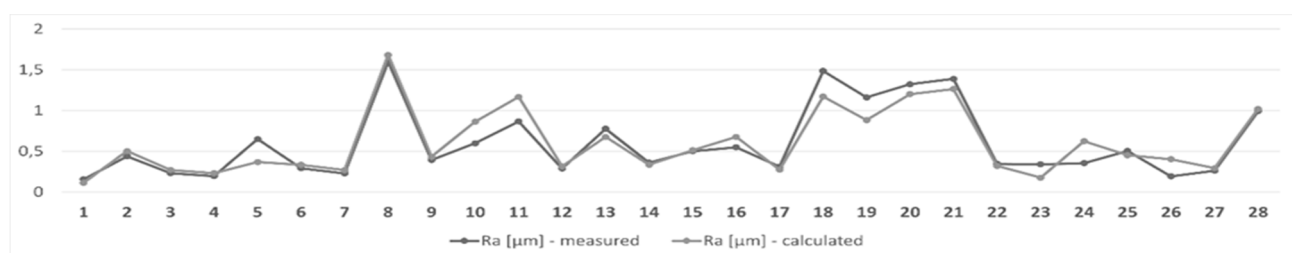


Fig. 7 Comparison of measured and calculated values of the parameter Ra

the greatest depth of cut, the lowest cutting speed, the smallest feed, the smallest step and the smallest angle of engagement, the surface roughness was higher than the others.

During the evaluation, the parameters Ra and Sa were also compared with each other. The values were again processed graphically.

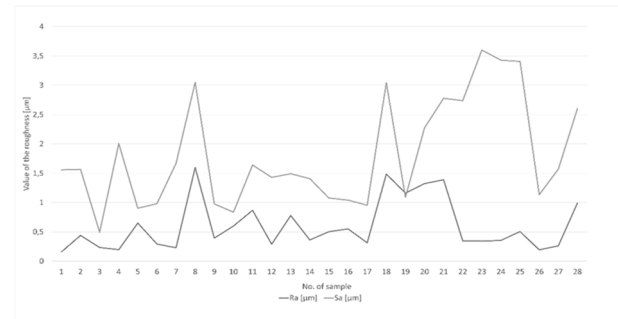


Fig. 6 Comparison of parameters Ra and Sa

From the graph it can be determined that the largest values of arithmetic roughness reached samples no. 8 and 18. For samples no. 23, 24, 25 only the parameter Sa was significant, which may mean that the roughness Ra was measured in places with lower roughness and just the roughness Sa showed that the roughness is higher in the whole measured surface. It was expected that these parameters would change similarly, in some cases this was not the case, e.g. for samples from no. 22-28, where greater cutting forces were created compared to other cases, at a cutting depth of 5 mm.

To compare the accuracy of the measurement, the statistical reliability was calculated for the individual parameters. Up to 5 factors that could affect the measurement results changed during the experiments. The overall comparison of the measured and calculated values is expressed as R^2 . For each parameter for comparison, the measured and calculated data are processed in the equation and in the graph.

For the parameter Ra an equation with a reliability coefficient was statistically calculated, the average accuracy was about 18%:

Equation for parameter Rz and reliability coefficient, for this parameter the average accuracy was about 32%:

$$Rz = -19.2 + 0.173.v_c + 288.f + 2.19.a_p - 26.9.s - 1.065.\alpha - 0.000212.v_c^2 - 10398.f^2 - 0.69.a_p^2 + 20.7.s^2 + 0.01645.\alpha^2 + 0.641.v_c.f + 0.01913.v_c.a_p - 0.0412.v_c.s - 0.000976.v_c.\alpha + 28.4.f.a_p + 260.f.s + 6.22.f.\alpha - 5.01.a_p.s - 0.1054.a_p.\alpha + 0.736.s.\alpha \quad R^2 = 88,04\% \quad (2)$$

