JOURNAL OF PRODUCTION ENGINEERING VOL. 27, NO. 1 (2024)
DOI: 10.24867/JPE-2024-01-022

Original research article

Journal of
Production Engineering

https://jpe.ftn.uns.ac.rs/index.php/jpe
ISSN: 1821-4932 (print), ISSN: 2956-2252 (online)

Cylinder accuracy analysis of tangential turning of disk-like workpieces with increased cutting speed

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ABSTRACT

Tangential turning, a precision high-speed finishing procedure, is crucial for achieving superior surface quality and dimensional accuracy in cylindrical workpieces. This advanced machining technique leverages tangentially applied cutting forces to minimize tool deflection and vibration, thereby enhancing the surface integrity of the final product. Despite its advantages, tangential turning poses challenges in maintaining cylindrical accuracy, necessitating a thorough investigation of cylindrical error. Cylindrical error, the deviation of the machined surface from a perfect cylinder, significantly impacts the functional performance of precision components. Factors such as tool wear, machine dynamics, and thermal effects can induce these errors, demanding comprehensive studies to optimize process parameters and tool paths. By thoroughly analyzing cylindrical error, manufacturers can refine tangential turning processes, ensuring high precision and consistency in high-speed finishing operations. This research underscores the importance of precision error analysis in advancing manufacturing capabilities and achieving stringent quality standards. Cylindrical accuracy is analyzed using the full factorial experimental design methodology to carry out practical cutting experiments, where the cutting speed, feed, and depth of cut were the altered variables. The cylindricity error, peak maximum departure, their ratio, and coaxiality are measured and analyzed. The main effect analysis and detailed study are elaborated using the determined equation. It is found that decreasing the studied parameters is advisable if increasing cylinder accuracy is needed.

ARTICLE INFO

Received: 28 April 2024
Revised: 27 May 2024
Accepted: 01 June 2024

KEYWORDS:
Cylindricity;
Design of experiments;
Tangential turning;
Shape accuracy.

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1. INTRODUCTION

Tangential turning is a specialized high-speed finishing procedure that significantly enhances surface quality and dimensional accuracy in cylindrical workpieces. Unlike conventional turning, which involves a perpendicular orientation of the cutting tool to the workpiece surface, tangential turning moves the tool tangentially to the surface. This approach allows for a more consistent cutting action, reducing the impact of tool deflection and vibration on the final product as shown by Kalpakjian & Schmid [1]. The principle behind tangential turning is the maintenance of a constant cutting force direction, which stabilizes the machining process. This method is particularly beneficial for high-speed applications where maintaining surface integrity is crucial. By minimizing dynamic forces acting on the tool and the workpiece, tangential turning leads to smoother finishes and improved geometric accuracy [2]. Li, Fine demonstrated that mechanistic modeling of cutting forces in tangential turning could optimize the cutting process, resulting in better surface quality and reduced tool wear [3]. Advanced machining techniques, including tangential turning, play a critical role in enhancing productivity and surface quality in modern manufacturing. Traditional machining methods often struggle with challenges such as excessive tool wear, high energy consumption, and suboptimal surface finishes, leading to increased production costs and extended manufacturing times [4]. In contrast, tangential turning and other advanced methods focus on optimizing cutting parameters, reducing tool deflection, and minimizing thermal effects. High-speed machining (HSM) has emerged as a

Published by the University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia.

