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*AISI 316L stainless steel,
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THE EFFECT OF CHANGES IN DEPTH OF CUT ON SURFACE ROUGHNESS IN MACHINING OF AISI 316 STAINLESS STEEL

Currently, process optimization is an important part of design of CNC toolpath, allowing overall process improvement in accordance to a range of criteria. Available CAE software for CNC toolpath optimization works only by changing the feed rate value specified in the base toolpath. The authors are planning to devise a solution allowing for optimization of other process parameters, including depth of cut. In some cases, it would be important for surface roughness to remain unaltered after optimization by means of increasing depth of cut. In this work, the effect of depth of cut on surface roughness was investigated. Depth of cut was altered for the roughing pass, while technological parameters for the finish pass remained constant. Roughness measurements were performed on-machine after rough turning and finish turning. The authors have found that depth of cut has a noticeable effect on investigated roughness parameters, both in the case of rough turning and subsequent finish turning operations.

1. INTRODUCTION

In design of technological processes, a concept of process optimization has gained widespread recognition, particularly in case of CNC machine tools. Process optimization can be understood as a search for the best available solution with accordance to assumed criteria, basing on previously assumed boundary conditions [1]. Those criteria are chosen by the end user depending on desired outcome, and can include for example: machining time, machining costs, tool life, surface finish or dimensional accuracy. Examples of boundary conditions include maximum and minimum values of process parameters recommended by the tool manufacturer, available spindle and feed motor power. Optimization can be done by means of analysing obtained experimental data to determine process parameters best suited to the desired outcome, or with the use of dedicated software. Examples of software solutions dedicated to process optimization are Vericut and Production Module 2D/3D.

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Working principles of CAE software designed for CNC machining process optimization, along with optimization results, have been described in previous work by the authors [2].

It is worth noting that all available commercial CAE software works by changing feed rate values in the CNC control program. Feed rates are easy to change, as their values are given explicitly in the program for each used tool or each machining pass, depending on the approach. However, this is not the best solution on the account of surface finish. An increase in feedrate has the most detrimental effect on surface roughness of all three basic process parameters (feed, cutting speed, depth of cut), as shown by experimental research [3,4,5]. Theoretical models proposed by Shaw (1) [6] and Boothroyd et al. (2) [7] to estimate surface roughness parameters take into account only the effect of feed rate, assuming it has the biggest impact of surface finish.

$$R_a = \frac{1000 f^2}{32r} \quad (1)$$

$$R_t = \frac{1000 f^2}{8r} \quad (2)$$

where: R_a – average surface roughness, μm ; R_t – total roughness profile height, μm ; f – feed rate, mm/min; r – tool nose radius, mm.

No available commercial CAE software solution allow for optimization of the technological process by changing cutting speed and depth of cut values. Cutting speed is easy to modify, as it is given in the control program in form of spindle speed value of constant surface speed value (G96 G-code). However, an increase in cutting speed affects tool life most severely of all three basic process parameters [8,9]. This is a possible explanation why this approach is forfeit in available software. On the other hand, the depth of cut has the least effect on tool life of three basic process parameters. Moreover, an increase the depth of cut value would result in the reduction in the number of machining required to machine the workpiece, thus reducing total machining time. However, depth of cut in the control program is directly tied to workpiece geometry and toolpath. There are no specific G-codes used to define the value of depth of cut, as it is in case of feed rate and cutting speed. Optimization of depth of cut requires interfering with toolpath coordinates (namely X and Z coordinate values for turning processes). This task would prove to be especially challenging for complex workpiece geometries. Currently, the authors are working on a solution which would allow for optimization of depth of cut in an automated way, while maintaining coherence of base and optimized workpiece geometries. Depending on end user requirements, it may also be required that the workpiece surface integrity, especially surface roughness is unchanged after optimization. Therefore, a need to determine whether a change in depth of cut for roughing passes has an effect on finished workpiece roughness parameters arises. An example of workpiece with potential for depth of cut optimization, where maintaining surface roughness parameters is essential for proper operation of the mechanism is described in [10]

Numerous works by other authors have investigated the effect of basic process parameters on surface roughness in milling and turning processes. Davim et al. [4] have investigated the effect of changes of cutting speed, feed rate and depth of cut on surface roughness in turning of 9SMnPb28k steel with the use of coated carbide tools. Wang et al.

