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Investigation of the Impact of Selected Face Milling Parameters on the Roughness of the Machined Surface for 1.4301 Steel

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ABSTRACT

The objective of this research was to analyze how different milling parameters impact the roughness of the surface produced during the machining process. Kinematic parameters, such as cutting speed and feed per tooth, as well as geometric parameters, such as axial and radial depth of machining, were considered in various configurations to determine which one had the greatest impact on the surface quality of 1.4301 stainless steel (also known as AISI 304, among other designations). This type of steel is commonly used in a number of industries, such as construction, automotive, food, chemical, decoration, oil, and petrochemical, owing to its favorable properties. It is also relatively cheap. The analyzed roughness parameters included *Ra*, *Rq*, *Rz*, *Rt*, which, considered collectively, provide a comprehensive picture of the overall surface quality. Based on the results, feed per tooth is the one parameter that was to a large degree responsible for the overall quality roughness of the surface of the analyzed samples. The remaining tested parameters also had an impact on the surface quality, which resulted in a dynamic increase or decrease in roughness (extremes), but not to the same degree as in the case of feed per tooth. At one point, for a relatively low axial depth of cut, a sudden increase in the resulting roughness was recorded.

Keywords: milling kinematic parameters; face milling; machined surface quality; 1.4301 steel; AISI 304; X5CrNi18.10

INTRODUCTION

The main task of the technologist planning the machining process is, apart from the correct selection of tools, to choose the appropriate parameters for the entire machining process. One commonly used indicator of surface quality is surface roughness [1]. Its value determines how smooth or rough a surface is and, depending on the intended use, can determine whether a part has been properly manufactured [2]. Studying the influence of roughness on various production processes, e.g. gluing, covering surfaces with other coatings, is still a significant problem for the industry. Demonstrating the effect of machining on roughness is an important step to improving various technological processes [3].

Low roughness results in a smoother and finer surface finish, which can improve the functionality and aesthetics of the workpiece. It also reduces friction and wear, increases corrosion resistance, and improves fatigue life. Therefore, low surface roughness is often desirable in applications requiring high precision and quality standards [4–6]. When it comes to subtractive manufacturing, especially chip machining, there are many significant milling process parameters that can affect the quality of the machined surface roughness and can be used in various combinations to achieve different results. Therefore, it often becomes a challenge to match them properly.

A study was conducted to predict surface roughness by identifying the appropriate cutting force that accounts for uncontrollable factors in end milling operations. The findings revealed that cutting tools are of great importance in affecting the cutting force as well as the roughness of the surface itself. However, it was discovered that, at least under those circumstances, varying the depth of cut had minimal impact on the surface roughness, to the point of it being statistically insignificant in the developed prediction model [7]. In another study, the Taguchi methodology was used to determine the correct levels of process parameters for milling mold surfaces from aluminum and carbon steel. In the first case, the results showed the influence of milling parameters on surface quality expressed as roughness [8, 9]. There are also other studies, conducted for cobalt alloys, describing how surface roughness is influenced by the most common milling parameters. [10].

Based on the tests using Taguchi's methodology presented in another source, it can be concluded that the axial depth of cut contributes to increasing the surface roughness in a specific range of parameters [11]. As can be seen in the literature pertaining to the subject, the Taguchi optimization technique is frequently employed to investigate the influence of cutting parameters on the surface roughness of different materials [12–14]. Optimization of input parameters such as radial depth of cut, feed rate, cutting speed shows the enormous effect of spindle and tool speed on surface roughness [15–17].

The correlation between tool wear morphology and roughness was investigated in a study dealing with face milling of hardened steel with carbide tools. Thanks to the knowledge of such parameters as cutting speed and feed per tooth, it is possible to avoid damaging the cutting edge [18]. Other surface roughness modeling studies have also been conducted. On their basis, it was found that the feed per tooth had the largest impact on the average surface roughness, followed by the cutting speed, for the examined material (X2CrNi18-9) [19]. Ultrasonic vibrations have also been used in face milling to ameliorate the surface microstructure and decrease the friction coefficient of TC4 titanium alloy. Based on these studies, a conclusion can be drawn that the roughness is reduced with an increasing cutting speed but has almost no impact on the friction coefficient [20]. The effect of vibrations on roughness during face milling has also been investigated [21]. Studies have also been conducted to analyze the influence of the milling environment, such as wet or dry, on the roughness of the surface of various kinds of steel, with lubrication being able to reduce it by up to 19.8% [19, 22, 23].

Another example of research in this field involved investigating how the relative position of the face mill and the machined piece, as well as the milling kinematics (conventional vs climb), impact the various components of cutting force and the surface roughness when performing face milling with a milling width greater than the diameter of the cutter, as opposed to them being equal [24]. Another study investigated how changing the cutting parameters and machining time affects tool wear and surface roughness during milling [25]. In the case of another study, a high-feed milling cutter allowed for a two-fold increase in the volume of cut and higher machining efficiency but resulted in greater surface roughness and vibration amplitudes [26]. In another article, an innovative approach using an artificial neural network (ANN) and a harmony search algorithm (HS) to obtain the best cutting parameters in face milling was proposed in another article [27]. Yet another study evaluated the use of optical systems for measuring surface roughness and proposed a program to make predictions about the value of optical surface roughness using a neural network algorithm trained on surface images obtained in face milling processes [28]. Models of deformation of heterogeneous coatings under local load [29, 30] and the problem of frictional contact of parts with reinforced surfaces [31] serve as a useful theoretical basis for studying the iteraction between the tool and the superficial layers of metal.

