UDC 621.91.01 **doi: 10.20998/2078-7405.2025.103.05**

FORM ACCURACY AND CUTTING FORCES IN TURNING OF X5CRNI18-10 SHAFTS: ASSESSMENT OF FEED FORCE VARIATION AND ITS RELATION TO FORM DEVIATIONS

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Received: 10 November 2025/ Revised: 19 November 2025/ Accepted: 29 November 2025 / Published: 15 December 2025

Abstract. *The study presented in this paper aims to provide insight into how cutting parameters, including cutting speed, feed, and depth of cut, influence feed force and form deviations during the X5CRNI18-10 shafts machining. Many experiments were carried out at two depths of cut levels (0.5mm and 1mm) to investigate the effects of cutting speed and feed on feed force, roundness, and waviness. The findings showed that increasing the depth of cut has the strongest influence on cutting force and form deviation. In parallel, higher feed affected the roundness and waviness, leading to a reduction in the surface quality due to the tool deflection and vibrations. Cutting speed had a small impact; however, it is still crucial to select cutting parameters carefully to secure a proper balance between dimensional accuracy, surface quality, and machining efficiency.*

Keywords: *cutting parameters; roundness; waviness; form deviations; turning.*

1. Introduction

The turning of austenitic stainless steel X5CrNi18-10 (equivalent to AISI 304) remains a major challenge for the mechanical engineering industry due to its poor machinability, caused by its high ductility, tendency to work harden, and friction between chips and tools. These issues result in high cutting forces, vibrations, and a reduction in the dimensional accuracy of the workpiece. Several studies reveal that variations in feed force can be directly correlated with geometric deviations, particularly circularity and cylindricity [1-4].

Cutting forces are generally broken down into three components: tangential (F_c), radial (F_r) and axial (F_f). Devices such as Kistler dynamometers can be used to measure these components with high precision. Recent investigations have indicated that the feed force varies significantly depending on the feed conditions, tool geometry and rigidity of the mounting, directly influencing shape accuracy [5,6]. Cutting speed (v_c), feed rate (f), and depth of cut (a) play a key role in influencing forces. An increase in feed rate generally causes a linear increase in feed force and a worsening of surface quality. However, a higher cutting speed tends to reduce the average force due to localized heat and reduced friction [7-9].

Varying feed force causes dynamic deflections of the tool and workpiece, resulting in circularity and cylindricity errors. Studies have shown that periodic oscillation of the axial force can generate measurable surface waviness even when the amplitude of variation remains low. FEM models and frequency analyses confirm the direct correlation between feed force instability and geometric deterioration [10,11]. The geometry of the tool, particularly the clearance, cutting and direction angles, significantly influences the feed component. The use of micro-grooved inserts or coated tools (TiAlN, CrN) reduces cutting forces and improves surface smoothness [12-14]. In addition, the rigidity of the tool-workpiece system is crucial for limiting deformation and vibration [15,16].

Force reduction strategies include the use of minimum quantity lubrication (MQL), nanofluids, and multi-objective optimization of cutting parameters tested to improve the quality of machined surfaces, which represents a major challenge in the manufacturing industry. Experimental approaches coupled with FEM simulation enable accurate prediction of forces and final shape [17,18]. Frequency analysis of force and vibration signals also provides reliable indicators for anticipating geometric errors [19]. Research confirms that variations in feed force are a key factor in generating shape errors when turning X5CrNi18-10 steel. A comprehensive understanding of the mechanical and thermal mechanisms involved, combined with real-time force sensors and predictive models, paves the way for adaptive control of machining accuracy [20,21].

This study was conducted to examine the impact of varying cutting parameters on cutting forces and shape error parameters, specifically, roundness and waviness, during the turning operation of X5CrNi18-10 stainless steel shafts. The investigation will focus on feed force as a key parameter that directly affects the surface quality. It represents the resistance subjected by the tool in the feed direction and is influenced by cutting speed, depth of cut, and feed. Evaluating how cutting parameters affect feed force and shape deviation can provide insight into the surface formation and assist in predicting surface imperfections. As well as these analyses can be used to establish the relations between the cutting parameters, force measured, and surface deviations.

