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FORM ACCURACY AND CUTTING FORCES IN TURNING OF X5CRNI18-10 SHAFTS: A STUDY ON CYLINDRICITY, COAXIALITY, STRAIGHTNESS, AND WAVINESS AT SMALL FEEDS

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Abstract. *This paper investigates how the cutting speed (vc), feed rate (f) and depth of cut affects the cutting forces and the quality of the surface during turning operations. For the study different experiments have been performed at two depths of cut (0.5 mm and 1.0 mm) to observe how they affect the cutting force, cylindricity, coaxiality (COAX DIN), straightness and waviness. From the results it can be said that the cutting forces and surface deviations increase with the increase in depth of cut. Cutting force normally brings down the forces and enhances surface quality but feed rate has exactly opposite impact. Thus, it is necessary to choose parameters wisely to keep machining efficiency and dimensional accuracy in balance.*

Keywords: *turning; cutting parameters; cutting forces; cylindricity; straightness; waviness.*

1. Introduction

In metal cutting industries, turning operation is one of the most used machining processes in the aim of manufacturing cylindrical parts with defined dimensions, surface quality and geometric tolerances. Furthermore, surface roughness is the key factor in evaluating machined parts. There is a demand for precise components with high accuracy, especially like shafts used in medical, aerospace and automotive systems [1,2]. The functional performance of the components is affected by shape error elements such as cylindricity, coaxiality and surface roughness as well as tool wear behaviour [3,4]. Austenitic stainless steel X5CrNi18-10 is used in many industries because of its good formability, corrosion resistance and mechanical strength. But it is still treated as a challenge when it comes to machining due to its low thermal conductivity, ductility and hardening behaviours. These can produce higher cutting forces and shape errors in addition to tool wear and poor chip control [5-7]. The effects on the tool-workpiece system are more pronounced when different feeds are used, which makes controlling cutting parameters a key to enhancing productivity [8]. The cutting force is the focus of any machining process.

Those forces generate cutting tool deflections, vibration, shape errors and heat that influence the surface integrity and lead to deviations affecting the accuracy of the machined part [9,10]. Based on many studies, the cutting forces can be increasing while increasing the feed and depth of cut. However, the cutting speed has minimal impact. These effects of studied parameters cannot be generalised because these effects depend on the workpiece material, tool type and cutting environments [11,12]. Making it hard to balance efficient material removal and dimensional accuracy, especially with stainless steels [13].

Numerous research studies focused on the influence of cutting parameters such as cutting speed, feed rate and depth of cut on surface roughness. However, fewer studies have examined cutting conditions on deeper geometrical errors like cylindricity, coaxiality, roundness and straightness. These errors are critical to be reduced, especially when they affect the functionality of the components [14,15]. Even though the small feeds enhance the surface roughness, they do not improve the shape accuracy of the part due to the unstable cutting conditions produced, which make the system sensitive to vibrations. This can cause misalignments on the machined parts [16,17].

This research examines the cutting forces and shape errors such as cylindricity, coaxiality, straightness and waviness under cutting parameters (cutting speed, depth of cut and feed) using X5CrNi18-10 stainless steel shafts during turning operation. This study focused on the influence of small feeds and how they affect the accuracy of the turned components. As mentioned in many studies, the small feed tends to enhance the surface quality. However, it can introduce challenges in terms of enhancing geometric precision due to produced vibration and dynamic disturbance which can result in misalignments and waviness impacting the accuracy and functionality of the part. The study tries to provide deep insight into process behaviour and the importance of optimising the cutting parameters in the aim of enhancing surface quality.

2. Experimental conditions and methods

The objective of this research is to study the impact of varying the cutting parameters on major cutting force and shape error elements during turning operations. To conduct the analysis, both experimental tests and theoretical calculations were carried out. In this study the feed was varied in two levels (0.08, 0.24 mm/rev), and cutting speed varied in two levels (200, 300 m/min) under two depths of cut, 0.5 and 1 mm.

At first an experiment test was carried out using stainless steel X5CrNi18.10 workpieces with 310 HV10 hardness. The material abbreviations stand for chromium-nickel austenitic stainless steel that is widely used due to its excellent corrosion resistance. Five workpieces with a 50 mm diameter divided into five surfaces of 30 mm length separated by 5 mm grooves were utilised to capture cutting forces and measure shape errors. However, only eight setups were selected to conduct this evaluation and were mentioned in Table 1.