Based on the literature review above, it can be concluded that the milling process is quite complex and still problematic in the industry and various types of solutions are still being sought to improve and facilitate the obtaining of the expected results when it comes to the condition or characteristics of the surface. The impact of milling parameters on the resulting surface roughness depends on many factors, e.g., the tool, the machine, the material, vibrations, and other conditions (dry/wet machining).

An important aspect of the work was the most effective use of the influence of parameters (feed per tooth, cutting speed, axial and radial depth of cut) on roughness of the machined surface. It should be borne in mind that the test results may differ to some extent depending on the tools used, the machine tool, and the material from which the semi-finished product is made.

AISI 304 steel was used in this study. It is an extremely versatile and commonly used type of stainless steel owing to its composition, mechanical properties, weldability, and resistance to corrosion and oxidation. Its excellent quality comes at a relatively low cost [32]. This steel is a standard grade steel that belongs to the group of austenitic chromium-nickel steels. It is used in the construction, automotive, chemical, food, decoration, petrochemical, and oil industries [33]. 1.4301 stainless steel is a widely used material in friction assemblies in chemical equipment, especially in moderately aggressive environments of chemical industries. This steel is a promising material for the manufacture of a number of parts of shell, plate, and stratified structures that are exposed to high loads [34–36]. It has good resistance to diluted acids and alkalis, organic acids, as well as inorganic and organic salt solutions, at various temperatures and concentrations. The material can also operate in aggressive environments with temperatures up to 350°C [37].

Machining 1.4301 steel presents difficulties because of its high ductility and the rate at which it hardens during the process. This steel is prone to generating edges on the cutting tool and does not break chips well, especially when the cutting depth falls into the minimal chip thickness zone and the "ploughing effect" becomes prominent. These challenges make machining of 1.4301 steel difficult, especially during microturning and milling processes [38]. Difficulties with the machining of the material prompted an experiment on the impact of milling machining.

In the literature pertaining to this subject, there are various types of research and experiments conducted in the field of milling, and some problems remain unresolved or are still being investigated. Many specialists are looking for different answers to the problems they have encountered. In the context of the review, the objective of the study was to analyze the impact of the variability of milling parameters on the surface roughness of 1.4301 steel and to determine the optimal parameter values for the milling process, especially seeing that there has not been much research done with this type of steel in the case of face milling.

MATERIAL AND METHODS

The material used to produce the samples was stainless steel, which, in accordance with the EN 1088 standard, is marked with the symbol 1.4301 (in the United States, it is more commonly known as AISI 304 steel). Table 1 presents the detailed chemical composition of 1.4301 steel. It has a relatively high chromium and nickel content, and the presence of those alloying elements is reflected in its being labeled as X5CrNi18.10 steel according to ISO.

Due to its advantageous properties, austenitic stainless steel is widely utilized in numerous industries, demonstrating its exceptional versatility and widespread popularity. Examples of the desirable properties of austenitic steel include high durability, ductility, excellent corrosion resistance, and toughness at low temperatures [40]. Some of its mechanical properties have been listed in Table 2.

Preparation of the samples

Rectangular prisms were cut out of stainless steel using the TruLaser 3030 laser cutting machine. The specimens were obtained for the purpose of investigating the influence of specific milling parameters on the quality of the machined surface, forming the basis for subsequent analysis. Because of the characteristics of the laser cutting process, the areas near the edge of each sample were inadvertently heat-treated. The actual dimensions of the samples were 32×52 mm.

To achieve a consistent and homogeneous structure for the entire semi-finished product,

Table 1. The composition of 1.4301 steel [39]

Element	C	Cr	Mn	Si	P	S	Ni	N	Fe
Min. content [%]	0	17.5	0	0	0	0	10.5	0	72
Max. content [%]	0.07	19.5	2	1	0.05	0.03	10.5	0.11	86.24

Table 2. The mechanical characteristics of 1.4301 steel [39]

Property	Value
Compressive strength	210 MPa
Proof stress	Min. 210 MPa
Tensile strength	520 to 720 MPa
Elongation	Min. 45%

roughing had to be performed. This process was carried out on the PRVOMAJSKA ALG-200B conventional milling machine. When it comes to conventional machines, stepless parameter selection is typically impossible. The PRVOMAJSKA ALG-200B has 18 values available for both the spindle speed (37–1900 rpm) and the milling feed rate (7–380 mm/min).

From the parameter values listed above, those that were closest to the ones obtained on the basis of calculations were selected. In this case, they were:
- Rotational speed: 950 [rpm],
- Feed rate: 300 [mm/min].

The tool used to perform the rough machining was an AKKO milling head marked with the code AFM90 AP16 D040 A16 Z04 H. The machining width for this head is 40 mm, and the entering angle of the tool is 90°. This gives us a cutting speed of approximately 119 m/min. It should also be added that the selected head allows one to mount four cutting inserts. The selected head was equipped with APKT 1604PDER-76 inserts, manufactured by ISCAR. The following drawing illustrates the dimensions and geometry of the tool, as depicted in Figure 1.

After the initial preparation of the samples on the conventional milling machine PRVOMAJSKA ALG-200B, finishing was carried out. The process was performed on the GSK YM-1165

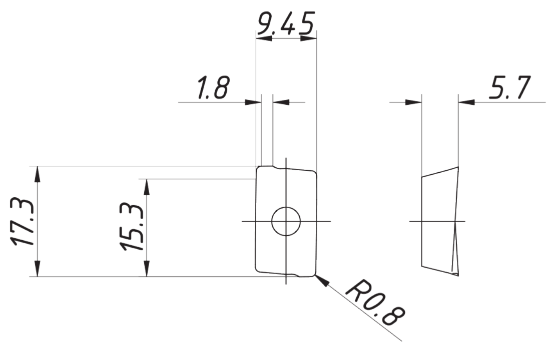

Figure 1. The dimensions and geometry of the APKT 1604PDER-76 insert

Table 3. Machining parameters

Parameter	Value
Cutting speed [m/min]	200; 220; 240*; 260; 280; 300
Feed per tooth [mm/tooth]	0.07*; 0.09*; 0.11; 0.13; 0.15*; 0.17
Axial depth of cut [mm]	0.5; 0.75; 1*; 1.25; 1.5; 1.75
Radial depth of cut [mm]	30; 27.5; 25*; 22.5; 20; 17.5

Note: * Parameters that were kept constant while the rest changed.