2. Experimental conditions and methods

In the aim of investigating the effects of cutting parameters in introducing cutting forces and shape error during the turning operation, theoretical calculations and experimental analysis were performed. For successful evaluation, experiments were carried out using chromium-nickel austenitic stainless-steel (X5CrNi18.10) specimens. The material employed in this study is known for its excellent corrosion resistance, making it suitable for machining applications. During the turning process, the cutting speed was varied between 200 and 300 mm/min, and the feed was varied at two levels, 0.08 and 0.24 mm/rev, while adjusting the depth of cut from 0.5 mm to 1mm.

Five workpieces of 50 mm were used; each workpiece was divided into five equal surfaces of 30 mm separated by grooves. These surfaces were utilized to measure cutting forces and shape deviations. However, to conduct this study, only eight setups were selected and are mentioned in Table 1.

The tests were performed in wet conditions (5% emulsion of “CIKS HKF 420” coolant oil) using a DDJNL2525M15 tool holder with a DNMG150604-MF1 CP500 carbide/ceramic insert, which is a suitable option for hard cuts. Then the tool was fixed on the HAAS ST-20Y-EU lathe. Moreover, a dynamometer and three amplifiers were mounted on the machine to capture cutting force in three directions, such as cutting force, feed force, and passive force. To calculate the force main and standard deviation, the obtained data were processed using Python codes. Furthermore, the Talyrond 365 precision measuring device was adjusted to standard procedures and methodologies from previous research to measure form deviations. However, the paper will focus on studying the influence of cutting variables only on feed force, roundness, and waviness.

Table 1 – Summary of the applied setups in the experiments

Setup	1	2	3	4	5	6	7	8
v_c [m/min]	200	300	200	300	200	300	200	300
f [mm]	0.08	0.08	0.24	0.24	0.08	0.08	0.24	0.24
a [mm]	0.5	0.5	0.5	0.5	1.0	1.0	1.0	1.0

The evaluated parameters were the following:

- F_f – Feed Directional Force [N]
- σ_f – Standard deviation of the Feed Directional Force [N]
- *RONp* –Maximum radial deviation of a peak from the reference circle. [μm]
- *RONv* – Maximum radial deviation of a valley from the reference circle. [μm]
- *SLOPEm* – Maximum value of the changing of the roundness profile [μm]
- W_a – Average Height of the Waviness Profile [μm]

To analyse the variables under evaluation, Equation 1 was formulated according to the Design of Experiments (DoE) approach. The polynomial equation presents the main parameters such as feed rate (f), cutting speed (v_c), and depth of cut (a), and their correlation. Moreover, to show how these variables affect the cutting force and form deviations, the constant coefficients (k_i) indicate factors with the major impact. This study aims to enhance and optimize the machining conditions with a focus on improving dimensional accuracy and surface quality.

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

3. Experimental results

Based on the previous section, evaluations were conducted to investigate the cutting parameters influence on feed force and shape deviations. The calculated equations 2,3,4,5,6, and 7 according to the formula in equation 1 represent the interaction between cutting variables such as feed, depth of cut, and cutting speed with feed force, roundness components, and waviness. In addition, tables 2,3,4,5,6, and 7 indicate the corresponding results of the feed force main, standard deviation, roundness elements (*RONp*, *RONv*, and *SLOPE*), and waviness.