revolutionary approach, enabling faster material removal rates and finer surface finishes. This method is especially advantageous for materials that are difficult to machine, as it improves surface integrity and dimensional accuracy [5]. Schulz and Moriwaki highlighted that high-speed machining techniques, including tangential turning, could achieve superior surface finishes and dimensional accuracy, which are essential for high-precision applications [6]. The integration of computer-aided design (CAD) and computer-aided manufacturing (CAM) systems has further enhanced the capability to innovate within the field. These technologies facilitate precise control over machining operations, making the production of highly complex and accurate components feasible [7]. This synergy between advanced machining methods and digital tools not only boosts productivity but also contributes to sustainable manufacturing practices by reducing material waste and energy consumption [8]. Recent advancements in tool materials and coatings have significantly improved the performance and longevity of cutting tools used in tangential turning. Sales et al. emphasized the importance of surface integrity in high-speed machining of hardened steels, highlighting advancements in tool materials and coatings that prolong tool life and enhance performance [9]. Similarly, El-Hofy discussed nontraditional and hybrid machining processes that offer solutions for manufacturing intricate geometries with high precision [10]. These developments feature the critical role of ongoing innovation in meeting the needs of modern manufacturing.
Cylindrical error, defined as the deviation of a machined surface from an ideal cylindrical shape, is a critical factor in the manufacturing of precision components. It directly affects the functional performance and assembly of cylindrical parts, which are common in numerous industrial applications. Controlling cylindrical error is vital, as even minor deviations can lead to significant issues in the operation and longevity of mechanical systems [11-12]. Several factors contribute to cylindrical error, including tool wear, machine tool rigidity, thermal effects, and dynamic forces during machining. Niaki and Mears investigated the impact of these factors on cylindrical error, finding that tool wear and thermal expansion are significant contributors to dimensional inaccuracies [13]. Similarly, Cao et al. demonstrated that dynamic forces generated during high-speed machining could induce vibrations, further exacerbating cylindrical errors [14]. Achieving and maintaining tight tolerances is essential in high-precision manufacturing to ensure the reliability and performance of mechanical assemblies. Cylindrical components, such as shafts, bearings, and cylinders, must adhere to stringent geometric specifications to function correctly within larger systems. Understanding and mitigating the sources of cylindrical error is, therefore, critical for producing high-quality parts [15-16]. Advanced metrology techniques, such as coordinate measuring machines (CMMs) and laser scanning, provide high-resolution data on the geometric accuracy of machined parts. These measurements enable manufacturers to identify deviations and implement corrective actions during the machining process [17]. Real-time monitoring and adaptive control systems can dynamically adjust machining parameters to compensate for factors like tool wear and thermal effects, thereby minimizing cylindrical error [18]. Furthermore, simulation and modeling tools have enhanced the understanding of cylindrical error formation. By simulating the machining process, researchers can predict the impact of various parameters on cylindrical accuracy and develop strategies to optimize the process. These simulations consider factors such as tool path optimization, cutting force analysis, and thermal behavior, providing valuable insights into the causes of cylindrical error and potential solutions [19-20].
Recent research highlights the ongoing efforts to address cylindrical error in high-precision manufacturing. For example, Wu et al. explored modeling and simulation of the cylindrical turning process to better understand error formation and develop strategies for its mitigation [21]. Esmaeilian et al. discussed the evolution of manufacturing technology, emphasizing the need for precision and accuracy in producing high-quality components [22]. Varga and Ferencsik explored various parameters influencing cylindricity error in alternator stators subjected to high and low-temperature storage tests [23]. Nagy and Varga investigated cylindrical accuracy and other quality parameters in the turning of shafts, using different coolants and lubricants [24]. Varga et al. further investigated shape accuracy achievable through diamond burnishing of cylindrical parts [25]. Using a factorial experiment design method, they analyzed how different process parameters and postprocessing techniques affected improvements in shape accuracy, specifically focusing on circularity error and cylindricity deviation in cylindrical test specimens, highlighting potential enhancements in circularity. Felhő et al. demonstrated the effectiveness of a well-planned design methodology in their research [26].
In conclusion, the development of novel machining methods, such as tangential turning, and the meticulous study of cylindrical error are paramount for advancing manufacturing capabilities. These efforts ensure the production of high-quality, precision components that meet the stringent demands of modern industries. As manufacturing continues to evolve, the integration of innovative machining techniques and advanced metrology will play a crucial role in achieving superior surface quality and dimensional accuracy, driving progress and competitiveness in the field [27-28].
In this paper, the achievable shape correctness is studied in tangential turning by changing the cutting speed, feed and depth of cut. Certain parameters of cylindricity are analyzed by the application of the Design of Experiments method.