CNC milling machine. The tool used to carry out the finish machining was the head used during the pre-machining. The use of a CNC milling machine allowed for precise and stepless definition of parameter values. The parameter values were selected such that one of the samples machined during the first stage could also be taken into account in the remaining stages. The parameter values listed in Table 3 were used.

Four test trials were conducted for different parameters. Each test was carried out for a different parameter value while keeping the remaining values constant. These variables included feed per tooth, rotational speed, axial and radial depth. Figure 2 depicts the machining process applied to the outer surface of each sample.

Roughness measurements

After the samples had been machined, roughness measurements were performed. They were carried out using the contact method with the help of the Formtracer SV-C4500 roughness measuring system manufactured by Mitutoyo.

In the case of contact roughness measurement methods, an important element of the measuring apparatus is the detector. During the tests, the 178-396-2 detector was used. The manufacturer of this device is also Mitutoyo, and the measuring stylus used in it has a radius of 2 μm and is marked with the symbol 12AAC731. Its specifications can be found in Table 4.

The selection of measuring conditions was made in adherence to the ISO 4288 [41] and ISO 3274 [42] standards for periodic profiles, as face-milled surface profiles typically display periodic characteristics. The roughness parameters used in this study included:
- the arithmetic mean deviation of the roughness profile relative to its center line,
- the root mean square (RMS) deviation of the roughness profile,
- the 10-point mean roughness height,

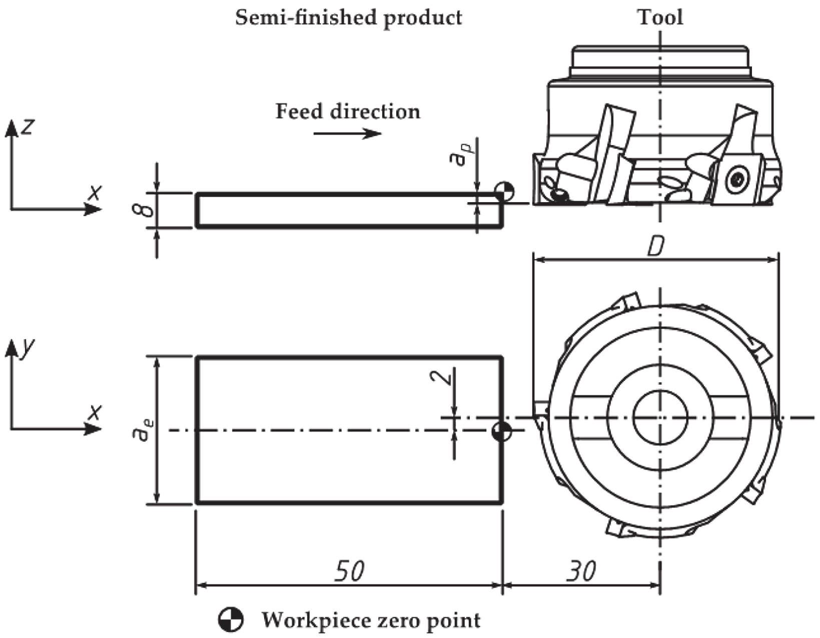

Figure 2. Schematic of milling machining: *D* – tool diameter; a_e – radial depth of cut, a_p – axial depth of cut

Table 4. Roughness detector 12AAC731 – technical specifications

Parameter	Value
Measuring force	0.75 mN
Stylus length	8.4 mm
Stylus tip radius	2 μm
Z1-axis range	800 μm
Z1-axis resolution	0.01 μm

- the total height of the surface roughness profile.

Some of those parameters are more sensitive to local deviations than others.

RESULTS AND DISCUSSION

The effect of cutting speed on surface roughness

When examining the influence of the cutting speed on the surface roughness, the remaining parameters had constant values and were set to:
- Feed per tooth: 0.15 mm/tooth,
- Axial depth of cut: 1 mm,
- Radial depth of cut: 25 mm.

The roughness parameter values measured for a varying cutting speed is shown on the bar chart in Figure 3. Trend lines are also included to show approximations for the four roughness parameters, together with polynomials that seem best to describe them. The highest roughness was registered for a cutting speed of 260 m/min, while the lowest roughness was recorded for that parameter set to 200 m/min.

The roughness values increase with the increasing cutting speed until they reach 260 m/min, and after that threshold, with the rest of the parameters unchanged, they start decreasing. The growth in the cutting speed in the range from 200 to 220 m/min did not change the value of the *Ra* parameter. In the case of the other parameters, there is a certain change in value; however, it should be remembered that these parameters are very sensitive to individual extreme deviations. Increasing the cutting speed to 240 and 260 m/min results in a significant increase in the value of all the obtained roughness parameters.

