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Original scientific paper

EXPERIMENTAL ANALYSIS OF THE INFLUENCE OF PROCESS PARAMETERS ON CYLINDRICITY IN TURNING PROCESS

Marija Cvetkovska, Dragana Stamenkova, Anastasija Lefkova, Ema Vasileska, Ognen Tuteski, Boban Kusigerski, Gligorče Vrtanoski

Faculty of Mechanical Engineering, "Ss. Cyril and Methodius" University in Skopje, P.O.Box 464, MK-1001 Skopje, Republic of North Macedonia
ema.vasileska@mf.edu.mk

A b s t r a c t: Cylindrical parts produced through turning often demand certain form tolerances such as cylindricity to ensure proper function, reliability, and performance. As manufacturing shifts toward higher accuracy and sustainability, understanding how process parameters influence cylindricity becomes increasingly essential. This study presents an experimental analysis of the influence of three fundamental cutting parameters – depth of cut, feed rate, and spindle speed – on the cylindricity of parts produced under dry turning conditions. The experiments were performed on steel E335 using a full-factorial design with parameters varied at two levels. Cylindricity was measured on each machined part and statistically analyzed to evaluate individual effects and interactions of the parameters. Results show that all three parameters significantly affect cylindricity, with spindle speed exhibiting the highest statistical influence. Higher spindle speeds were associated with improved cylindricity, while increased feed rate and depth of cut tended to degrade form accuracy. A regression model was fitted to the experimental data to quantify the influence of each parameter and predict cylindricity deviations based on cutting conditions. The findings align with recent literature and offer practical insights for optimizing dry turning operations to achieve higher geometric precision.

Key words: turning process; design of experiment; regression analysis; cylindricity; process parameters

ЕКСПЕРИМЕНТАЛНА АНАЛИЗА НА ВЛИЈАНИЕТО НА ПАРАМЕТРИТЕ НА ПРОЦЕСОТ ВРЗ ЦИЛИНДРИЧНОСТА ПРИ СТРУЖЕЊЕ

А п с т р а к т: Ротациони делови добиени со стружење често бараат строги толеранции на форма како што е цилиндричност. Со стремежот на индустријата кон поголема точност и одржливост, сè поважно станува разбирањето на влијанието на параметрите на процесот врз цилиндричноста. Во овој труд експериментално се испитува влијанието на три параметри – длабочината на режење, поместот и бројот на вртежи на парчето – врз цилиндричноста добиена при стружење без користење на разладно средство. Експериментите се изведени на челик E335, користејќи сефакторен експеримент со менување на параметрите на две нивоа. Статистичката анализа покажа дека сите три параметри значително влијаат врз цилиндричноста, при што најголемо влијание има бројот на вртежи. Поголемиот број на вртежи доведува до помала вредност на цилиндричноста, додека зголемениот помест и длабочината на режење резултираат со поголема вредност. Регресионен модел беше искористен за да се моделира цилиндричност врз основа на параметрите на режење. Добиените резултати се во согласност со литературата и придонесуваат кон оптимизирање на процесот на стружење без разладно средство.

Клучни зборови: стружење; дизајн на експеримент; регресиона анализа; цилиндричност; процесни параметри

1. INTRODUCTION

Turning is one of the most widely used manufacturing processes for producing cylindrical parts with high precision and repeatability. Critical components, such as automotive shafts and aerospace pins, achieve their cylindrical form through turning operations, which reliably create axisymmetric surfaces [1, 2]. The importance of turning is to shape parts to the desired dimensions but also to achieve the required geometric accuracy to ensure proper function. In particular, cylindrical parts often demand form tolerances such as cylindricity to meet quality and performance requirements [3].

Achieving high tolerance of cylindricity in turned parts can be challenging because many factors in the turning process can induce form errors. Machine tool imperfections (e.g., spindle misalignment or bed deflection) and tool wear can contribute to deviations from ideal geometry [4]. On the process side, the cutting parameters used in a lathe have a strong influence on the resulting form of the workpiece [5], as well as on its surface roughness [6]. These parameters determine the cutting forces, temperatures, and dynamics during material removal, all of which affect how closely the part adheres to a true cylindrical shape. Researchers have found that controlling cylindricity is more complex than controlling surface roughness, due to interactions between multiple inputs in turning [7]. In particular, an aggressive combination of parameters can lead to excessive tool deflection or vibration, resulting in deviations such as out-of-roundness or taper along the length of the part. Selecting optimal parameters can minimize such errors and yield near-ideal cylindrical surfaces. Numerous studies in the literature have investigated how turning parameters impact form accuracy of metal components [8–11]. A consistent finding across the literature is that the most influential parameters affecting cylindricity are the feed rate, spindle speed, and depth of cut. For example, Patel et al. reported that in dry turning of Al 7075 alloy, feed rate had the most significant impact on both circularity and cylindricity errors due to its strong influence on cutting force and vibration, followed by depth of cut and cutting speed [12]. Rafai and Islam concluded that feed rate, cutting speed, and depth of cut were influencing factors for diameter error and circularity in the dry turning of AISI 4340 [13].