The HAAS ST-20Y-EU lathe, with lubrication provided by a 5% emulsion of "CIKS HKF 420" coolant oil, performed the cutting tests by mounting a DNMG150604-MF1 CP500 carbide/ceramic insert with a negative rake angle, fixed on a DDJNL2525M15 tool holder, into the machine. The tool used is suitable for hard cuts. In the aim of saving the generated cutting force, a dynamometer was connected to the machine with three amplifiers to capture the changes. The cutting forces were divided into three components: major cutting force, feed force and passive force, but only major cutting force was selected to be studied in this paper. This measurement then was plotted using Python, and force main and standard deviation were calculated.

Finally, the shape error of the workpieces used was measured by the Talyrond 365 precision measuring device, based on standard procedures and methodologies from previous research. Each test run, a 22.0 mm axial length of the cylinder was

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_c – Major Cutting Force [N]
- σ_c – Standard deviation of the Major Cutting Force [N]
- *CYLt* – Total Cylindricity error [μm]
- *COAX* – Coaxility error [μm]
- *STRt* – Straightness error [μm]
- W_z – Maximum Height of the Waviness Profile [μm]

Based on DoE methodology, the polynomial was formulated equation (presented in Equation 1) in the aim of modelling and analysing the parameters under evaluation. The equation factors presented the main variables (feed rate f, cutting speed v_c and depth of cut a_p) and their interactions. The constant (k_i) in the equation provides information on how the mentioned factors affect the cutting force and shape error parameters and highlights the ones that have a bigger influence. This study facilitates the optimisation of machining conditions for enhanced 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

Various evaluations were performed to complete investigation of the cutting parameters variations. To study the effect of cutting parameters on cutting speed and shape error components, Equations were calculated. The chosen error parameters are the following cylindricity, coaxiality, straightness and waviness. The tables 3,4,5,6 and 7 show respectively the measurement of Major cutting force, standard variation of cutting force, cylindricity, coaxiality, straightness and waviness. The formulas for the calculations of output parameters under investigation were taken from Equation 1. Equation 2 defines the cutting force in the interested region.

$$F_c(v_c, f, a) = ((22.56a - 12.74)f + 0.32a - 0.13)v_c + (-4812.a + 3747.)f - 37.5a + 58.9 \quad (2)$$

The equation for the variation in standard deviation is given by Equation 3:

$$\sigma_c(v_c, f, a) = ((0.39a - 0.46)f - 0.034a + 0.042)v_c + (-85.9a + 131.7)f + 8.67a - 10.63 \quad (3)$$

The cylindricity error can be calculated with the following Equation 4:

$$CYLt(v_c, f, a) = ((0.2188a + 0.3269)f - 0.01571a - 0.07666)v_c + (-23.01a - 80.19)f + 3.004a + 24.38 \quad (4)$$

The error in coaxiality is given by the Equation 5 below:

$$COAX(v_c, f, a) = ((-0.04875a + 0.01375)f - 0.0047a + 0.01130)v_c + (13.00a + 30.81)f + 1.939a - 5.515 \quad (5)$$

Straightness error can be verified mathematically by Equation 6:

$$STRt(v_c, f, a) = ((-0.10a + 0.07)f + 0.012a - 0.0076)v_c + (24.1a - 14.5)f - 2.33a + 1.53 \quad (6)$$

Finally, the waviness can be represented mathematically by Equation 7:

$$W_z(v_c, f, a) = ((0.003917a + 0.006832)f + 0.001539a + 0.000310)v_c - (0.5626a + 1.506)f - 0.3856a + 0.0284 \quad (7)$$

Table 2 – Measurement results of the Major Cutting Force

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

Result	130.21	121.65	298.16	266.29	131.58	229.36	275.53	530.49

Table 3 – Measurement results of the Standard Deviation of the Major Cutting Force

σ_c [N]	Setup							
No.	1	2	3	4	5	6	7	8
Result	1.50	1.84	7.17	3.25	2.07	2.26	7.17	6.24

Table 4 – Measurement results of the Total Cylindricity error

CYLt [µm]	Setup							
No.	1	2	3	4	5	6	7	8
Result	8.63	3.67	7.93	9.95	9.39	4.52	10.35	14.21