Another increase in the cutting speed, to the value of 280 m/min, causes the trend to reverse. There is a decrease in the value of all tested parameters. Changing the value of the cutting speed from 280 to 300 m/min results in a decrease in the values of the parameters describing the surface roughness profile. It is worth mentioning, however, that this change is half as small as the difference between the values obtained for the speed of 260 and 280 m/min. It is shown in the literature that for some materials, with further increasing of the cutting speed, another trend reversal can be expected [43]. Unfortunately, the use of higher

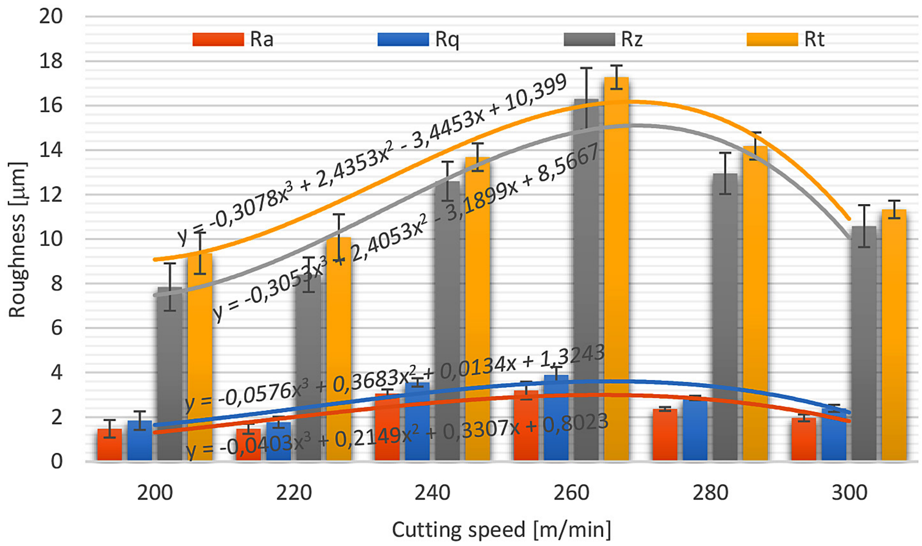

Figure 3. The correlation between cutting speed and the roughness of the analyzed surface

cutting speeds was associated with the risk of tool damage, which did not allow to test this assumption [44]. The study of the impact of cutting speed on the roughness of the machined surface brought the following conclusions:

- Initially, an increase in the cutting speed results in an increase or no change in the values of the parameters describing the roughness profile.
- There is a cutting speed value above which the values of the parameters describing the roughness profile decrease with an increasing cutting speed.

The foregoing conclusions and references to the literature show that in order to obtain the best possible surface finish, the appropriate range of cutting speeds should be used [43]. In each case, the words “appropriate” and “best” may mean a different end result. The lowest roughness was obtained for 200 m/min, and the highest for 260 m/min. Depending on the intended use of the workpiece, specific roughness values may be expected. The roughness obtained is also influenced by the type of material used.

The effect of feed per tooth on surface roughness

When examining the impact of the feed per tooth on the surface roughness, the remaining parameters had constant values and were respectively:

- Cutting speed: 240 m/min,
- Axial depth of cut: 1 mm,
- Radial depth of cut: 25 mm.

The results of the roughness measurements for an increasing feed per tooth value are presented graphically on the bar chart in Figure 4. The highest roughness was registered for a feed per tooth of 0.13 mm/tooth (closely followed by that obtained for 0.15 mm/tooth), while the lowest roughness was recorded for 0.07 mm/tooth.

Additionally, the more interesting roughness profiles are shown in Figure 5. The scale remains the same for each, so it is easier to compare them. From the previous plot we saw that the roughness values increase with the increasing feed value and the differences are quite noticeable, except between the last two samples, where the results are very similar, even though the roughness patterns themselves are quite different.

A low step of 0.02 mm/tooth was used between the individual feed per tooth values. With such a small step, we have obtained proof that even the smallest change in the feed per tooth parameter has an enormous impact on the roughness of the machined surface. In the case of the feed per tooth, it is clearly visible that the smoothness of the machined surface deteriorates with the increase in the parameter value. The fluctuations of the roughness parameter values depend on the sensitivity of the individual parameters to local deviations. A sample had also been made for a feed per tooth value of 0.17 mm/tooth. However, during the machining process, the cutting blade was damaged, so the corresponding sample was not taken into account during the measurements. In the literature, one can find confirmation of the existing trend that

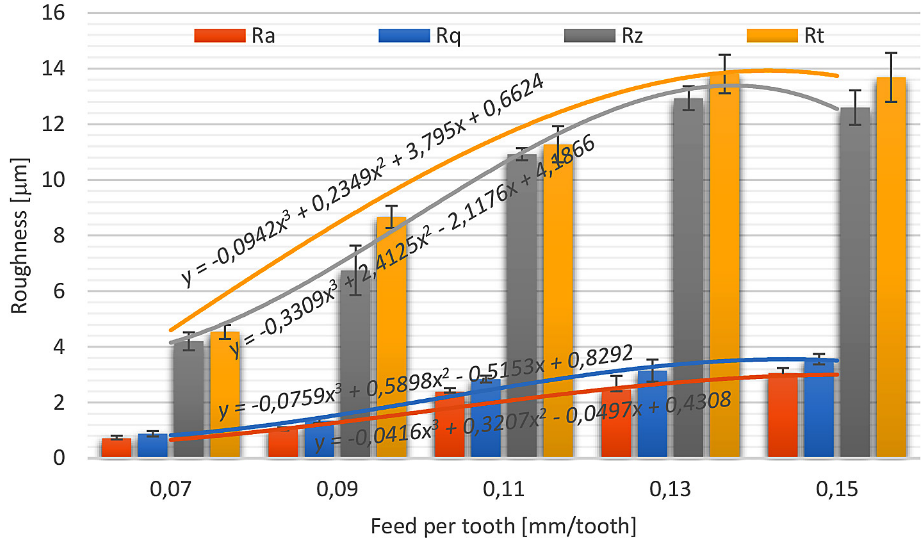

Figure 4. The correlation between feed per tooth and the roughness of the analyzed surface