2. EXPERIMENTAL CONDITIONS AND METHODS

The goal of the research was to examine the shape correctness in tangential turning. To accomplish this, cutting experiments and theoretical evaluations using the Design of Experiments (DOE) methodology were performed. The following equipment was utilized in the experiments. An EMAG VSC 400 DS hard machining center was used for this study. A tangential tool with a 45°

inclination angle. The indexable turning tool, produced by HORN Cutting Tools Ltd., was composed of two parts: the S117.0032.00 insert and the H117.2530.4132 holder. The cutting part of the tool was an uncoated carbide insert of MG12 grade. During the experiments, cylindrical workpieces with an outer diameter of 70 mm were machined. The selected material was 42CrMo4 grade alloyed steel, which was hardened to 60 HRc before the experiments. The surfaces intended for tangential turning were pre-machined using a standard CNMG 12 04 12-PM 4314 cutting insert from SANDVIK Coromant, which was mounted in a PCLNR 25 25 M12 tool holder.

The effects of varying the setup parameters in tangential turning were sought to be analyzed, specifically the cutting speed (v_c), feed per workpiece revolution (*f*), and depth of cut (*a*). Both lower and upper limit values were selected for each parameter according to the DOE method. The study focused on the increased range of these parameters. Consequently, the cutting speeds were set at 200 m/min and 250 m/min, the feeds at 0.3 mm and 0.6 mm, and the depths of cut at 0.1 mm and 0.2 mm. These 3x2 limit values resulted in $2^3 = 8$ different setups, as shown in Table 1. The results were analyzed using the Design of Experiments (DOE) methodology. In this analysis, the lower and upper limits were converted as illustrated in Table 1.

Shape error measurements following the cutting experiments were conducted using a Talyrond 365 precision measuring instrument. The parameters in the measurement program were selected based on standard protocols and previous practical experience. An important aspect was the selection of the appropriate reference cylinder. In this study, the Least Squares Cylinder (LSCY) was employed due to its stability and widespread use. It utilizes the axis utilized for centering and leveling components to the rotational datum. Alternative reference cylinders were considered, revealing susceptibility to axis deviation under extreme data conditions [29, 30].

Measurements were taken across seven planes with a 2.75 mm separation between each, resulting in the measurement of a cylinder with a 16.5 mm axial length per run. The analyzed parameters (according to the ISO 12180-1 standard [29]):

- *CYLt* – Cylindricity, the minimum radial separation of two cylinders, coaxial with the fitted reference axis [μm]
- *CYLp* – the peak maximum departure from the fitted reference [μm]
- *Coax* – The diameter of a cylinder that is coaxial with the datum axis and will just enclose the axis of the cylinder [μm]

Equations were determined to compute and illustrate the analyzed parameters using polynomial equations, as detailed in Equation 1. This equation shows the variables (*f*, v_c, *a*) and their combinations, with constants (k_i) representing the contributions of each factor.

$$y(f, v_c, a) = k_0 + k_1 f + k_2 v_c + k_3 a + k_{12} f v_c + k_{13} f a + k_{23} v_c a + k_{123} f v_c a \quad (1)$$

Table 1 – *Experimental setups and the transformed values.*

Setup	1	2	3	4	5	6	7	8
Selected values of the setup parameters								
$f\left[\frac{mm}{rev}\right]$	0.3	0.6	0.3	0.6	0.3	0.6	0.3	0.6
$v_c\left[\frac{m}{min}\right]$	200	200	250	250	200	200	250	250
$a\,[mm]$	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
Transformed values of the setup parameters								
$f'\,[-]$	-1	1	-1	1	-1	1	-1	1
$v_c'\,[-]$	-1	-1	1	1	-1	-1	1	1
$a'\,[-]$	-1	-1	-1	-1	1	1	1	1

The parameters of cylindricity are expressed by the function *y*(*f*, v_c, *a*) within this context. These equations serve to quantify and visualize how variations in cutting speed, feed rate, and depth of cut influence the geometric properties of the machined surfaces. They provide a structured approach to analyze and optimize machining processes for achieving desired levels of dimensional accuracy and surface integrity.

3. RESULTS

Following the procedures outlined in the previous section, both the cutting experiments and the measurements of form accuracy were conducted. The cylindricity error parameters, as discussed earlier, are presented in Table 2. Additionally, peak height (*CYLp*) values were assessed relative to the cylindricity error (*CYLp* / *CYLt*), providing a clearer indication of how various parameters affect the bearing capacity of the profile. This ratio offers insights into the performance implications of dimensional variations in the machined components.