The feed directional force within the investigated region is expressed by Equation 2:

$$F_f(v_c, f, a) = ((8.68a - 7.538)f - 0.923a + 1.02)v_c + (-872.a + 404.1)f + 123.8a - 28.14 \quad (2)$$

Its variation in standard deviation can be described using Equation 3:

$$\sigma_f(v_c, f, a) = ((-0.473a + 0.12)f + 0.013a + 0.045)v_c + (205.2a - 80.85)f - 8.98a - 4.182 \quad (3)$$

Roundness Peak error is determined according to Equation 4:

$$RONp(v_c, f, a) = ((0.15a - 0.055)f - 0.015a + 0.0061)v_c + (-34.1a + 11.3)f + 3.5a - 0.39 \quad (4)$$

Roundess Valley error is evaluated using Equation 5.

$$RONv(v_c, f, a) = ((-0.004a + 0.049)f + 0.004a - 0.005)v_c + (0.87a - 11.1)f - 0.9a + 2.04 \quad (5)$$

The mathematical expression for slope error is presented in Equation 6:

$$SLOPEm(v_c, f, a) = 0.0001((-12.5a + 50.6)f + 0.2a – 2)v_c + (0.4a - 1.2)f - 0.01a + 0.1 \quad (6)$$

Finally, the average waviness is formulated in Equation 7:

$$W_a(v_c, f, a) = ((-0.00025a + 0.004)f + 0.0006a - 0.0008)v_c + (0.8a - 0.9)f - 0.2a + 0.23 \quad (7)$$

Table 2 – Measurement results of the Feed Directional Force

F_f [N]	Setup							
No.	1	2	3	4	5	6	7	8

Result	91.7	122.0	-15.6	-36.4	95.9	114.8	57.9	95.2

Table 3 – Measurement results of the Standard Deviation of the Feed Directional Force

σ_f [N]	Setup							
No.	1	2	3	4	5	6	7	8
Result	1.69	6.00	1.53	4.02	2.95	6.03	11.63	9.10

Table 4 – Measurement results of the Roundness Peak

RON_p [µm]	Setup							
No.	1	2	3	4	5	6	7	8
1	0.90	0.81	0.78	1.70	1.01	1.09	0.64	3.86
2	0.57	0.87	0.72	1.04	0.99	0.90	0.64	1.25
3	1.30	1.11	0.74	0.66	0.96	0.52	0.57	1.20
Avg.	0.92	0.93	0.75	1.13	0.99	0.84	0.62	2.10

Table 5 – Measurement results of the Roundness Valley

RON_v [µm]	Setup							
No.	1	2	3	4	5	6	7	8
1	0.72	1.16	0.83	1.87	0.94	1.28	0.90	2.27
2	0.71	0.87	0.67	1.48	0.78	1.49	0.67	1.51
3	1.29	0.97	0.68	1.39	0.79	0.55	0.45	1.24
Avg.	0.91	1.00	0.73	1.58	0.84	1.11	0.67	1.67

Table 6 – Measurement results of the Maximum Slope

SLOPEm [µm]	Setup							
No.	1	2	3	4	5	6	7	8
1	0.060	0.088	0.060	0.312	0.064	0.088	0.126	0.252
2	0.055	0.088	0.048	0.058	0.078	0.119	0.044	0.109
3	0.076	0.081	0.053	0.070	0.062	0.050	0.041	0.086
Avg.	0.064	0.086	0.054	0.147	0.068	0.086	0.070	0.149

Table 7 – Measurement results of the Average Height of the Waviness profile

W_z [µm]	Setup							
No.	1	2	3	4	5	6	7	8
1	0.039	0.016	0.109	0.098	0.009	0.019	0.137	0.237
2	0.040	0.018	0.081	0.137	0.010	0.020	0.118	0.194
3	0.035	0.022	0.085	0.175	0.007	0.016	0.122	0.160
Avg.	0.038	0.019	0.092	0.137	0.009	0.018	0.126	0.197

4. Discussion

By using the data in the tables mentioned in the previous section, surface plots were generated for each studied parameter. These plots indicate how feed force components and form deviation variables vary while changing cutting parameters.