In recent years, the rise of new industrial revolutions has enabled the adoption of advanced modeling techniques, including artificial intelligence methods [14, 15]. For instance, response surface methodology and genetic algorithms have been used to optimize cutting conditions and enhance cylindricity [16]. A recent study using artificial neural networks to model turning of aluminum AA7075 confirmed that the best results for overall surface integrity were obtained with a combination of low feed rate and high cutting speed [17].

Another key aspect in manufacturing is the machining environment: whether cutting is done dry or with coolant. Although dry turning has environmental and economic benefits, eliminating the need for cutting fluid disposal and reducing health hazards; the absence of coolant can result in higher cutting zone temperatures and faster tool wear, which potentially impact surface quality and accuracy [18]. The literature suggests that a balanced setting of lower feed rate, adequate (not very high) cutting speed, and small value of depth can yield the best cylindricity in dry turning of metals, even though it shows to have a negative effect on the tool wear [19].

Given the importance of turning for cylindrical components and the critical role of cylindricity in part functionality, understanding how cutting parameters affect this tolerance is of high practical relevance. Therefore, the current study extends this body of knowledge by experimentally analyzing the effect of depth of cut, feed rate, and spindle speed on the cylindricity of lathe-turned steel workpieces made of steel E335 under dry cutting conditions. In this work, a design of experiments approach is employed to analytically vary the three cutting parameters and measure the resulting cylindricity of the machined parts. The findings contribute to a better understanding of how cutting conditions affect cylindricity and provide insights for optimizing lathe operations to achieve higher machining accuracy.

2. EXPERIMENTAL EQUIPMENT

The experiments were carried out on a conventional lathe manufactured by Prvomajska (Croatia, model TVP 250). The lathe operates on a three-phase power supply at 50 Hz, with a rated power of 11.2 kW. The nominal current of the lathe is 23 A, increasing to 25 A during high-speed operations for stable performance across the cutting conditions.

A PSSNR2525M12 tool holder (Pafana, Poland) with a SNMG120408-MF insert (Sandvik Coromant, Sweden) were employed. The selected insert has a nose radius of 0.8 mm and a negative rake geometry, in order to enhance cutting stability and efficient chip removal while maintaining surface integrity and dimensional accuracy.

Cylindricity measurements of the machined parts were performed using a Mitutoyo Roundtest RA-400, shown in Fig. **1**. The instrument is capable of assessing roundness, cylindricity, and flatness among others. The RA-400 is equipped with a precise G-series digital servo motor, auto-focus functionality, and a maximum resolution of 65 nanometers. For collecting data for characterization of the surface form and cylindricity estimation, measurements were conducted along 20 mm length of each workpiece using a spiral scanning pattern.

Fig. 1. Mitutoyo Roundtest RA-400 instrument used for cylindricity measurements

3. EXPERIMENTAL DESIGN

A full-factorial experimental design was employed to investigate the influence of the machining parameters on cylindricity during dry turning process. The tests were performed on structural steel E335, characterized by controlled impurities with maximum values of P ≤ 0.045%, S ≤ 0.045%, and N ≤ 0.012%, and a carbon content around 0.17–0.20%, according to EN 10025-2:2004.

Three process parameters were used in the study: depth of cut (a_p), spindle speed (n), and feed rate (f_n), because as aforementioned these are widely recognized in the literature as the most significant factors affecting geometrical accuracy in turning processes. Each parameter was varied at two levels (low and high), with the corresponding values presented in Table 1. A full-factorial 2^3 experimental design was employed to evaluate all possible combinations of these factors, to make a comprehensive analysis of their individual contributions and possible interactions on cylindricity deviations.

T a b l e 1

Variable factors with their levels employed in the full-factorial experiment

Factor	Low level	High level
Depth of cut, a_p (mm)	0.5	1.0
Feed rate, f_n (mm/rev)	0.08	0.315
Spindle speed, n (rpm)	100	400

Each experimental combination was replicated three times for statistical reliability of the results. As a result, the total number of experiments conducted was 24. The sequence of the experiments was randomized to mitigate external influences.