Table 5 – Measurement results of the Coaxility error

COAX [µm]	Setup							
No.	1	2	3	4	5	6	7	8
Result	0.06	0.87	5.69	6.33	0.69	1.07	6.58	6.40

Table 6 – Measurement results of the Straightness error

STRt [µm]	Setup							
No.	1	2	3	4	5	6	7	8
1	0.20	0.18	0.07	0.65	0.08	0.42	0.57	0.18
2	0.06	0.04	0.51	0.45	0.52	0.51	0.85	0.45
Avg.	0.13	0.11	0.29	0.55	0.30	0.47	0.71	0.32

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

W_z [µm]	Setup							
No.	1	2	3	4	5	6	7	8
1	0.064	0.246	0.048	0.279	0.029	0.260	0.043	0.611
2	0.057	0.196	0.053	0.380	0.024	0.320	0.036	0.466
3	0.050	0.241	0.067	0.432	0.012	0.291	0.029	0.349
Avg.	0.049	0.228	0.045	0.364	0.019	0.290	0.032	0.475

4. Discussion

The paper continues with the analysis of the experimental results and the deducted equations.

The alteration of the major cutting force is analysed at first (Figure 1). For lower depth of cut in first plot, it can be noticed that cutting forces F_c increases a little bit with feed rate f and decreases noticeably with the cutting speed v_c. The plot is almost flat, which shows less dependency of F_c to feed rate at this setting. The rage of cutting forces is about 300 *N* to 500 *N*, where the smallest values occurring at high cutting speeds and lower feed rates. This behavior can be depicted as a sign of stable and efficient cutting conditions with moderate force requirements.

While for the higher depth of cut in second plot), both feed rate and cutting speed shows higher dependency on cutting force F_c increases rapidly with both parameters and showing steep surface profile. The range of forces is higher also. Which is from around 200 *N* to 600 *N*, where the highest values can be noticed at high feed and speed. Thus, it depicts increased tool engagement and removal of material and results in higher loads on the system. It can be said that cutting on these conditions needs careful parameter control to not engage excessive forces.

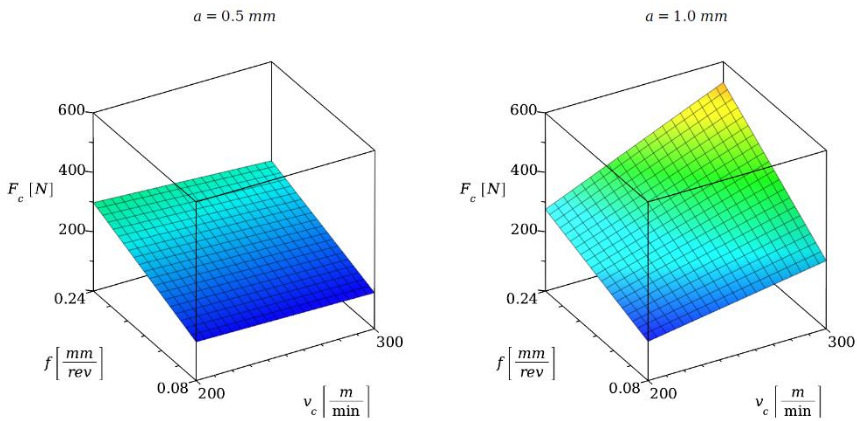

Figure 1 – Alteration of the Major Cutting Force in the studied range

The standard deviation of the major cutting force is analysed next (Figure 2). The first plot with lower depth of cut shows clear decrease in specific cutting force σ_c with increase in cutting speed v_c and feed rate *f* clear slope can be observed in both directions with higher values σ_c up to 8 *N* corresponding to low speeds and high feed rates. This behaviour depicts smaller efficiency at lower cutting speeds and moderate dependence to feed changes at shallow depths.

At higher depth of cut, the behaviour of σ_c remains similar with slight decrease in the curvature. The values of specific cutting forces still go down with increasing the v_c, but the effect of feed rate becomes stronger across the surface. The range of values is still the same but smooth slopes can be seen. Which depicts higher stability for cutting behaviour.