Table 2 – *Accuracy measurement results.*

Setup	1	2	3	4	5	6	7	8
$CYLp\,[\mu m]$	3.26	9.14	6.88	7.04	4.53	9.02	13.47	12.01
$CYLt\,[\mu m]$	5.65	11.74	11.00	12.15	7.30	15.78	24.64	23.31
$\frac{CYLp}{CYLt}\,[-]$	0.58	0.78	0.63	0.58	0.62	0.57	0.55	0.52
$Coax\,[\mu m]$	1.43	2.76	0.52	1.99	0.74	1.15	2.17	1.29

After completing the measurements and their analysis, methods for calculating the studied parameters were established using equations detailed in the preceding section. Equation 2 specifies the calculation for the peak maximum departure.

$$CYLp(f, v_c, a) = 26.59 + 13.22f - 0.1314v_c - 681.9a - 0.0047fv_c + 729.1fa + 3.372v_c a - 3.247fv_c a \quad (2)$$

Equation 3 presents the function for cylindricity error (*CYLt*), depicting its mathematical representation.

$$CYLt(f, v_c, a) = 20.45 + 97.45f + 0.0759v_c - 195.3a - 0.03661fv_c - 15.66fa + 1.11v_c a - 0.1534fv_c a \quad (3)$$

Furthermore, Equation 4 defines the ratio of maximum peak departure from the reference material to the cylindricity error (*CYLp*/*CYLt*), offering insights into dimensional deviations relative to the reference and aiding in the assessment of surface characteristics and machining precision.

$$\frac{CYLp}{CYLt}(f, v_c, a) = -2.67 + 8.433f + 0.0138v_c - -18.48a - 0.03467fv_c - 44.33fa - -0.078v_ca + +0.18fv_ca \quad (4)$$

Equation 5 assists the calculation of coaxiality (COAX) between the axis of the reference cylinder and the datum axis.

$$Coax(f, v_c, a) = -2.67 + 8.433f + 0.0138v_c - -18.48a - 0.03467fv_c - 44.33fa - -0.078v_ca + +0.18fv_ca \quad (5)$$

3. DISCUSSION

The next step is the evaluation of data, following the specification of methods and equipment used, along with the presentation of measured results and derived equations. This analysis proceeds in two stages through the processing of measurements and formulated equations. Firstly, main effect plots illustrating the impact of varied technological parameters on cylinder accuracy are drawn and analyzed. Secondly, surface diagrams based on Equations 2-5 are plotted and assessed to depict the specific influence of feed, cutting speed, and depth of cut on the cylindricity parameters under study in tangential turning.

3.1 Main effect analysis

Main effect plots were created to initially assess the impact of the three parameters under study. Each cylinder accuracy parameter was evaluated individually based on the shown plots in Figure 1.