[5] conducted experimental studies regarding the effect of changes in base process parameters and cutter geometry on surface roughness in slot milling of Al2014-T6 aluminium alloy. The effect of cutting parameters on surface roughness in hard turning of AISI 4140 steel has been investigated by Asilturk et al. [3]. Kopač et al. [11] tried to determine optimal values of base process parameters in turning of cold formed C15 steel workpieces. While these research papers provide insight into the effect of depth of cut in combination with changes in other parameters, there is a lack of research clearly showing the effect of depth of cut on surface roughness while keeping other process parameters constant.

The aim of this work is to investigate the effect of depth of cut on surface roughness and workpiece finish quality, without changes in other process parameters. Such testing is necessary for validation of the approach proposed by authors (process optimization by changing depth of cut without adversely affecting workpiece quality), before proceeding with further work regarding process optimization by increasing depth of cut.

2. EXPERIMENTAL RESEARCH

The experimental test were carried out on an Okuma GENOS LS200 CNC lathe. A workpiece made of AISI 316 stainless steel was used. The workpiece is shown in Fig. 1.

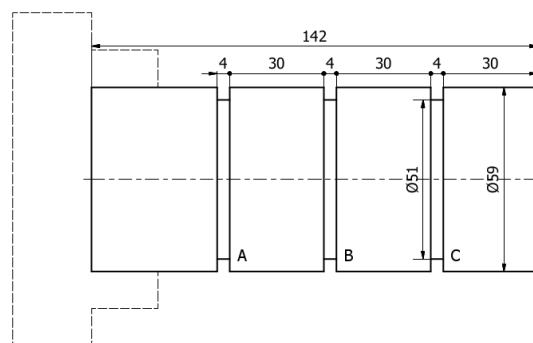


Fig. 1. Workpiece with three areas (A, B, C) corresponding to different depth of cut values used for experimental tests

Process parameters were selected on the basis of values provided by the tool manufacturer. Three different depth of cut a_p values were assumed for rough turning of each part of the workpiece. Total depth of cut for all workpiece areas was 3 mm. Parameter values and tools used for the experiment are shown in Table 1. Surface roughness was measured with the use of MAHR MarSurf PS 10 mobile roughness measuring instrument in three workpiece sections. Each section of the workpiece (A, B, C as shown in Fig. 1 and Table 1.) was correspondent to a different depth of cut value for rough turning. Surface roughness measurements were taken on-machine, first after rough turning, then after finish turning. The sampling length was $L_t = 4.8$ mm, while the cut off length was 0.4 mm both at the beginning and end of the assumed sampling length.

Table 1. Values of technological parameters used for experimental tests

| <u>Rough turning</u> | | | |
|------------------------------|-------------------|--------|--------|
| Insert | WNMG 080412 – 5MR | | |
| | Area A | Area B | Area C |
| Depth of cut a_p , mm | 1 | 1.5 | 3 |
| Number of passes | 3 | 2 | 1 |
| Feed rate f , mm/rev | 0.15 | | |
| Surface speed v_c , m/min | 150 | | |
| <u>Finish turning</u> | | | |
| Insert | CNMG 120408 – MF | | |
| Depth of cut a_p , mm | 0.2 | | |
| Feed rate f , mm/rev | 0.15 | | |
| Surface speed v_c , m/min | 220 | | |

3. RESEARCH RESULTS

The analysis of results focused on the evaluation of the effect of depth of cut a_p on surface roughness. The effect of changes in depth of cut for rough turning on surface roughness obtained in a subsequent finish turning operation was of particular interest. The following surface roughness parameters were investigated: Ra , Rq , Rz , Rt . Each measurement was repeated six times. Measurement results were averaged and standard deviation was calculated for measured roughness parameter. Averaged measurement results are shown in Table 2, and standard deviations for those parameters are shown in Table 3.