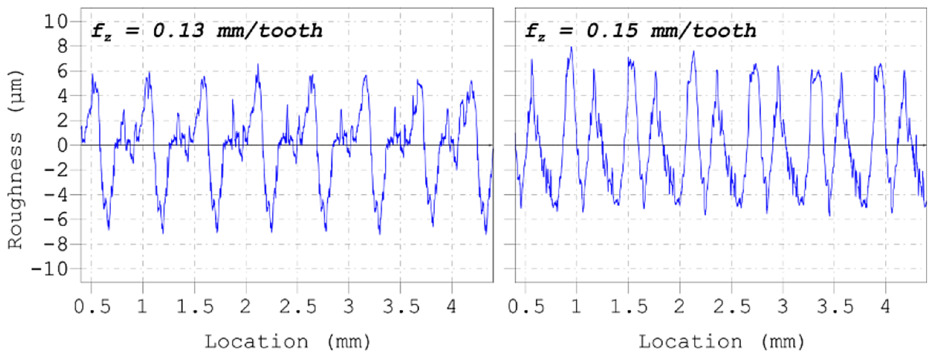

Figure 5. Comparison of the more interesting roughness profiles, obtained for feed per tooth values of 0.13 and 0.15 mm/tooth

with the increase of the feed per tooth, the surface roughness increases. However, it is worth noting that the range of feed values for each material may be different [2].

Reducing the feed causes more flank wear and shorter tool life. Increasing the feed increases the machining temperature and increases flank wear. However, compared with the cutting speed, its effect on tool life is minimal. Increasing the feed increases the machining efficiency and increases the roughness with a linear trend [45], although in the case of the parameters more sensitive to local peaks and valleys, the surface roughness appears to stabilize after reaching a feed per tooth value of 0.13 mm/tooth.

In a study making use of a neural network and a harmony search algorithm, it was also shown that as feed per tooth increases, the resulting surface roughness tends to increase, as well, while that was not the case with cutting speed (as expected) or depth of cut [27].

The effect of axial depth of cut on surface roughness

When the relationship between axial depth of cut and surface roughness was being investigated, the remaining parameters had constant values and were as follows:

- Cutting speed: 240 m/min,
- Feed per tooth: 0.07 mm/tooth,
- Radial depth of cut: 25 mm.

The surface roughness values obtained for a varying axial depth of cut are depicted on the bar chart in Figure 6. The highest roughness was registered for an axial depth of cut of 0.75 mm, while the lowest roughness was recorded for the parameter set to 0.5 mm. The particularly interesting roughness profiles obtained for a varying axial depth of cut are shown in Figure 7. The scale is the same for all the plots. The highest peaks occur for a value of 0.75 mm, and the roughness pattern is noticeably different from the rest.

Tests were also carried out pertaining to the effect of the axial depth of cut on the surface roughness with a step of 0.25 mm. An axial depth of cut of 0.5 mm is the lowest allowable value for the blades used. Applying any other value below that threshold brings us closer to the point where the milling process becomes similar to grinding. This phenomenon allows for obtaining a better surface roughness; however, it results in a rapid wear of the tool not intended for this type of machining.

The samples obtained using an axial depth of cut of 0.75 mm show significantly higher values of surface roughness parameters compared with those for 0.5 mm and for 1 mm. That was the case for all of the analyzed roughness parameters. The reason is most likely that the a_p value there was 0.75 mm, which is very close to 0.8 mm, that is, the measure of the corner radius of the insert. This may have introduced some unwanted phenomena, such as vibrations during face milling, causing the surface to deteriorate.

The roughness values obtained for the sample machined using an axial depth of cut of 1 mm are similar to those obtained for the sample made using an axial depth of cut of 0.5 mm. When increasing the axial depth of cut to 1.25 mm and 1.5 mm, a slight improvement in all parameters describing the roughness of the obtained surface can be observed.

The use of an axial depth of cut of 1.75 mm causes a slight reversal of the trend, because all the tested parameters describing the surface roughness take higher values than in the case of using an axial depth equal to 1.5 mm.

It should be noted that changes in the values of the parameters describing the surface roughness profile are insignificant. This observation is confirmed by the research conducted by Okopujie Imhade and Okonkwo Ugochukwu [46]. The foregoing work involved an experimental study of the effect of cutting parameters on roughness during shoulder milling for aluminum in a minimum lubrication setting. The results indicate that the and parameters have the greatest impact on

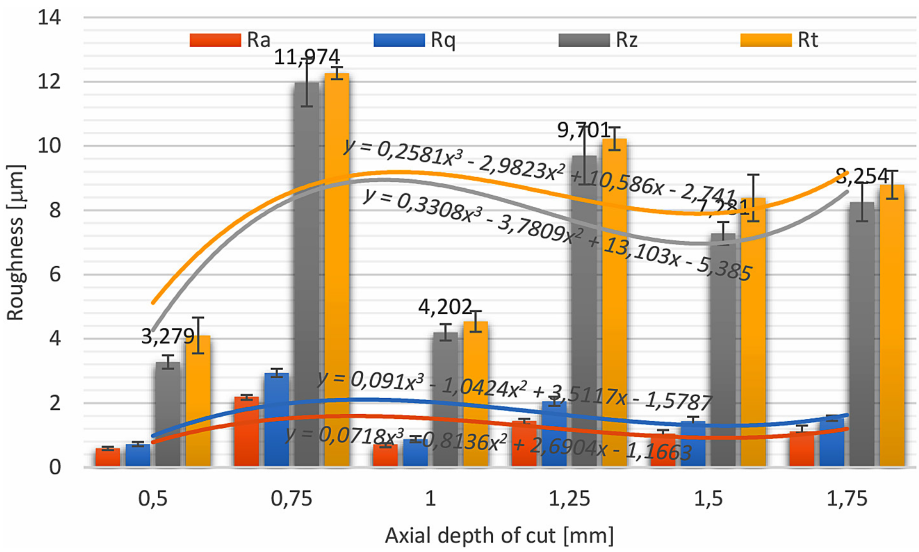

Figure 6. The correlation between axial depth of cut and the roughness of the analyzed surface