4. RESULTS AND ANALYSIS

Cylindricity was measured for each machined sample in the experimental trials. The data were analyzed using Minitab Statistical Software. Fig. **2** displays the individual values of cylindricity as a function of the values of the feed rate, depth of cut, and spindle speed. Each data point represents a single experimental observation, with symbol shapes distinguishing the two spindle speed levels: red squares for 400 rpm and blue circles for 100 rpm. The plot shows that the higher level of spindle speed (400 rpm) leads to lower cylindricity values, indicating better form accuracy. In contrast, lower spindle speeds (100 rpm) are resulting with greater deviations from ideal cylindricity. Moreover, an increase in feed rate and depth of cut tends to result in an increase in cylindricity deviation, suggesting that both parameters have a negative impact on form precision when elevated.

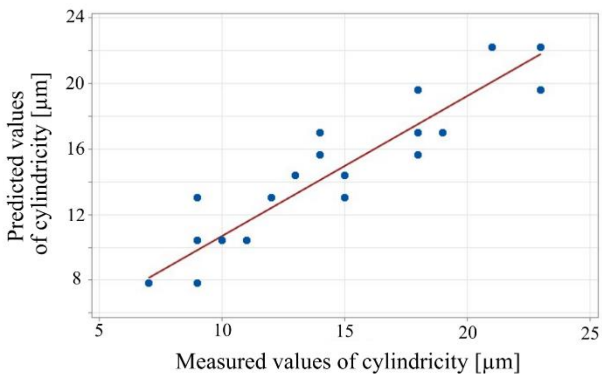

Fig. 2. Individual value plot of cylindricity values from the experiment samples as a function of process parameters

These results are confirmed by various literature works. Studies report that for most materials tested, increasing the cutting speed leads to reduced cylindricity error in turning operations [20]. In practical terms, using a faster spindle speed (within machine and tool limits) generally improves geometric accuracy. It's worth noting that the influence of speed on cylindricity is often less pronounced than feed or depth effects [21]. Studies confirm that a higher feed rate results in a thicker chip per revolution and greater cutting force, which tends to deflect the tool or workpiece and produce a less perfectly cylindrical shape [22, 23] Furthermore, studies show a clear trend of greater depth of cut leading to larger cylindricity error, since the cross-sectional area of the cut is increased, raising cutting forces and potential deflection [24, 25].

These conclusions are further confirmed by the main effects plot of the measured cylindricity values, shown in

Fig. **3**, which illustrates that increasing depth of cut and feed rate leads to worsening of the geometrical accuracy, resulting in higher cylindricity deviations. In contrast, increasing spindle speed has a positive influence, resulting in improved cylindricity and enhanced form accuracy.

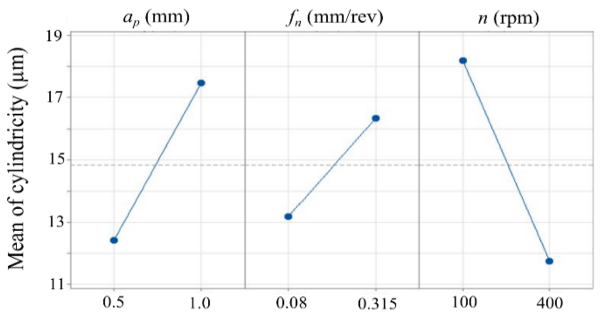

Fig. 3. Main effects plot of investigated process parameters on cylindricity

From the interaction plot for cylindricity (Fig. **4**), it can be observed that no significant interactions are present between the investigated cutting parameters, as indicated by the approximately parallel lines in each subplot. The lack of strong interaction effects suggests that each factor influences cylindricity independently, without notable interaction effects on the output variable.

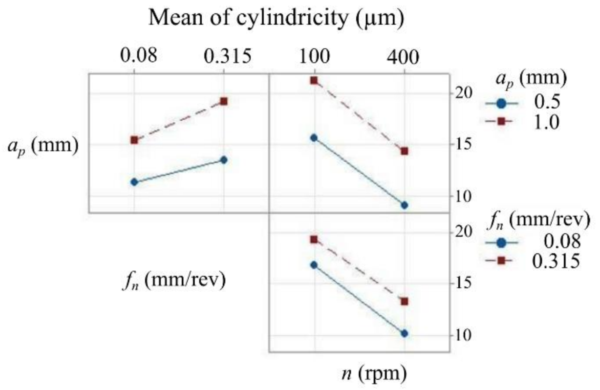

Fig. 4. Interaction plot of investigated process parameters on cylindricity

The ANOVA analysis provides a statistical assessment of the significance of each cutting parameter on cylindricity, and the results by this analysis are given in Table 2. The P-values shown in the table are rounded on three decimal places. As shown, all three factors have statistically significant effects on cylindricity, with P-values less than 0.05. Among them, the results show that spindle speed exhibits the highest influence, as indicated by the largest F-value (61.80), followed by depth of cut (F-value equal to 39.20), and then feed rate (F-value equal to 9.86). This finding is consistent with previous studies showing that spindle speed can have a dominant effect on form accuracy, since spindle speed governs the dynamic behavior of the machining system, influencing factors such as tool–workpiece interaction frequency, vibration tendencies, and thermal stability [26].