Table 2. Roughness parameter measurement results for three workpiece areas after rough and finish turning

| | Area A ($a_p=1$ mm) | | Area B ($a_p=1.5$ mm) | | Area C ($a_p=3$ mm) | |
|------|-------------------------|--------|---------------------------|--------|-------------------------|--------|
| | Rough | Finish | Rough | Finish | Rough | Finish |
| Ra | 0.87 | 0.88 | 0.89 | 0.88 | 1.04 | 1.01 |
| Rq | 1.03 | 1.09 | 1.18 | 1.01 | 1.30 | 1.17 |
| Rz | 4.19 | 4.31 | 6.17 | 4.27 | 6.71 | 4.65 |
| Rt | 4.64 | 4.65 | 8.33 | 4.77 | 7.77 | 5.14 |

Table 3. Standard deviation of roughness parameter measurements for three workpiece areas after rough and finish turning

| | Area A ($a_p=1$ mm) | | Area B ($a_p=1.5$ mm) | | Area C ($a_p=3$ mm) | |
|------|-------------------------|--------|---------------------------|--------|-------------------------|--------|
| | Rough | Finish | Rough | Finish | Rough | Finish |
| Ra | 0.04 | 0.02 | 0.11 | 0.02 | 0.05 | 0.05 |
| Rq | 0.05 | 0.02 | 0.15 | 0.04 | 0.06 | 0.05 |
| Rz | 0.24 | 0.32 | 0.81 | 0.26 | 0.47 | 0.14 |
| Rt | 0.33 | 0.26 | 1.34 | 0.32 | 0.5 | 0.20 |

A graphical representation of measurement results is shown in Figures 2–5.

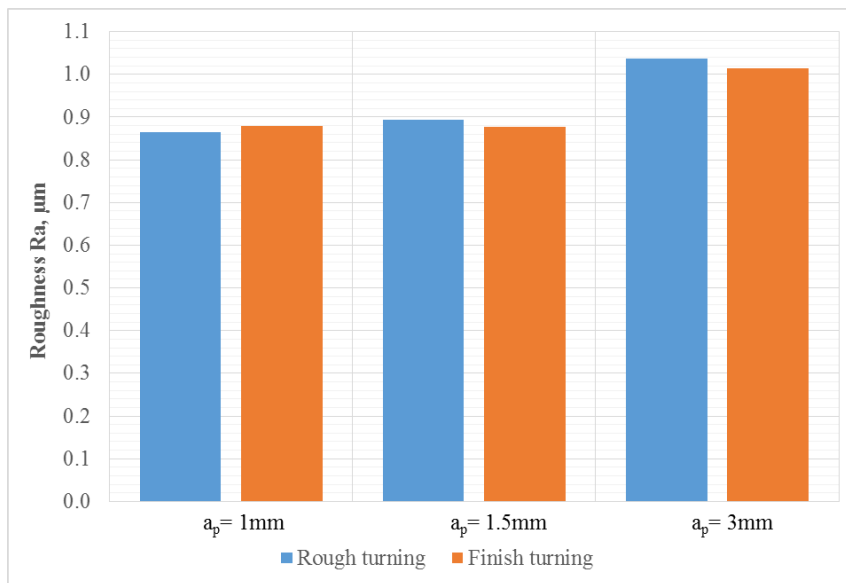


Fig. 2. Arithmetic mean surface roughness Ra vs. depth of cut for rough and finish turning

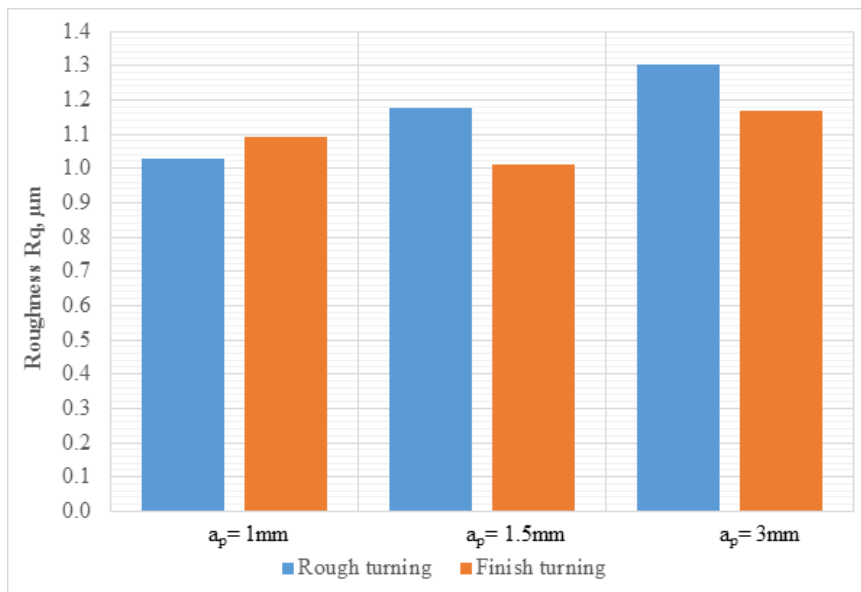


Fig. 3. Root mean square deviation surface roughness Rq vs. depth of cut for rough and finish turning