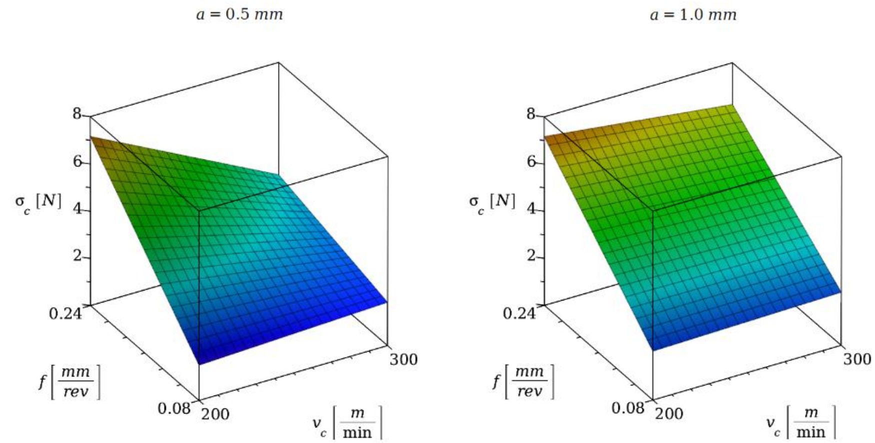

Figure 2 – Alteration of the Standard deviation of the Major Cutting Force in the studied range

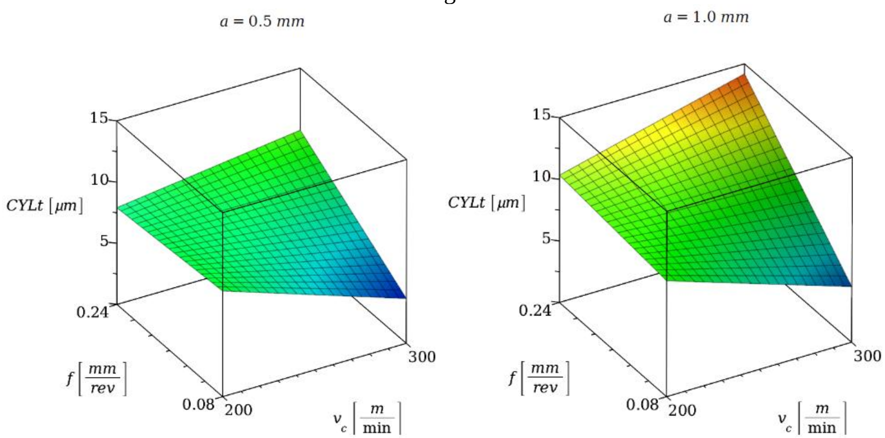

Figure 3 – Alteration of the Total Cylindricity error in the studied range

The cylindricity error (Figure 3) changes moderately with feed rate and cutting speed. *CYLt* has small but direct relation with feed rate, while indirect relation exists between *CYLt* error and cutting speed. The range of error is roughly from 5 μm to 13 μm. This behaviour depicts less geometrical accuracy at lower cutting speed and higher feeds at shallow depth of cut. For higher depth of cut the cylindricity error has more distinct reaction to both parameters. And it increases with both feed rate and cutting speed reaches up to 15 μm. The higher inclination shows that with the increase in any of the parameters, cylindricity becomes poorer and corresponds to bigger tool deflection and vibration effects at higher depth of cut.

At lower depth of cut in the first plot, steady increase in coaxiality error (*COAX*) with feed rate and small increase in coaxiality with cutting speed can be noticed (Figure 4). *COAX* reaches its maximum value of 8 µm at low cutting speed and it drops to less than 2 µm at high speeds and low fee rates. The smooth slope depicts predictable and controlled error behaviour at shallow depth, where cutting depth is the more effective parameter in reducing the error. *COAX* shows the same behaviour at 1.0 mm depth of cut, increasing with feed and decreasing with cutting speed. But the surface is more uniform, and it has the same maximum value of 8 as in first plot. That predicts that at higher depth the *COAX* is less sensitive to parameter changes, but the general behaviour is almost consistent.