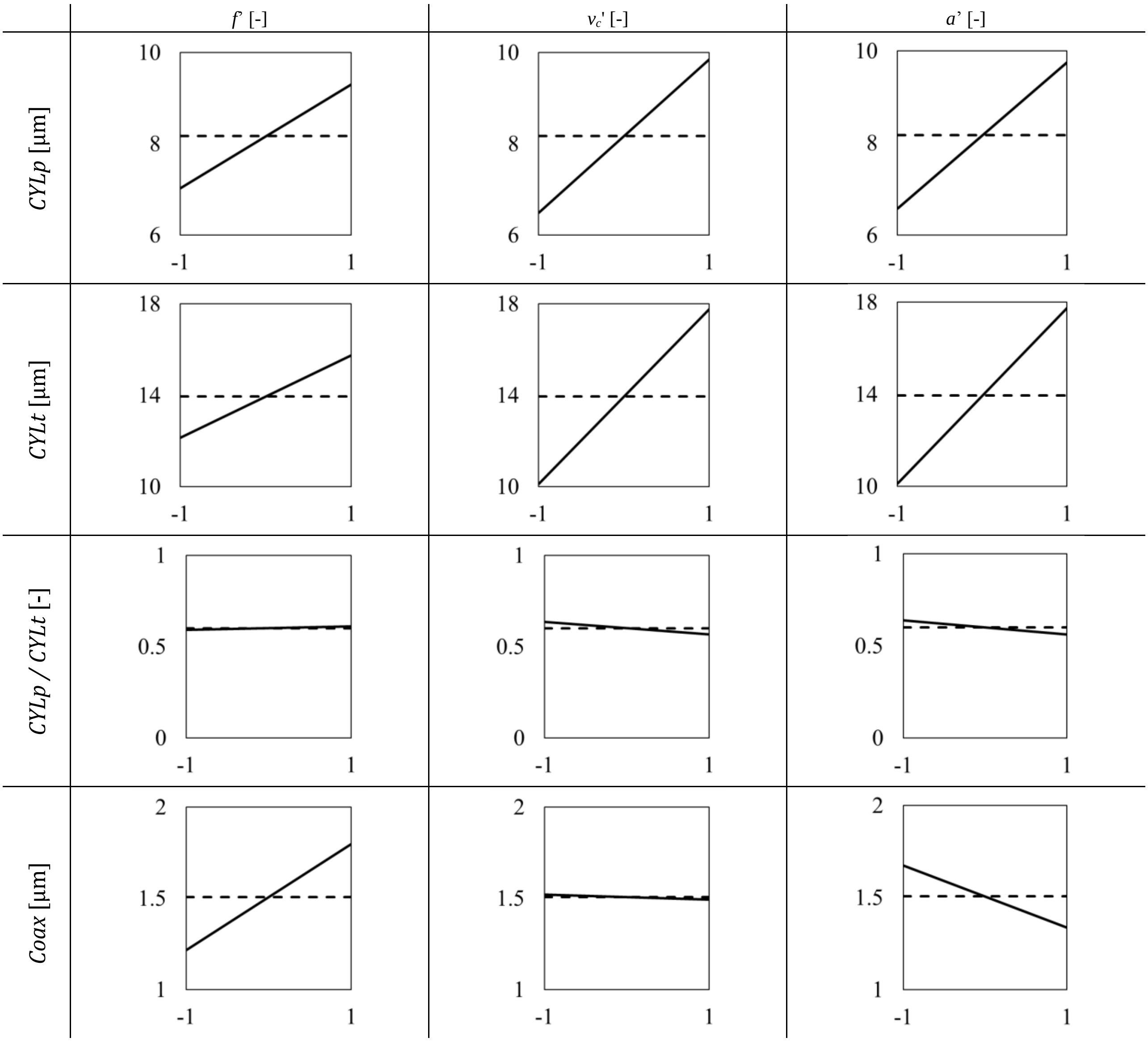

Fig. 1 The total cylindricity error in function of the studied variables

The methodology to determine the graphs in Figure 1 was the following. First, the mean of averaged values was calculated and depicted as a dashed line. Subsequently, two additional means were computed for each of the three cutting parameters, distinguishing between results obtained at the lower (-1) and upper (1) limits of these parameters. These two averages were connected by a continuous line. The direction and steepness of these lines illustrate the primary influence of each cutting parameter on the cylindricity parameters being investigated.

At first, the main effect of the feed change is studied. It can be seen in Figure 1, that the increase of the studied cylindricity parameters can be expected by the increase of the feed. However, it has no effect on the ratio of the maximum peak departure and the total cylindricity. This can be explained by the phenomenon, that the shape of the machined surface will be similar, when the feed is increased in the analyzed value range, only its periodicity will be higher. This results in increasing values of the studied shape error parameters, while the structure of the marks affecting the cylindricity parameters remain nearly the same. Looking at the graphs describing the main effect of the cutting speed in Figure 1, more statements can be made about the changing accuracy parameters.

The cutting speed has an increasing effect on the maximum peak departure and the total cylindricity. However, it slightly decreases their ratio. To increase the cutting speed, the spindly speed is needed to be increased. This results in an increased vibration in the dynamical system of the machining, which contributes in the increasing shape error. The slight change in the ratio can be explained by the different material removal speed, which effects the plasticity of the workpiece. As interesting finding is the almost no effect on the coaxility of the cutting speed in the studied range.

The last altered setup parameter (depth of cut) has an interesting effect on the studied accuracy values. While it mainly increases the maximum peak departure and the total cylindricity, it has a decreasing effect on the coaxility. By the increase of the depth of cut, the chip width and the shape of the chip also changes, leading to a different resultant major cutting edge angle value. This leads to different distribution of the cutting force components, which changes the load on the dynamical system.