As can be seen in Figures 2–5, the depth of cut a_p has a noticeable effect on measured values of roughness parameters. For the assumed range of process parameters, there is a general increase in surface roughness parameter values for greater depths of cut, as expected. Better overall surface quality was obtained after finish turning, regardless of initial depth of cut used for rough turning.

The smallest improvement of surface roughness after finish turning is notable in the case of arithmetic mean surface roughness Ra . Smallest differences in Ra values, of all

roughness parameters, were also noted between each assumed depth of cut. This is evident in Fig. 2. The maximum difference in Ra for rough turning is 16%, between cutting depths $a_p=1$ mm and $a_p=3$ mm. The biggest improvement (of 3%) in Ra value after finish turning was noted for $a_p=3$ mm. Differences were even smaller for other investigated depths of cut.

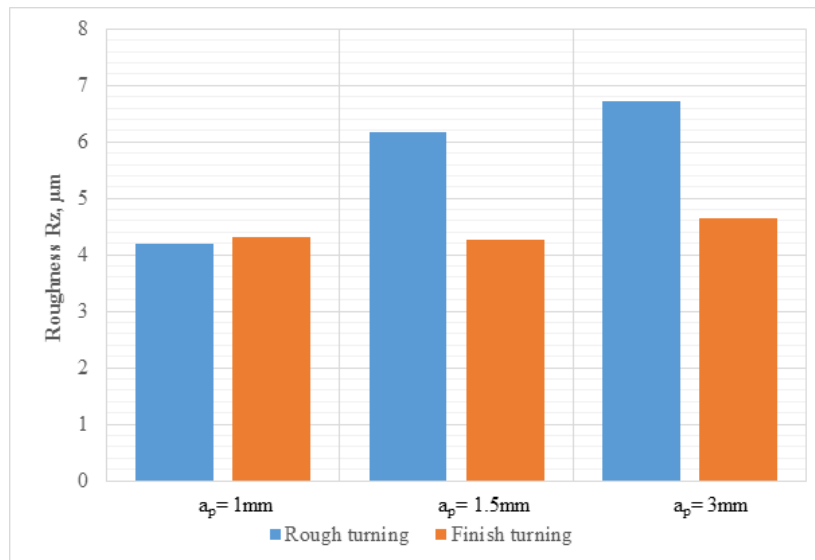


Fig. 4. Surface roughness depth Rz vs. depth of cut for rough and finish turning

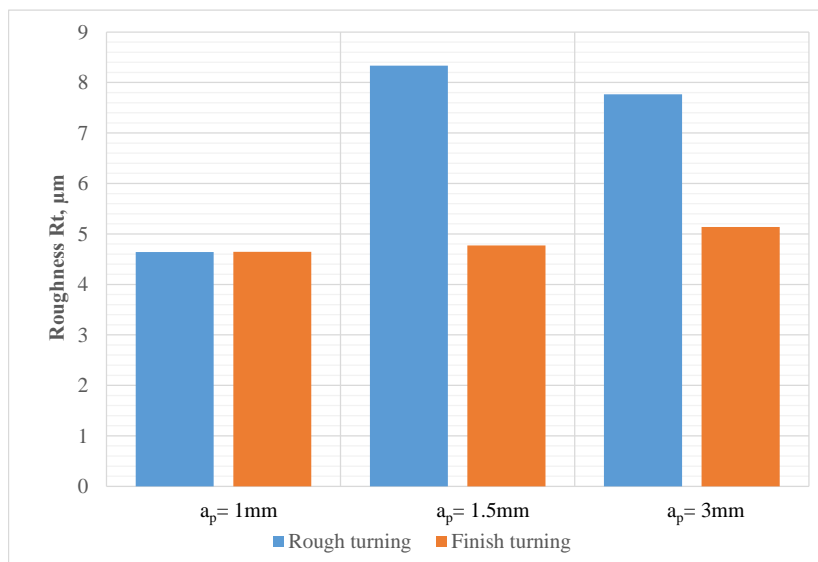


Fig. 5. Total height of the roughness profile Rt vs. depth of cut for rough and finish turning