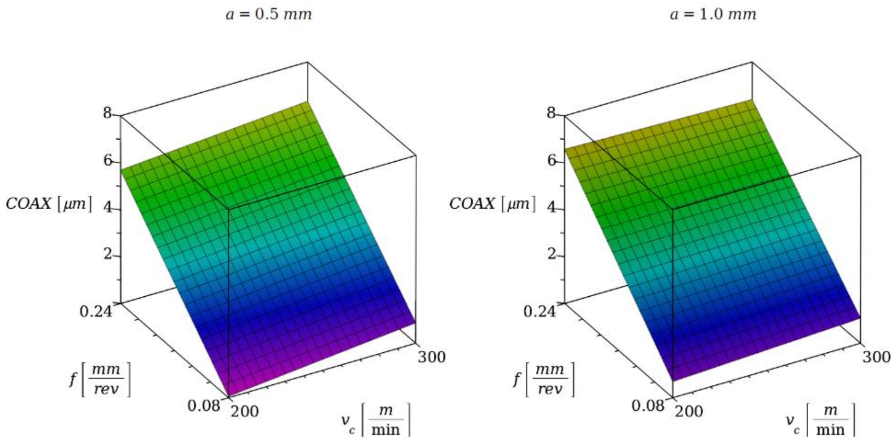

Figure 4 – Alteration of the Coaxility error in the studied range

Figure 5 shows the alteration of the straightness error. The first figure denotes the relation of straightness error (*STRt*) with feed rate is direct while it is indirect with cutting speed. The range of error is about 0.2 µm to 0.8 µm and reaches to highest at high feed and low cutting speed. The slope clearly signifies the impact of both parameters on straightness at shallow depth, but cutting speed is more impactful in reducing the error. At higher depth of cut the *STRt* shows similar relation, direct with feed rate and inverse with cutting speed. But the surface is less steep, and the error lies between 0.3 µm and 0.7 µm. This depicts a more stable and less sensitive response at higher depth of cut. But higher feed rates can still lead to higher errors.

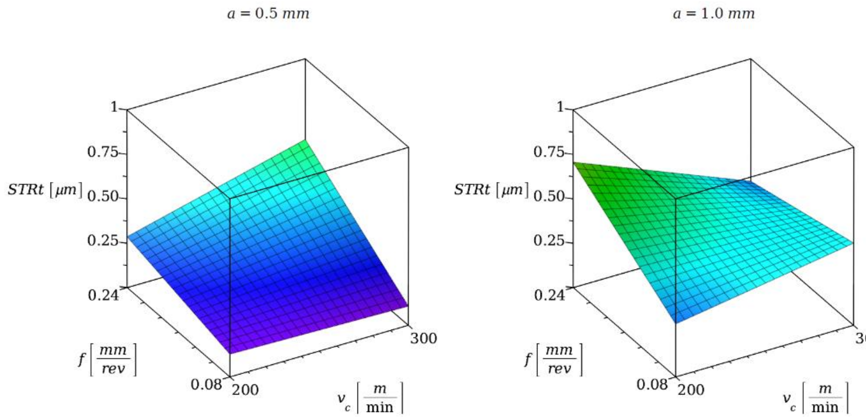

Figure 5 – Alteration of the Straightness error in the studied range

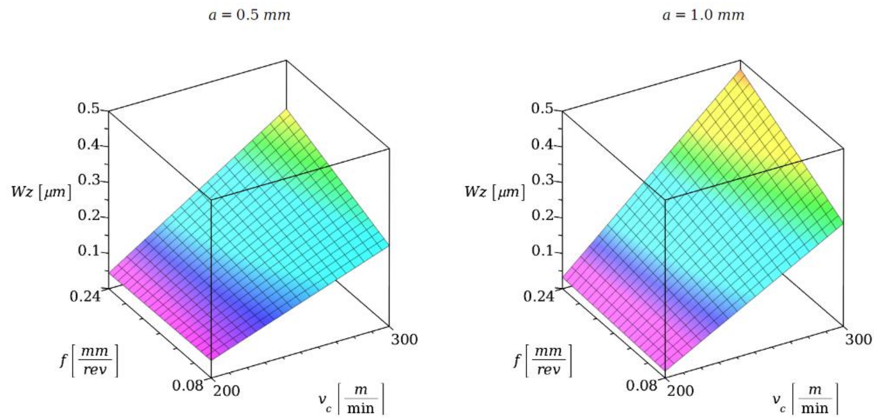

Figure 6 – Alteration of the Maximum Height of the Waviness profile in the studied range