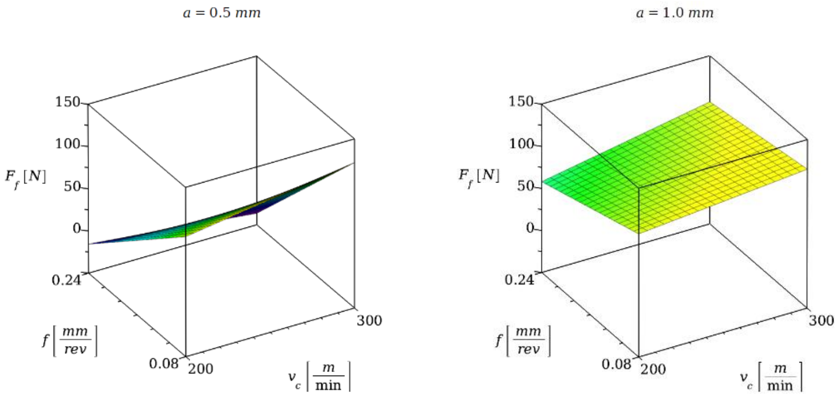

Figure 1 – Variation of the Feed Directional Force in the studied range

Figure 1 shows the changes in the feed force while varying the cutting speed and feed at two levels of depth of cut. At a depth of cut of 0.5 mm, the feed directional force increases progressively with increasing the cutting speed from 200 m/min to 300 m/min, while it decreases noticeably when the feed rate goes from 0.08 mm/rev to 0.24 mm/rev. The analysis suggests that the resistance in the feed direction can be reduced by adjusting the feed rate value, which can enhance the shape removal and minimize the friction effects. However, the rise in the feed force due to the cutting speed can be explained by the interaction between the tool and the workpiece, which can cause thermal effects.

At a cutting depth of 1.0 mm, in the process of increasing the cutting force, the feed force seems to increase slightly due to the introduced friction and temperature at the cutting zone. In parallel, the variation of the feed rate from 0.08 mm/rev to 0.24 mm/rev showed a Modest increase in the feed directional force. In conclusion, the findings suggest that at a smaller depth of cut and higher feed rates value the force remains small. Furthermore, the force range in the 1mm depth of cut is greater compared to the 0.5 mm depth of cut, indicating that the use of more material while machining requires more cutting force, which highlights the need for controlling the cutting parameters to avoid high tool stress.

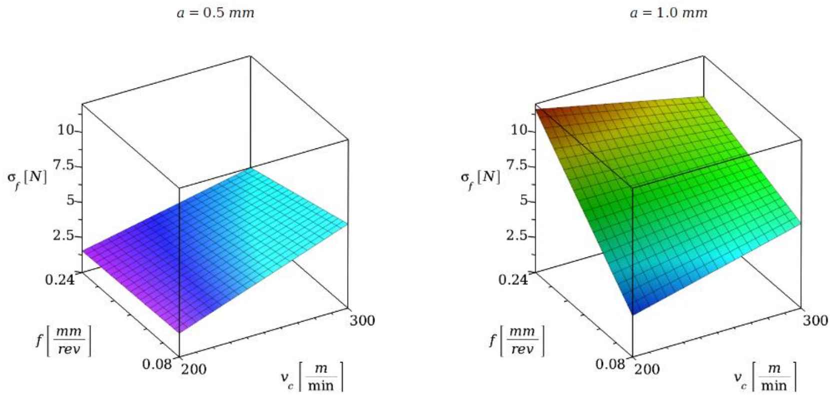

Figure 2 – Variation of the Standard deviation of the Feed Force in the studied range

Figure 2 represents the standard deviation of the feed force (σ_f) as a function of cutting parameters. The plot of 0.5mm depth of cut shows that the standard deviation increases slightly with varying cutting speed from 200 mm/min to 300 mm/min, while changing the feed rate seems to have no effect. However, the results demonstrate that the cutting process was smooth, and less force variation was detected. Compared to the first analysis, the standard deviation at 1.0 mm seems to be more sensitive to both cutting parameters. σ_f rises while increasing the feed, but it is more noticeable at lower speed and higher feed (200 mm/min-0.24 mm/rev). The findings can be clarified by the fact that removing more material can make the process less stable and lead to strong force variation; As a result, the control of cutting speed will be essential to optimize the machining conditions.