Similar observations can be drawn from the analysis of changes in root mean square deviation surface roughness Rq values shown in Fig. 3. Higher values of Rq were noted with the increase in depth of cut for rough turning. The total difference in Rq between cutting depths of $a_p=1$ mm and $a_p=3$ mm was 21%. It is worth noting that the smallest value

of $Rq=1.01 \mu\text{m}$ was obtained for $a_p=1.5 \text{ mm}$, which is against the observed general trend for roughness parameters to decrease with the drop in depth of cut used for rough turning. Rq observed for $a_p=1.5 \text{ mm}$ was 8% smaller than Rq measured for $a_p=1 \text{ mm}$.

The surface roughness depth Rz also increases for greater depths of cut, which is shown in Fig. 4. This is especially evident in the case of rough turning. Differences in Rz between three used a_p values are respectably 32% between $a_p=1 \text{ mm}$ vs. $a_p=1.5 \text{ mm}$ and 8% between $a_p=1.5 \text{ mm}$ vs. $a_p=3 \text{ mm}$. Differences in Rz after finish turning are much smaller – only 1% between $a_p=1 \text{ mm}$ and $a_p=1.5 \text{ mm}$, and 8% between $a_p=1.5 \text{ mm}$ and $a_p=3 \text{ mm}$. Maximum difference in Rz after finish turning vs. rough turning was observed for $a_p=3 \text{ mm}$. It can be seen that the influence of finish turning on the reduction in Rz value is more significant than in the case of Ra and Rq parameters.

The effect of depth of cut on total height of the roughness profile Rt is shown in Fig 5. Interestingly, the highest Rt value ($Rt=8.33 \mu\text{m}$) was observed for $a_p=1.5 \text{ mm}$. The most significant reduction in Rt after finish turning vs. rough turning was also noted for $a_p=1.5 \text{ mm}$, equaling 43% ($Rt=4.77 \mu\text{m}$ vs. $Rt=8.33 \mu\text{m}$). It is also worth noting that finish turning did not improve surface quality in the aspect of Rt value in the case of $a_p=1 \text{ mm}$, with Rt value staying practically constant at $4.64 \div 4.65 \mu\text{m}$.

4. CONCLUSIONS

Basing on the analysis of research results, the following conclusions can be drawn:

- Contrary to theoretical equations (1, 2), depth of cut a_p has a substantial effect on surface roughness parameters Ra and Rt measured after rough turning. For the assumed range of process parameters, the biggest difference caused by use of different depth of cut for rough turning was 16% for Ra , and as much as 44% for Rt .
- Depth of cut used for rough turning has a less significant effect on surface roughness parameters measured after subsequent finish turning. However, the effect of depth of cut used for a previous operation has a visible effect on measured parameters. The biggest dependence of depth of cut used in rough turning on surface obtained after finish turning can be seen for Ra , resulting in the difference of 13% between the lowest and highest value measured after finish turning.
- Increasing the depth of cut has a significant effect on spindle load, therefore affecting the dynamic behaviour of the machine tool. Although no visual or sonic indicators of chatter were observed in the range of research parameters, an increased depth of cut may have affected machine-tool-workpiece system stability, affecting the results. Therefore, future research will include an in-depth investigation of potential chatter vibrations.
- In the case of Rz and Rt parameters, the effect of depth of cut used for rough turning has the smallest effect on values of those parameters measured after finish turning, with differences not exceeding 7%.

Overall, the depth of cut has a noticeable effect on roughness parameters, both for rough turning only and for subsequent finish turning operations. In cases where maintaining

a certain quality of surface finish and roughness parameter values is essential, introduction of additional finishing operations, such as grinding, may be needed to ensure that surface finish is unchanged after depth of cut optimization. The authors are planning further research for a wider range of technological parameters and tool geometries.

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