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CUTTING FORCE DISTRIBUTION IN TANGENTIAL TURNING OF 42CRMO4 ALLOY STEEL: INFLUENCE OF HIGH CUTTING SPEEDS AND HIGH FEED RATES

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Abstract. *This study investigates the cutting force distribution during tangential turning of 42CrMo4 alloy steel under high cutting speeds and high feed rates. The experiments were conducted by varying cutting speed (200 and 250 m/min), feed rate (0.3 and 0.8 mm/rev), and depth of cut (0.1 and 0.2 mm). The major cutting force, feed directional force, and thrust force components were measured, and their maximum values and relative ratios were analysed. The results indicate that both cutting speed and feed rate have a significant influence on the magnitude and distribution of the cutting force components. Higher cutting speeds generally led to a reduction in cutting force values, while increased feed rates resulted in higher force magnitudes and altered force ratios. The obtained data contribute to a better understanding of the cutting mechanics in tangential turning, supporting process optimization and the selection of appropriate cutting parameters for improved machining performance.*

Keywords: *design of experiments; cutting force; experiment; tangential turning.*

1. Introduction

In modern manufacturing, the continuous demand for higher productivity, improved surface quality, and extended tool life has driven the development of advanced machining processes [1]. Turning, as one of the most fundamental and widely applied cutting operations, plays a crucial role in the production of rotationally symmetric parts across various industries, including automotive, aerospace, and general engineering [2]. To meet the increasing requirements for precision and efficiency, alternative turning methods have been developed [3], among which tangential turning [4] offers several notable advantages. Tangential turning is a variant of conventional turning where the cutting tool is mounted tangentially relative to the workpiece surface. This tool orientation modifies the cutting mechanics, leading to potentially lower cutting forces [5], more stable cutting action, and enhanced chip removal [6]. As a result, tangential turning can improve tool life, surface finish, and dimensional accuracy, particularly in the machining of difficult-to-cut or high-strength materials [7]. Despite these advantages, the detailed understanding of the cutting mechanics in tangential turning, especially under specific process conditions, remains limited and requires further investigation.

Tangential turning represents a non-conventional turning method where the cutting insert is positioned tangentially to the workpiece surface, as opposed to the traditional radial orientation [4]. This configuration leads to distinct cutting mechanics, often resulting in favourable force distributions and potential improvements in tool life, surface integrity, and process stability. While tangential turning has received growing attention in recent years, its behaviour under specific cutting conditions, especially at high cutting speeds [8] combined with high feed rates [9], remains insufficiently explored.

Understanding the cutting forces generated during any machining operation is essential for process optimization [10,11], tool design [12,13], and prediction of surface quality [14,15]. In tangential turning, the distribution of cutting forces among the major cutting force, feed directional force, and thrust force differs from conventional turning due to the altered engagement of the cutting edge and chip formation mechanics. The analysis of these force components and their ratios provides valuable insights into the efficiency and stability of the cutting process. High cutting speeds are often employed in modern manufacturing [16] to enhance productivity, reduce cycle times, and improve surface finish. However, when combined with high feed rates and shallow depths of cut, the force dynamics may change significantly. Such conditions are frequently encountered in finishing operations or when machining precision components made of alloy steels such as 42CrMo4 [17-19]. This material, widely used in the automotive, aerospace, and general engineering industries, offers a good balance of strength, toughness, and machinability, making it a common choice for components requiring high dimensional accuracy and surface quality [20-22]. Despite the practical relevance of these cutting conditions, there is still limited experimental data available concerning the detailed behaviour of cutting force components in tangential turning of 42CrMo4 alloy steel. The lack of comprehensive studies underlines the need for targeted investigations to support the development of more accurate force models, improve cutting parameter selection, and enhance overall process control.

The present study aims to address this gap by experimentally analysing the cutting force components during tangential turning of 42CrMo4 alloy steel at high cutting speeds and high feed rates. The maximum values of the major cutting force, feed directional force, and thrust force are measured under various cutting conditions, and the ratios between these force components are evaluated. The findings of this research contribute to a better understanding of cutting force distribution in tangential turning and offer practical guidelines for optimizing machining parameters in similar high-speed, high-feed applications.

2. Experimental conditions and methods

The objective of this study was to analyse the cutting forces generated during tangential turning operations. To achieve this, a series of cutting experiments were performed on an EMAG VSC 400 DS hard machining centre. Before the tangential turning experiments, the surfaces of the workpieces were pre-machined using a conventional turning tool equipped with a SANDVIK CNMG 12 04 12-PM 4314 insert. The tangential turning was carried out using a tool system with a 45° inclination angle, supplied by HORN Cutting Tools Ltd., consisting of the S117.0032.00 insert and the H117.2530.4132 holder. The cutting edge was an uncoated carbide insert (MG12 grade). The workpieces used were cylindrical specimens with an outer diameter of 60 mm, manufactured from 42CrMo4 alloy steel. Prior to machining, the material underwent hardening heat treatment, resulting in a hardness of approximately 410 HV10.