Furthermore, the interaction terms between the three factors did not show a significant effect based on the P-values being higher than the threshold value for statistical significance of 0.05. The findings support the trends observed in the main effects and interaction plots and align well with published literature on the influence of cutting parameters on form accuracy. From the ANOVA results all investigated factors will be included in the regression model. Since the results show no significant interactions between the factors, the regression equation will be formulated in linear form with first-degree terms.

T a b l e 2.

Results of ANOVA for cylindricity

Source	F-value	P-value
a_p (mm)	39.20	0.000
f_n (mm/rev)	9.86	0.005
n (rpm)	61.80	0.000

The results of the linear regression analysis showed the following predictive equation for cylindricity (µm):

$$C = 10.46 + 10{,}43 \cdot a_p + 11.13 \cdot f_n - 0.02183 \cdot n \quad (1)$$

where: C is cylindricity, a_p is the depth of cut (mm), f_n is the feed rate (mm/rev), and n is the spindle speed (rpm). The model demonstrated a strong fit, with a coefficient of determination (R^2) of 85.37%, indicating that 85.37% of the variation in cylindricity is explained by the selected cutting parameters. The positive coefficients for a_p and f_n confirm their increasing effect on cylindricity deviation, while the negative coefficient for n supports the observation that higher spindle speeds reduce cylindricity error.

Fig. **5** presents a scatter plot of the predicted values versus the actual cylindricity measurements, providing a visual assessment of the regression model's accuracy. The red line represents the ideal case where predicted values perfectly match the actual data. The distribution of points closely follows this line, indicating a strong correlation between the predicted and observed values. While some scatter and minor deviations from the line are visible, the overall trend confirms that the regression model effectively captures the relationship between the process parameters and cylindricity, supporting the reliability of the linear regression model.

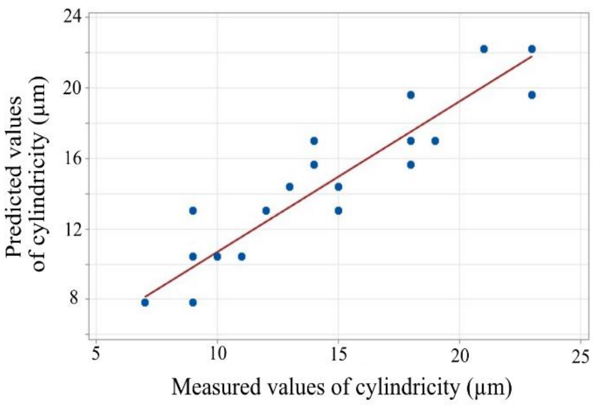

Fig. 5. Scatter plot results of the fitted regression model for cylindricity

5. CONCLUSION

This study investigated the influence of the three most significant cutting parameters: depth of cut, feed rate, and spindle speed, on the cylindricity of steel parts produced through rough dry turning on a conventional lathe. A full-factorial experimental design (2^3) was employed. Statistical analysis was conducted using Minitab software to quantify the individual and combined effects of the process parameters on the measured cylindricity. The findings showed that all three cutting parameters significantly affect cylindricity, with spindle speed as the most influential factor. Increasing spindle speed resulted in improved cylindricity, demonstrating better form accuracy under higher rotational speeds. Depth of cut and feed rate both had a positive correlation with cylindricity error, with larger values increasing cylindricity deviations. No significant interactions between factors were observed in the interaction plots. Therefore, first-degree linear regression model was fitted to correlate the cylindricity output as a function of the three process parameters, which resulted with a high accuracy of R^2 = 85.37%. These findings emphasize the importance of optimizing machining parameters to enhance precision and quality in turning applications.

For future research, the investigation will be expanded to include different materials and tool geometries to generalize the findings. Incorporating in-process monitoring methods, such as force or vibration sensors, can also provide deeper insights into the mechanisms affecting cylindricity and enable the development of adaptive control strategies.

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