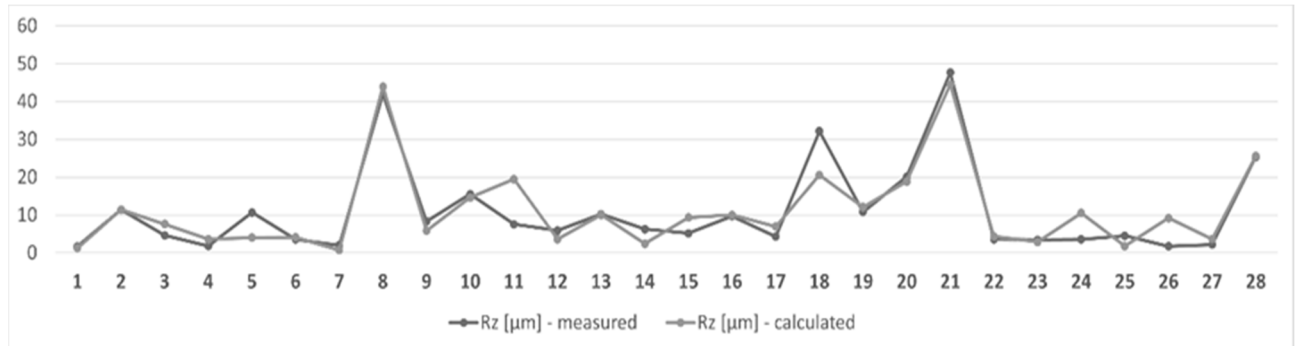


Fig. 8 Comparison of measured and calculated values of the parameter Rz

For parameter Sa the equation and reliability coefficient were calculated as follows, for parameter the average accuracy was about 20%:

$$Sa = -3.67 + 0.0142.v_c + 88.6.f - 0.216.a_p + 4.46.s - 0.1062.\alpha - 0.000012.v_c^2 - 542.f^2 + 0.177.a_p^2 - 3.10.s^2 + 0.001410.\alpha^2 - 0.0762.v_c.f - 0.000850.v_c.a_p + 0.00062.v_c.s + 0.000047.v_c.\alpha + 4.30.f.a_p - 9.3f.s + 0.025.f.\alpha - 0.316.a_p.s - 0.00786.a_p.\alpha + 0.0278.s.\alpha \quad R^2 = 86,02\% \quad (3)$$

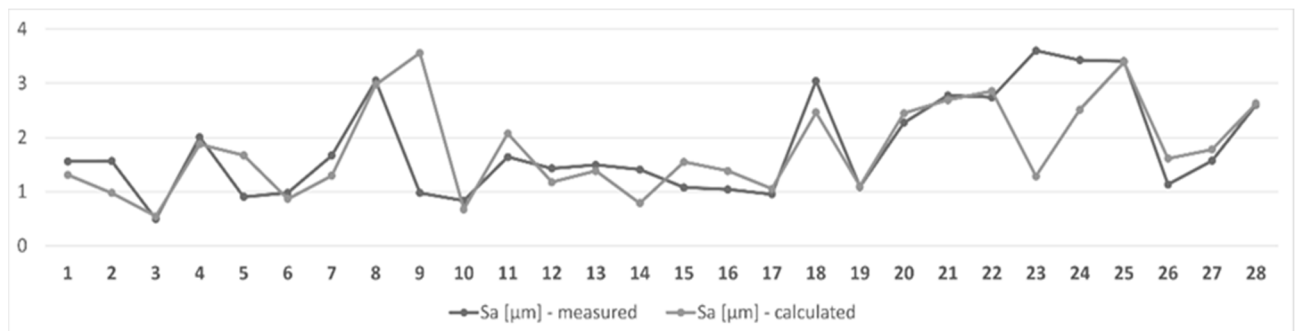


Fig. 9 Comparison of measured and calculated values of the parameter Sa

For parameter Sz, the following equation and comparison in the graph apply, for this parameter the average accuracy was about 9%:

$$Sz = 106 - 0.293.v_c + 9749.f + 137.5a_p - 339.s - 8.20\alpha + 0.000446.v_c^2 - 121988.f^2 - 23.93.a_p^2 + 262.s^2 + 0.1457.\alpha^2 - 0.35.v_c.f + 0.0743.v_c.ap - 0.114.v_c.s - 0.00384.v_c.\alpha - 444.f.ap + 1369.f.s + 28.8.f.\alpha + 4.27.ap.s - 0.543.ap.\alpha - 0.727.s.\alpha \quad R^2 = 93,79\% \quad (4)$$