The effects of cutting parameters on the roundness peak error (RON_p) were presented in Figure 3. At a small depth of cut of 0.5 mm, the RON_p seems to be stable or to have minor changes, especially at higher cutting speed and higher feed. These results show that the produced surface has a uniform shape and less deformation, which means the tool performed the cutting process under stable conditions.

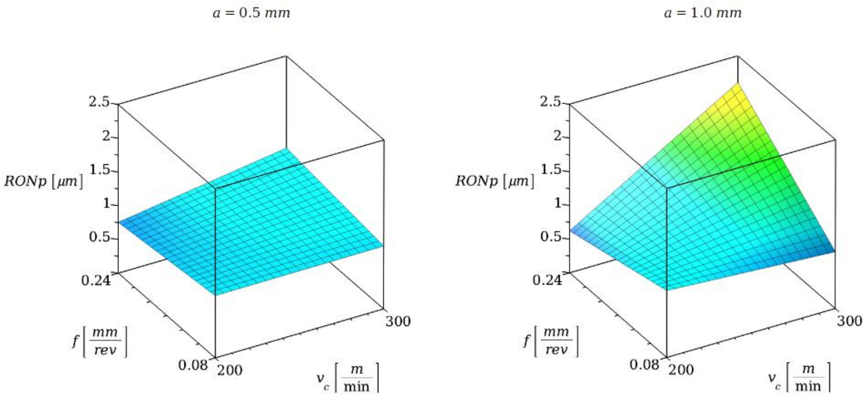

Figure 3 – Variation of the Roundness Peak error in the studied range

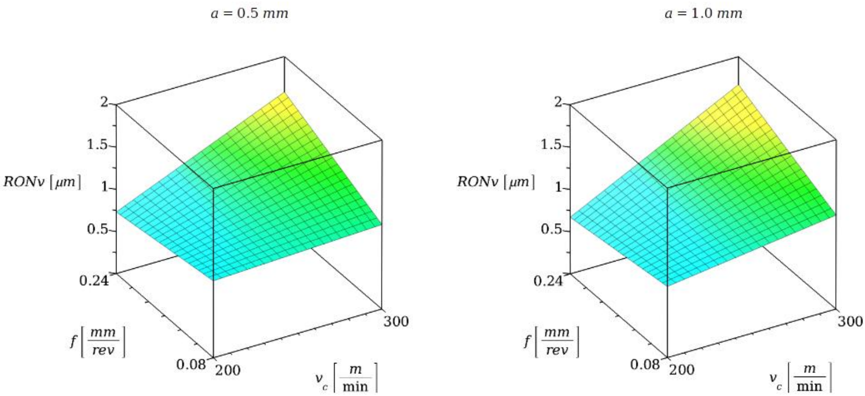

Figure 4 – Variation of the Roundness Valley error in the studied range

Furthermore, the roundness peak error appears to grow with increasing the depth of cut to 1mm, and the effects of cutting speed and feed are more visible. The plot reveals that higher values of cutting variables lead to deviation from the ideal round shape, which can cause less accuracy of the machined part. Therefore, to reduce the roundness errors and enhance the accuracy, it is necessary to keep balanced feed and cutting speed values.

Another parameter of roundness was analysed and presented in Figure 4. At both depths of cut, the Roundness Valley error (RON_v) tends to increase with increasing the cutting speed and the feed, which means that both cutting parameters affect the accuracy of the machined surface. The deviations from the original circle are more pronounced at higher speed (300 mm/min) and higher feed (0.24 mm/rev), which means more mechanical load and heat effects can produce deformation in the machined part. However, the depth of cut seems to have a minor influence on RON_v. As a result, the proper selection of cutting parameters can improve the process conditions and prevent vibrations and deformations to achieve better roundness and dimensional accuracy.