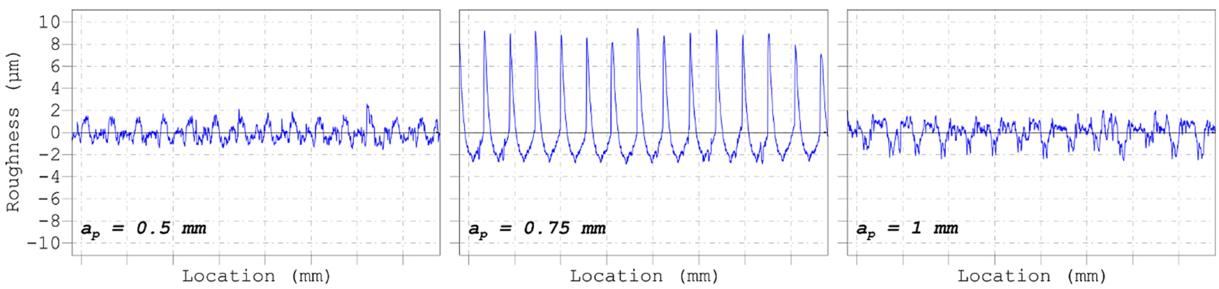

Figure 7. Comparison of the more interesting roughness profiles, obtained for the axial depth of cut values from 0.5 to 1 mm

the surface roughness, while has a significant but not the greatest impact, which is consistent with the conducted research.

In another series of experiments examining the effect of machining time as well as cutting parameters on tool wear and surface roughness during high-speed milling of Al6061 with face carbide inserts, it was found that the most significant factors in connection with surface roughness were the axial depth of cut and feed rate [25]. In the present study, no such dependency was found.

A similar study found the effect of the axial depth of cut to be negligible, while cutting speed had the highest degree of influence on surface roughness. The responses of machined surface roughness and milling tool cutting forces under the different milling parameters (v_c, f, and a_p) were experimentally investigated for pure copper [47].

The effect of radial depth of cut on surface roughness

During the analysis of the influence of the radial depth of cut on the surface roughness, the remaining parameters had constant values and were:

- Cutting speed: 240 m/min,
- Feed per tooth: 0.09 mm/tooth,
- Axial depth of cut: 1 mm.

The results of the roughness measurements for an increasing radial depth of cut are presented graphically on the bar chart in Figure 8. The highest roughness was recorded for a radial depth of cut of 27.5 mm, whereas the lowest roughness was registered for 22.5 mm.

In the literature, we can find the information that obtaining the best possible surface roughness is associated with the use of a radial depth of cut of 50 to 75% of the tool diameter [48].

The tests carried out showed that the lowest roughness was obtained for a radial depth of cut of 22.5 mm. Slightly worse parameters were obtained for 20 mm. A value of 20 mm constitutes 50% of the tool. For the other radial depth of cut values, higher roughness values were obtained.

The tests also indicated that the influence of the radial depth of cut on surface roughness is negligible. To make the best use of the effect of the radial depth of cut on the surface finish, a tool with a diameter close to twice this parameter should be used. It is worth adding, however, that for a different tool geometry and a different selection of the machined material, these values may differ. Figure 9 illustrates the difference between the maximum and minimum for each of the milling and roughness parameters. Those extremes are the most noticeable for feed per tooth, but it may not be the best reflection of the degree to which changes in the milling parameters influence the final surface roughness, seeing that any values in between are ignored.

In this comparison, the differences between the *Rz* and *Rt* ranges for cutting speed, feed per

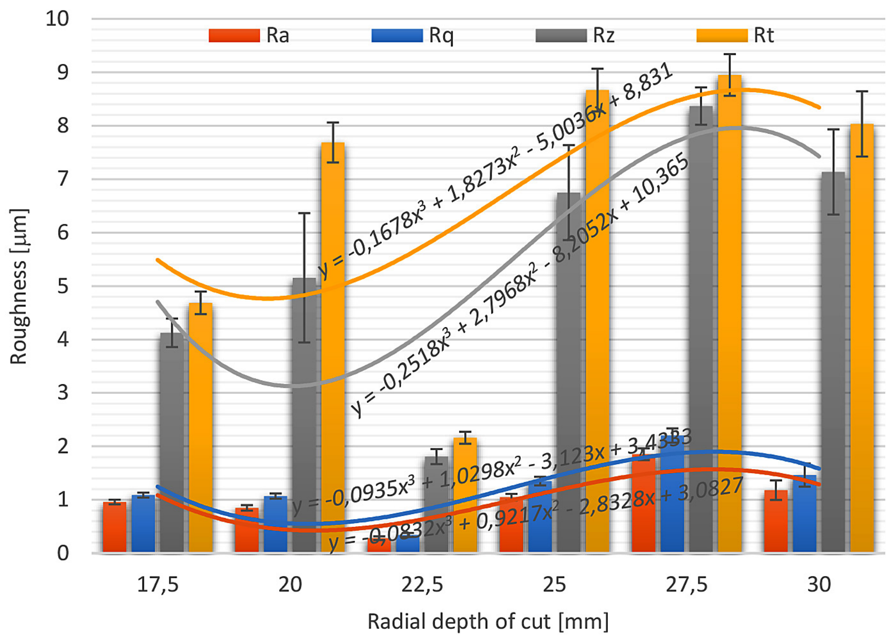

Figure 8. The correlation between radial depth of cut and the roughness of the analyzed surface