3.2 Detailed analysis of the technological parameters

The detailed analysis of the effect of feed, cutting speed and depth of cut on the studied shape error parameters follows the study of the main effects. The study is carried out based on the determined Equation 2-5. Surface plots are drawn to visualize the effects of the changed setup variables on the accuracy parameters. Figure 2-5 present the determined graphs, which are used in the analysis. A separate diagram is drawn for 0.1 mm and 0.2 mm depths of cut, so the effects can be analyzed in the two levels.

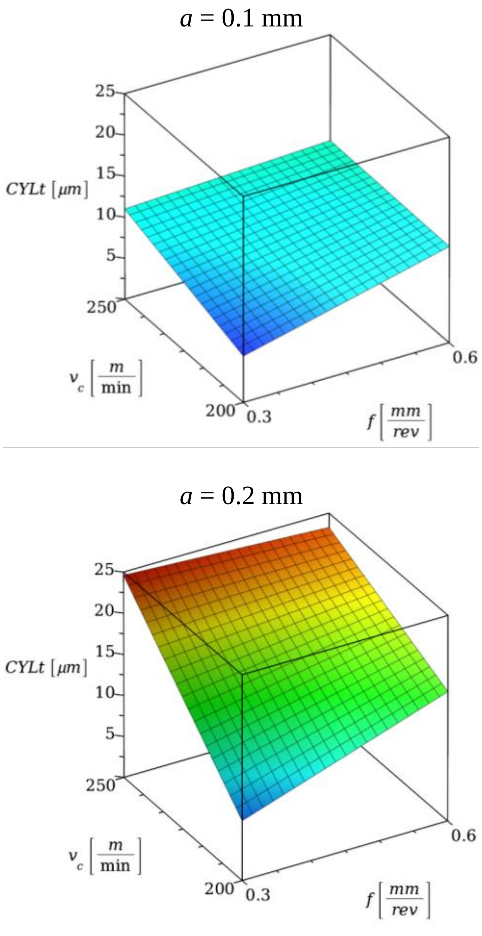

Fig. 2 The total cylindricity error in function of the studied variables

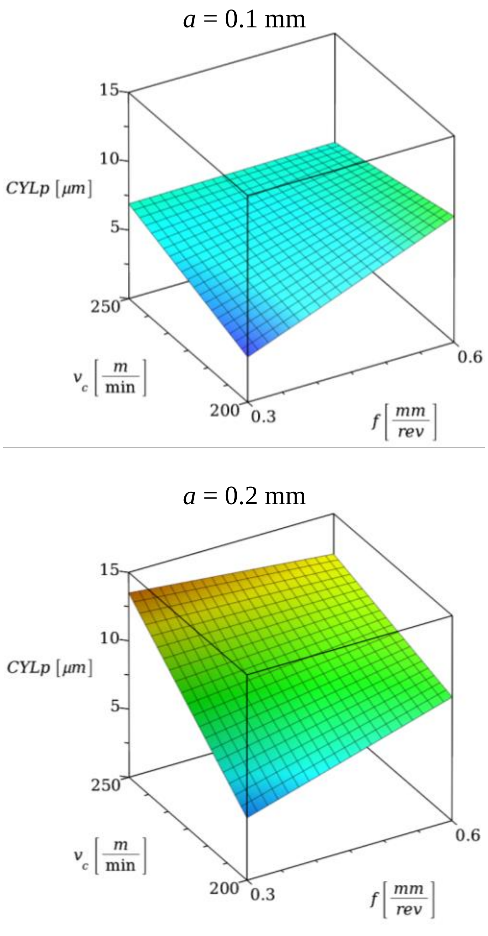

Fig. 3 The peak maximum departure in function of the studied variables

Figure 2 shows the alteration of the total cylindricity error in function of the studied variables. It can be clearly seen that the increase of the depth of cut greatly increase the *CYLt* parameter when 250 m/min cutting speed is applied. A two-fold increase in the depth of cut resulted in a nearly two-fold increase. However, on the lower cutting speed, there is still an incensement, but its extent is much lower (1.5-fold). Changing the cutting speed from 200 m/min to 250 m/min results in an increasing error, which extent affected by mainly the chosen depth of cut. A slight (1.2-fold) increase can be seen, when 0.1 mm depth of cut is applied. However, the change will be greater (1.5-2.0-fold), when the depth of cut is 0.2 mm. The feed has an increasing effect, when 200 m/min cutting speed is applied, while its effect is much less, when 250 m/min is used.