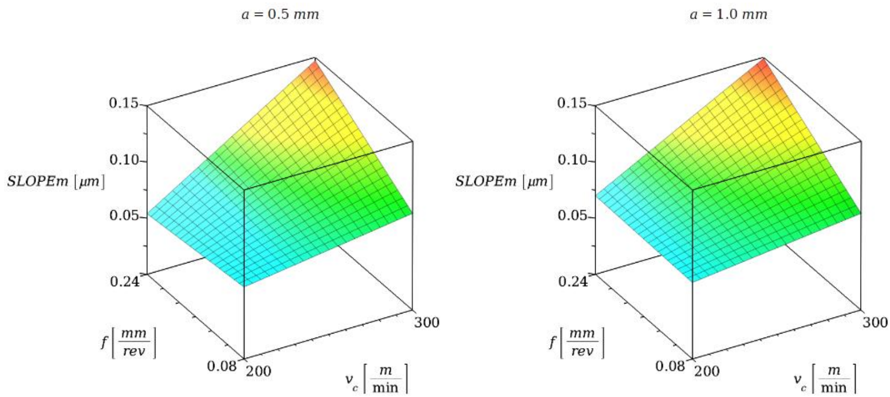

Figure 5 – Variation of the Slope error in the studied range

Figure 5 studies the changes in $SLOPE_m$ as a function of cutting speed, feed, and depth of cut. The plots look similar in both depths of cut and have the same behaviours while changing the speed and the feed. Indicating that the depth of cut may not have a direct relation with the slope. Moreover, $SLOPE_m$ grows significantly with increasing the cutting speed from 200 m/min to 300 m/min and the feed from 0.08 mm/rev to 0.24 mm/rev. But the errors are more visible at higher values of cutting speed and feed. The analysis of roundness components reveals that it is critical to adjust the cutting parameters, especially cutting speed and feed, due to their dominant effects in developing machining errors. That can be illustrated by the heat and tool vibration generated by the interaction between the tool and the workpiece in the cutting zone, which influence the machined part accuracy and surface integrity.

Finally, Figure 6 examines the effect of cutting parameters on surface waviness (W_a). At a depth of cut of 0.5 mm, increasing the cutting speed at a low feed (0.08 mm/rev) slightly reduces the waviness, while at a higher feed rate (0.24 mm/rev), the waviness tends to increase noticeably. In general, an increase in feed values has a direct relationship with higher waviness values.

The second plot represents the waviness variation at 1mm depth of cut when W_a seems to be affected by both parameters, and the changes are more pronounced at higher feed and cutting speed. The findings showed that to reduce surface waviness, it is essential to select optimal cutting parameters.

As a conclusion, all the parameters studied appear to have a direct relation with cutting parameters; these outcomes lead to the development of new methodologies in order to enhance accuracy and efficiency.

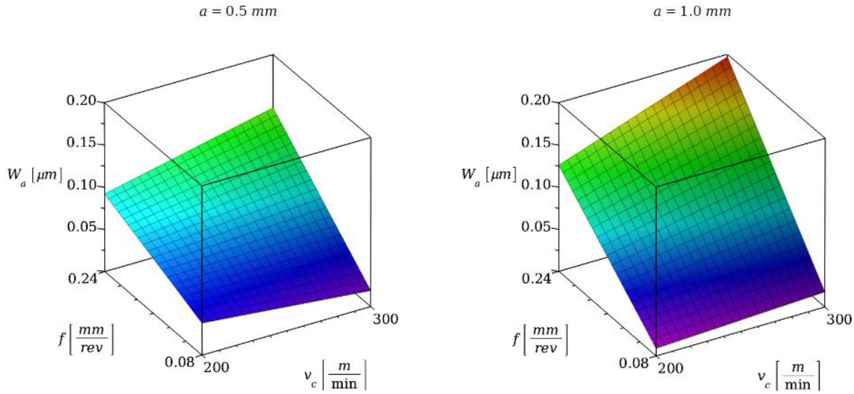

Figure 6 – Variation of the Average Height of the Waviness profile in the studied range