tooth, and axial depth of cut are practically negligible, and the only parameter that stands out from the rest is a_e. It can be seen that the smallest difference between the roughness extremes has the a_e parameter. Compared to other tested parameters, evidently for variable a_e, the roughness is more stable in the range of extremes (the smallest difference). The greatest range of extremes has the test with variable f_z. Which shows that the change of this parameter has the greatest impact on the value of the expected surface roughness. Parameters a_p and v_c are comparable. Knowing the effect of the values of individual parameters on roughness makes it easier for the operator to assess the impact of machining on surface quality, which can result in savings for companies.

Figure 10 shows the average roughness for each tested milling parameter, together with the corresponding standard error. The mean roughness value can be used to determine the effects that can be expected during machining. This is important from a practical point of view, because it is possible to determine the level of significance of the change of parameters on the surface roughness for each of the parameters. Analyzing the data, it can be seen that the cutting speed in the tested range increases the roughness value for all four tested parameters. A comparable effect can be obtained for changing the feed per tooth. In order to significantly reduce the roughness, you should choose to change the radial depth or axial depth parameter. On average, the smoothest surface was

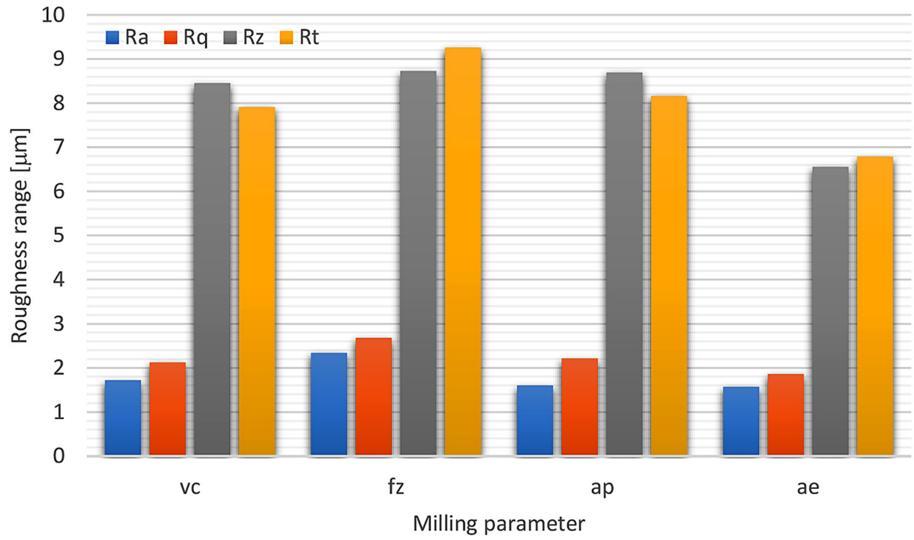

Figure 9. A bar chart presenting the differences between the two extreme (maximum and minimum) roughness values for each parameter

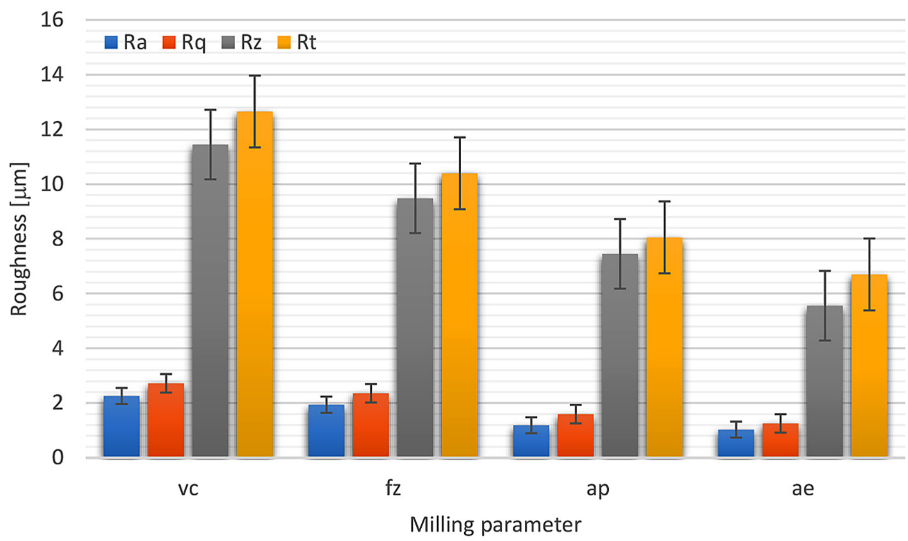

Figure 10. A bar chart showing the average roughness for each milling parameter

obtained for axial depth, and the roughest for cutting speed.

Statistical analysis

Although some general trends had already been observed, a four-way ANOVA test was additionally performed for each of the output parameters (the obtained roughness values) to assess or confirm which one of them had the greatest impact on the resulting roughness. All the possible combinations of the parameters were taken into consideration. The collective results of the statistical analysis are shown in Table 5.