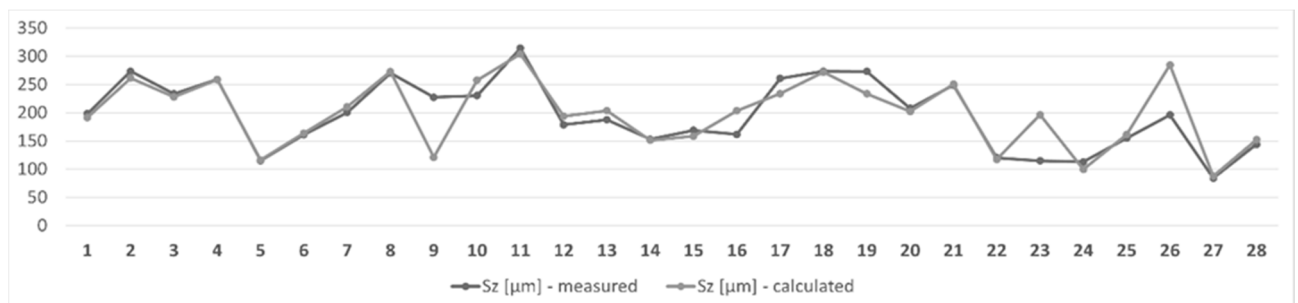


Fig. 10 Comparison of measured and calculated values of the parameter Sz

During the measurement of the cutting forces, the coordinate system was used according the coordinate system of the dynamometer a the milling machine. The results are shown in the graph:

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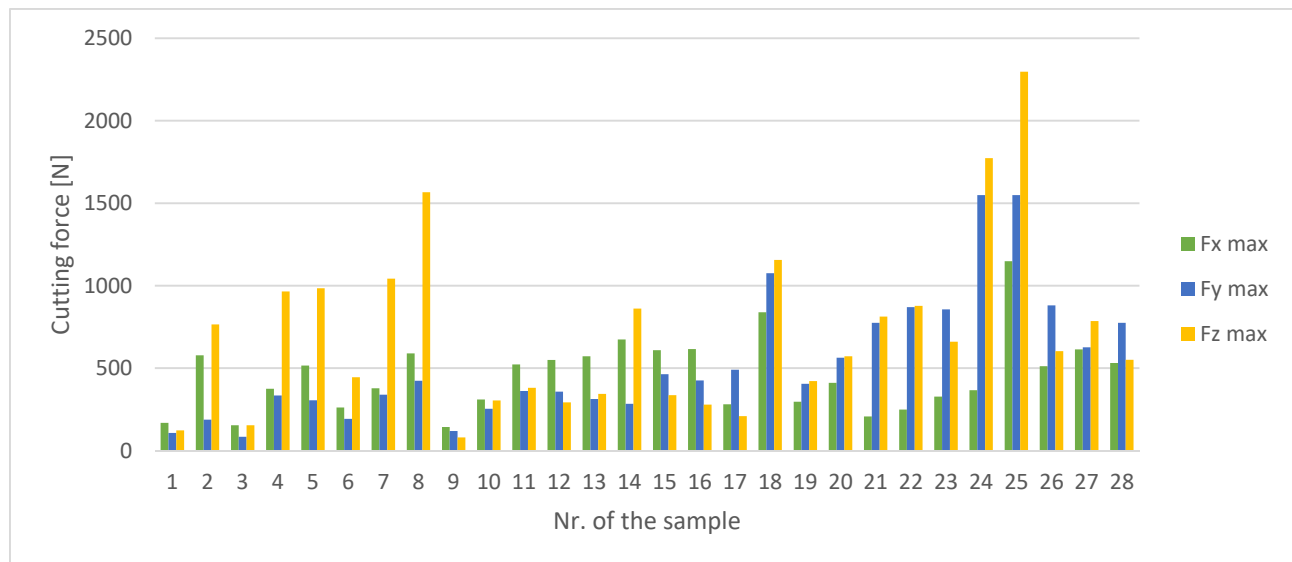


Fig. 11 Maximal values of cutting forces

The graph shows the greatest values of the cutting forces components. The highest values ($F_x = 1148,877\text{ N}$, $F_y = 1549,243\text{ N}$, $F_z = 2296,875\text{ N}$) are in the sample Nr. 25 with cutting parameters $v_c = 300\text{ m}\cdot\text{min}^{-1}$, $f = 0.06\text{ mm}$, $s = 1\text{ mm}$, $a_p = 5\text{ mm}$ and $\alpha_{\text{eng}} = 10^\circ$. The measurement of the cutting forces was not the main aim of the executed experiments in this case.

The next graphs show the main influence of individual factors without mutual interactions. The steeper the curve relative to the horizontal x-axis, the higher the interaction.

If the curve rises, the dependent variable also increases due to a change in the factor. If the curve decreases, the variable decreases due to increasing values of the factor. The shape of the curve can also indicate a specific dependence. Due to the fact that the equation, which was created after the translation of the measured points, is a polynomial of the second degree, these dependences are also captured under the influences.

A negative factor means that the values of the investigated parameter decrease as the factor values increase.