5. Conclusions

This paper discussed the relationship between cutting parameters, feed force, and form deviations, including roundness and waviness, during the turning operation of X5CrNi18-10 stainless steel shafts. The experimental tests were carried out under controlled conditions employing the HAAS ST-20Y-EU turning machine, dynamometer, and shape error measurement instruments to collect the form and shape deviation data.

The results indicated that the depth of cut is the most influential parameter on cutting forces and form deviations. Increasing the depth of cut from 0.5 to 1.0 mm significantly increased the cutting forces and form errors. At the same time, feed rate was strongly correlated with roundness and waviness errors, as higher feed rates increased these errors due to increased tool deflection and vibration. The cutting speed was less influential but still played a role in surface integrity due to thermal and dynamic effects.

In general, this study emphasizes the need for effective control and optimization of the cutting parameters-feed rate and cutting speed-aiming to maintain stability of the process and accuracy at the surface. The approach undertaken in this work, combining experimentation with analysis, thus helps in identifying the role of variables used in the process with respect to dimensional errors and hence establishes some guidelines for obtaining higher precision and better surface quality during the turning of austenitic stainless steel.

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ТОЧНІСТЬ ФОРМИ І СИЛИ РІЗАННЯ ПРИ ТОКАРНІЙ ОБРОБЦІ ВАЛІВ X5X5XH18-10: ОЦІНКА ЗМІНИ ВЕЛИЧИНИ ПОДАЧІ І ЇЇ ЗВ'ЯЗОК З ВІДХИЛЕННЯМИ ФОРМИ

Анотація. *Токарна обробка аустенітної нержавіючої сталі X5CrNi18-10 (еквівалент AISI 304) залишається серйозною проблемою для машинобудівної промисловості через її погану оброблюваність, спричинену високою пластичністю, схильністю до загартування та тертям між стружкою та інструментами. Дослідження, представлене в цій статті, має на меті дати уявлення про те, як параметри різання, включаючи швидкість різання, подачу та глибину різання, впливають на силу подачі та відхилення форми під час обробки валів зі сталі X5CRNI18-10. Було проведено багато експериментів на двох глибинах різання (0,5 мм і 1 мм) для вивчення впливу швидкості різання та подачі на силу подачі, округлість та хвилястість. Експериментальні випробування проводилися в контрольованих умовах з використанням токарного верстата HAAS ST-20Y-EU, динамометра та приладів для вимірювання похибки форми для збору даних про відхилення форми. Результати показали, що глибина різання є найбільш впливовим параметром на зусилля різання і відхилення форми. Збільшення глибини різу з 0,5 до 1,0 мм значно збільшувало зусилля різання і похибки форми. У той же час швидкість подачі сильно корелювала з помилками округлості та хвилястості, оскільки вища швидкість подачі збільшувала ці похибки через збільшення прогину інструменту та вібрації. Швидкість різання була менш впливовою, але все одно відігравала роль у цілісності поверхні через термічний та динамічний вплив. В цілому в даному дослідженні наголошується на необхідності ефективного контролю та оптимізації параметрів різання - швидкості подачі та швидкості різання - уточнення для збереження стабільності процесу та точності на поверхні. Підхід, застосований у цій роботі, що поєднує експерименти з аналізом, таким чином допомагає виявити роль змінних, що використовуються в процесі, щодо похибок розмірів і, отже, встановлює деякі рекомендації для отримання вищої точності та кращої якості поверхні під час токарної обробки аустенітної нержавіючої сталі.*

Ключові слова: *параметри різу; округлість; хвилястість; відхилення форми; токарна обробка.*