Lastly, the waviness is analysed (Figure 6). It can be noticed in the first plot that waviness W_z has direct relation with both feed rate and cutting speed. The range of roughness lies in between 0.05 μm to 0.45 μm. At higher feed rate and cutting speed a gradual inclination can be observed which indicates that roughness becomes more noticeable with aggressive machining. Thus, both feed and cutting speed take part in surface degradation. By increasing the depth of cut, W_z increases more rapidly with feed rate and cutting speed, with almost same maximum value of 0.5 μm. The slope is higher and shows more dependence on parameter changes. This demonstrates that the high cutting conditions will lead to more roughness and higher depth of cut increases the effect of mechanical interaction on the smoothness of surface.

5. Conclusions

The study investigated the effects of cutting speed, feed rate, and depth of cut on cutting force and surface quality in turning operations. Cutting forces became higher with the increase in the depth of cut from 0.5 mm to 1.0 mm significantly, and the effect of feed and speed on all the output values was also magnified. At smaller value of depth of cut (0.5 mm) cutting force went down and were less affected by feed. While the higher depth of cut (1.0 mm) has more impact and rose the forces sharply up to 600 *N*. specific cutting forces went down for both dept of cuts. Surface errors had direct relation with feed rate and indirect with cutting speed. And these effects were more noticeable at higher depth of cut. It can be summarized that higher depth of cut signifies both mechanical and geometrical deviations and the control of feed and cutting speed is necessary to surface quality and reducing cutting forces particularly for higher depth of cut, in turning operations.

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Мухаммад Хамза Дауд, Ель Майдуб Вафае, Іштван Станкович, Мішкольц, Угорщина

ТОЧНІСТЬ ФОРМИ І СИЛИ РІЗАННЯ ПРИ ТОЧІННІ ВАЛІВ ЗІ СТАЛІ X5X5XH18-10: ДОСЛІДЖЕННЯ ЦИЛІНДРИЧНОСТІ, СПІВВІСНОСТІ, ПРЯМОЛІНІЙНОСТІ І ХВИЛЯСТОСТІ ПРИ МАЛИХ ПОДАЧАХ

Анотація. *Шорсткість поверхні є ключовим фактором при оцінці оброблених деталей. Існує потреба в точних деталях, особливо таких як вали, що використовуються в медичних, аерокосмічних та автомобільних системах. На функціональні характеристики компонентів впливають такі похибки форми, як циліндричність, співвісність і шорсткість поверхні, а також поведінка при зносі інструменту. Аустенітна нержавіюча сталь X5CrNi18-10 використовується в багатьох галузях промисловості завдяки її хорошій формоздатності, стійкості до корозії та механічної міцності. Але вона все ще розглядається як проблемна, коли справа доходить до механічної обробки через його низьку теплопровідність, пластичність і загартування, які можуть спричиняти вищі зусилля різання та похибки форми на додаток до зносу інструменту та поганого контролю стружки. Метою даного дослідження є вивчення впливу зміни параметрів різання на основні сили різання і похибки форми елементів при токарних операціях. Для проведення аналізу були проведені як експериментальні випробування, так і теоретичні розрахунки. У цьому дослідженні подача варіювалася на двох рівнях (0,08, 0,24 мм/об), а швидкість різання варіювалася на двох рівнях (200, 300 м/хв) при двох глибинах різання, 0,5 і 1 мм. Зусилля різання стали вищими зі збільшенням глибини різання з 0,5 мм до 1,0 мм значно, а також було збільшено вплив подачі та швидкості на всі вихідні значення. При меншому значенні глибини різання (0,5 мм) зусилля різання знижувалося і на них менше впливала подача. У той час як більша глибина різання (1,0 мм) має більший вплив і різко зростає зусилля до 600 Н. Питомі зусилля різання знижуються для обох випадків різання. Поверхневі похибки мали пряму залежність від величини подачі і непряму – від швидкості різання. І ці ефекти були більш помітні при більшій глибині різання. Можна підвести підсумок, що більша глибина різання при токарних операціях означає як механічні, так і геометричні відхилення, а контроль подачі та швидкості різання необхідний для якості поверхні та зменшення сили різання, особливо при більшій глибині різання.*

Ключові слова: *токарна обробка; параметри різання; зусилля різання; циліндричність; прямолінійність; хвилястість.*