The influence of the factors on the investigated parameter R_a is recorded in fig. a) - as can be seen, the most significant influence was the displacement f and the angle of engagement α_{eng} . If it is possible to speak of a positive factor during the shift, at the angle of view, its meaning has changed during the course.

The shape of the curve indicates that the linear interaction has a more significant effect at lower values of the displacement, at higher values it passes into the interaction f^2 . The angle of engagement has a parabolic interaction throughout, which confirms the ambiguity of the factor (it is both positive and negative).

The influence of the factors on the investigated parameter R_z is recorded in fig. b). The most significant effect is observed at the feed f and the angle of engagement α_{eng} . During the feed, it is a positive factor, at the angle of engagement, its meaning has changed du-

ring machining, so its influence is both positive and negative, and thus as an influence factor it is ambiguous.

The influence of the factors on the investigated parameter S_a is shown in fig. c). The most significant effect is at feed f and step s , both of which are positive. With the depth of cut a_p and the angle of engagement α , their meaning has changed, the influence is both positive and negative, the influence factors are ambiguous.

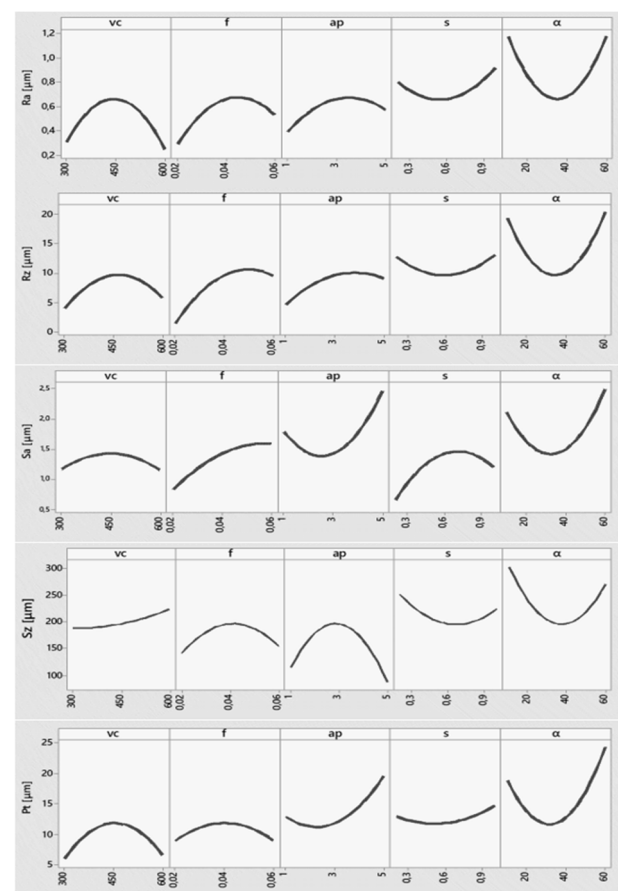


Fig. 12 Influence of individual parameters on surface quality

The influence of the factors on the investigated parameter S_z is shown in fig. d). The depth of cut a_p and the angle of cut α have the greatest influence. Their meaning has changed, so the impact is ambiguous.

4 Conclusion

The aim of the experiments was to evaluate the surface quality after machining by trochoid milling. The cutters used in the experiments were machined by the roughing method, but the surface quality found was close to the values of the finishing methods, so there is no need to use the finishing method, which is economically advantageous. With increasing cutting angle at low cutting speed, the surface quality deteriorated and the surface would need to be modified by further machining. From the measured data it was possible to determine the accuracy of measurements compared to statistical calculations:

- R_a maximum by 51.91%, minimum by 2.26%,
- R_z maximum by 81.29%, minimum by 0.13%,
- S_a by a maximum of 72.56%, by a minimum of 0.46%,
- S_z maximum by 46.85%, minimum by 0.24%.

The effect of the depth of cut a_p and the angle of engagement α had the most frequent effect on the surface quality of the grooves.

Trochoid milling has great potential for use mainly on operations during which large amounts of material are removed and at the same time roughness needs to be monitored, thus reducing the need for finishing. With suitable set parameters, it is possible to achieve a surface quality that is generally considered to have already finished the surface. The presented results can be a basis for further research, but also as a tool for setting cutting parameters - the already mentioned equations, which show the dependence of surface roughness on cutting parameters. The equations can be used as an "end-use engine", as they can be embedded in various computer programs (Excel, Matlab) or simulators (Matlab, Ansys, etc.)

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