The *p*-values obtained for feed per tooth () are the lowest in all four cases, which suggests that they are the most statistically significant. Assuming a rather stringent level of significance, 0.01, the *p*-values computed for the four roughness parameters are clearly the smallest in the case of and fall decidedly into the range of being statistically significant (even for thresholds lower than 0.01).

According to F-distribution tables, for a probability level of 0.01 and the number of degrees of freedom $df_1 = 7$ (numerator) and $df_2 = 15$ (denominator) respectively, we have a critical F-value of 4.142. This confirms that for each computed roughness parameter, the results are statistically significant by a wide margin. The cutting speed in the case of is on the verge of being statistically significant with an F-value of 4.162 when considering the same probability level.

Based on the results, it is evident that feed per tooth is the one parameter that was to a large degree responsible for the overall surface roughness of the tested samples. Modifying the other parameters had no such bearing on the obtained surface quality. It appears that, while the average roughness was less affected by changes to , the machined surface was more likely to exhibit local unevenness, as indicated by the *p*-values for *Ra*, *Rz*, *Rq*, and *Rt*. Overall, the results of the statistical analysis confirm the earlier observations.

From among the other parameters, as noted before, the cutting speed (v_c) comes closest to being statistically significant, particularly for . There appears to be no strong correlation otherwise.

Table 5. A four-way ANOVA test for *Ra*, *Rz*, *Rq*, and *Rt*

Category	DoFs	SS	MSS	F-value	*p*-value
Summary for *Ra*					
v_c	1	1.15	1.15	2.892	0.106214
f_z	1	7.064	7.064	17.766	0.000521
a_p	1	0.019	0.019	0.047	0.830066
a_e	1	0.586	0.586	1.475	0.240267
Residuals	18	7.157	0.398	—	—
Summary for *Rz*					
v_c	1	32.35	32.35	4.162	0.05629
f_z	1	104.82	104.82	13.486	0.00174
a_p	1	8.46	8.46	1.089	0.3105
a_e	1	21.2	21.2	2.728	0.11596
Residuals	18	139.9	7.77	—	—
Summary for *Rq*					
v_c	1	1.596	1.596	2.582	0.1255
f_z	1	8.782	8.782	14.209	0.0014
a_p	1	0.094	0.094	0.152	0.7008
a_e	1	1.01	1.01	1.634	0.2174
Residuals	18	11.125	0.618	—	—
Summary for *Rt*					
v_c	1	27.44	27.44	3.617	0.073329
f_z	1	125.19	125.19	16.498	0.000732
a_p	1	8.58	8.58	1.13	0.301783
a_e	1	17.07	17.07	2.25	0.150956
Residuals	18	136.59	7.59	—	—

Note: DoFs – the number of degrees of freedom, SS – the sum of squares, MSS – the mean of the sum of squares, F-value – test statistic from the F-test, p-value – p-value of the F-statistic.

CONCLUSIONS

The study involved analyzing the influence of the common milling parameters on the quality of the machined surface of 1.4301 steel, also known as AISI 304 steel. The analysis was performed because no similar tests had been found for the 1.4301 steel alloy. The recorded roughness profiles constituted the basis for further examination and developing a relationship between the analyzed milling and roughness parameters.

The impact of geometric milling parameters on the roughness of the machined surface is, in comparison with the subject of the impact of kinematic parameters, a less frequently discussed topic. Particularly noteworthy is the text by Okopujie and Okonkwo, as the research underlying this article was conducted in a similar manner [46]. It should be emphasized, however, that in the aforementioned study, a much smaller range of milling parameter values was taken into account.

It was established that the milling parameter with the greatest impact on the final surface roughness in the case of the tested material was feed per tooth. It had been confirmed by every type of analysis performed, both visual and numerical, including a four-way ANOVA, which took into consideration the dependencies between all four milling parameters [2]. The differences between the rest of the parameters were less obvious. An interesting observation was that the samples machined using an axial depth of cut of 0.75 mm displayed significantly higher values of surface roughness parameters compared with those for 0.5 mm and even for 1 mm, which could have been due to the axial depth of cut being very close to the corner radius of the insert. Such information had not been found in the literature on milling.

In general, as confirmed by the findings, a larger feed per tooth will result in a rougher surface finish, whereas a smaller feed per tooth will produce a smoother surface finish. This is mainly because a larger feed per tooth means that the tool has to remove more material with each pass, which can lead to more tool marks and surface irregularities. Conversely, a smaller feed per tooth means that the tool is removing less material with each pass, resulting in a smoother surface.

Nonetheless, the optimal feed per tooth depends also on other factors, such as the material being machined, the cutting tool geometry, and the cutting speed. A higher cutting speed and a sharper cutting tool may allow for a larger feed per tooth without increasing surface roughness. Therefore, it is important to consider all these factors together when selecting the appropriate feed per tooth to achieve the desired surface roughness.

When it comes to high surface roughness, 1.4301 steel may be suitable for applications where corrosion resistance is the primary concern, such as in chemical processing, food processing, and medical equipment. The high surface roughness can provide a larger surface area for passive oxide formation, which helps to protect the steel against corrosion [49,50].

If the surface roughness is low, it may be more suitable for applications where smoothness and aesthetic appearance are important, such as in architecture, automotive components, and household appliances. Low surface roughness can improve the appearance of the material, make it easier to clean, and reduce the risk of contamination.

There is a vast array of milling parameters, or machining parameters in general, that can influence the surface roughness of a workpiece, but from among the ones tested in this study, feed per tooth turned out to have the greatest impact on the machined surface. The cutting speed, axial depth of cut, as well as radial depth of cut, while still important, did not prove to be as directly correlated with the resulting roughness.

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