The variation in maximum peak departure is illustrated in Figure 3, in function of the studied variables. It is evident that increasing the depth of cut elevates the *CYLp* parameter slightly, when a cutting speed of 200 m/min is used. The error increases with the depth of cut, but to a lesser extent (1.5-fold). At the higher cutting speed, doubling the depth of cut nearly doubles the cylindricity error. Increasing the cutting speed from 200 m/min to 250 m/min results in a greater error, with the magnitude of this increase largely dependent on the chosen depth of cut. A slight increase (1.1-fold) is noted with a 0.1 mm depth of cut, while a larger increase (1.8-2.6-fold) occurs at 0.2 mm.

The feed rate also has an increasing effect on the *CYLp* cylindricity error at a cutting speed of 200 m/min, while its impact is much less pronounced at 250 m/min.

The alteration of the ratio of the maximum peak departure and the total cylindricity error can be analyzed by the study of Figure 4. The first interesting fact is the stabilizing effect of the depth of cut, which increase has a lowering effect. When *a* is increased to 0.2 mm, a lower variance can be observed in the value of the ratio. Its value is between 0.52 and 0.62. However, the value is between 0.58 and 0.78 when 0.1 mm depth of cut is applied. The higher depth of cut increases the chip width and the chip height slightly, thus leading to a more stabilized chip removal which results in a more coherent surface. The increase of the cutting speed has an overall lowering effect, but the extent of this depends on the applied feed. When 0.6 mm feed is applied, a 20% decrease can be achieved in the ratio, when the cutting speed is increased. Overall, the feed has decreasing effect on the ratio. The only difference is when 200 m/min cutting speed and 0.1 mm depth of cut is applied, where the two-fold increase of the feed resulted a nearly 1.8-fold increase in the ratio.

Coaxility is the final shape accuracy parameter, which is analyzed based on Figure 5. The increase of the cutting speed has a neglect able lowering effect in 3 times from the 4 parameter pairs, while the 1.25-fold increase of v_c results in an almost two-fold increase in the Coaxility.

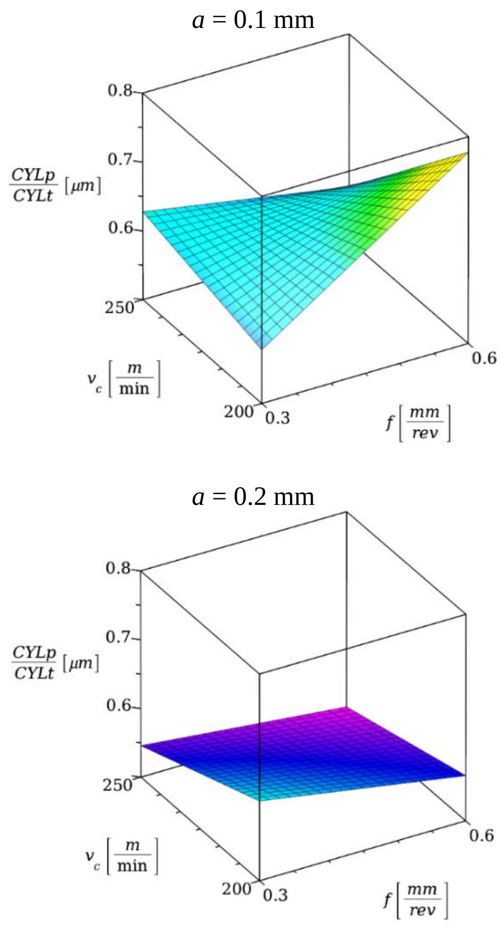

Fig. 4 The ratio of the maximum peak departure and the total cylindricity error in function of the studied variables

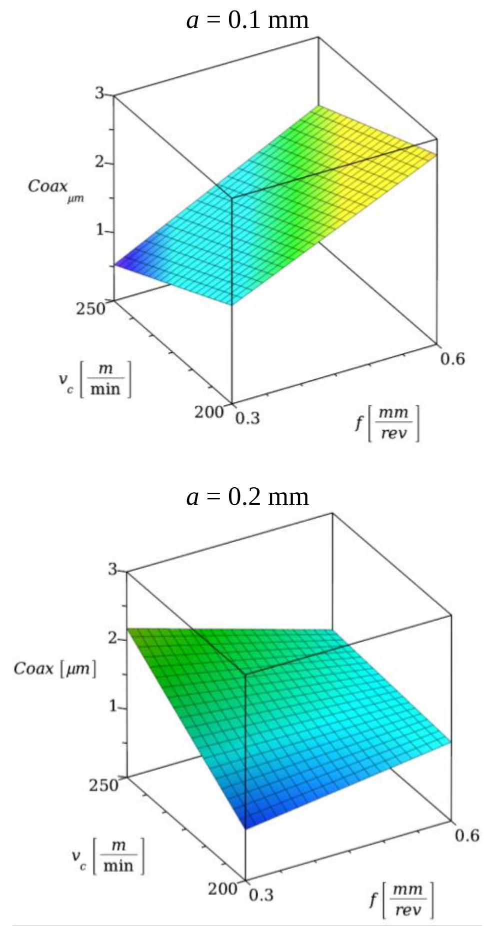

Fig. 5 The coaxility error in function of the studied variables

The depth of cut has a small lowering effect, when the following parameters combinations used: f = 0.3 mm and v_c = 200 m/min; or f = 0.6 mm and v_c = 250 m/min. When the higher feed and lower cutting speed is applied, a nearly 2-fold decrease can be seen with the 2-fold increase in the depth of cut. However, a 4-fold increase can be seen in the coaxility by the 2-fold increase in the depth of cut, if the higher cutting speed and lower feed is applied. The increase of the feed increases the *Coax* parameter in 3 out of 4 parameter-pairs, where the higher effect can be expected, when 200 m/min cutting speed and 0.1 mm depth of cut is applied. A slight decrease in the coaxility can be expected, when the cutting speed is 250 m/min and the depth of cut is 0.2 mm.

The varied setup parameters have various effect on the different parameters describing the shape accuracy. By the application of the determined equations, the exact effects of the feed, cutting speed and depth of cut are explained.

3. CONCLUSIONS

The study of shape correctness in machining is critical for ensuring the precision and quality of manufactured components. Accurate shape and dimensional consistency are essential for parts to fit and function correctly in their intended applications. Any deviation from the desired shape can lead to assembly issues, reduced performance, and increased wear, ultimately impacting the reliability and lifespan of the product. Shape correctness directly influences the efficiency and cost-effectiveness of production, as higher accuracy reduces the need for additional machining and rework.

The study analyzed the effects of feed rate, cutting speed, and depth of cut on shape error parameters in machining. Utilizing the determined equations, surface plots were generated to visualize these impacts, with separate diagrams for 0.1 mm and 0.2 mm depths of cut. The results indicated that increasing the depth of cut significantly raises the total cylindricity error (CYLt), especially at a higher cutting speed of 250 m/min, with a nearly two-fold increase observed. Changing the cutting speed from 200 m/min to 250 m/min also increased the error, with the extent depending on the depth of cut. The feed rate had an increasing effect on the cylindricity error at 200 m/min, but its impact was less at 250 m/min. The maximum peak departure (CYLp) showed similar trends. Additionally, the depth of cut had a stabilizing effect on the ratio of maximum peak departure to total cylindricity error, and the feed rate generally decreased this ratio. Coaxiality was affected variably by the setup parameters, with specific combinations of cutting speed and feed rate showing significant changes.

The following conclusions can be highlighted for tangential turning in the studied parameter ranges:

- Increasing the feed increases the cylindricity error.
- The coaxility can be lowered, when the feed is decreased or the depth of cut is increased.
- The cylindricity error can be lowered, if lower depth of cut is applied.

ACKNOWLEDGEMENTS

The author fully acknowledged the University of Miskolc for supporting this work.

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