In the experiments, the effects of cutting speed (v_c), feed per revolution (f), and depth of cut (a) on the cutting forces were studied. The parameter levels were determined according to a full factorial (2^3) experimental design. For each parameter, two levels were selected: cutting speeds of 200 m/min and 250 m/min, feeds of 0.3 mm/rev and 0.8 mm/rev, and depths of cut of 0.1 mm and 0.2 mm, resulting in eight distinct test conditions (summarized in Table 1).

Table 1 – Experimental setups

Setup	1	2	3	4	5	6	7	8
v_c [m/min]	200	250	200	250	200	250	200	250
f [mm]	0.3	0.3	0.8	0.8	0.3	0.3	0.8	0.8
a [mm]	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2

The cutting forces were recorded during machining using a Kistler 9257A three-component dynamometer. The measurement system included three Kistler 5011 charge amplifiers, a NI-9215 data acquisition unit connected to a cDAQ-9171 chassis, and data collection was managed through NI LabVIEW software. The dynamometer directly provided the cutting force components without the need for additional calculations.

The following cutting force components were evaluated in this investigation:

- F_c – the main cutting force acting along the cutting speed direction [N]
- F_f – the feed force acting in the feed direction [N]
- F_p – the passive force acting perpendicular to the previous ones [N]

The data analysis employed models based on the factorial design, where the dependent variable (y) was expressed as a function of the cutting parameters, and the coefficients (k_i) represented the influence of each parameter and their interactions.

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

3. Experimental results

The cutting experiments were completed, and cutting forces were measured for each parameter combination. The recorded force–time signals were analysed, and the peak values of each force component were determined during the steady-state cutting phase, where the chip cross-section remained constant. These maximum values are summarized in Table 2. The corresponding mathematical models, derived through appropriate numerical analysis methods, are presented in Equations 2–4.

Table 2 – Measurement results

Setup	1	2	3	4	5	6	7	8
F_c [N]	197.9	204.0	421.1	406.7	393.1	388.2	687.2	663.3
F_p [N]	205.9	279.4	503.8	531.9	463.6	553.5	627.8	755.1
F_f [N]	61.1	72.9	172.4	177.9	149.4	274.6	328.0	348.1

$$F_c(v_c, f, a) = 192.6 - 0.9953 v_c - 246.5 f - 1793.2 a + 1.387 v_c f + 14.93 v_c a + 7960.3 f a - 27.14 v_c f a \quad (2)$$

$$F_f(v_c, f, a) = 132.7 - 0.8291 v_c - 293.7 f - 1109.6 a + 1.569 v_c f + 7.897 v_c a + 4265.7 f a - 14.45 v_c f a \quad (3)$$

$$F_p(v_c, f, a) = 319.1 - 2.808 v_c - 402.8 f - 3591.1 a + 5.190 v_c f + 35.75 v_c a + 7676.4 f a - 54.76 v_c f a \quad (4)$$

In addition to evaluating the individual force components, the analysis also included the investigation of the relationships between the forces. Examining the ratios of the cutting forces provides further insight into the chip formation mechanisms and helps characterize how the cutting process responds to different parameter settings. Accordingly, based on the results in Table 2, the force ratios F_c/F_p, F_c/F_f, and F_p/F_f were calculated for each of the eight experimental conditions. The calculated ratios are presented in Table 3. The corresponding mathematical expressions for these ratios, used for further analysis and interpretation, are shown in Equations 5–7.

Table 3 – Calculated ratios of the cutting forces

Setup	1	2	3	4	5	6	7	8
F_c/F_p [-]	0.961	0.730	0.836	0.765	0.848	0.701	1.095	0.878
F_c/F_f	3.239	2.799	2.443	2.285	2.632	1.413	2.095	1.905

[-]								
F_p/F_f [-]	3.370	3.834	2.922	2.989	3.104	2.015	1.914	2.169

$$F_c / F_f (v_c, f, a) = 1.657 + 0.0157v_c + 4.082f + 7.693a - 0.03626v_cf - \\ - 0.085v_ca - 25.31fa + 0.1807v_cfa \quad (5)$$

$$F_c / F_p (v_c, f, a) = 1.213 + 0.00124v_c + 0.1803f + 6.507a - 0.00735v_cf - \\ - 0.05695v_ca - 4.953fa + 0.08726v_cfa \quad (6)$$

$$F_p / F_f (v_c, f, a) = 1.125 + 0.0128v_c + 2.243f - 6.81a - 0.012146v_cf + \\ + 0.04891v_ca + 0.127fa - 0.09437v_cfa \quad (7)$$

3. Discussion

The evaluation of the influence of the cutting parameters on the cutting forces was performed in two stages. Initially, the maximum values of each individual force component were analysed, followed by the assessment of the ratios between these force components.

The main cutting force (Figure 1) exhibited clear dependency on both feed rate, depth of cut, and cutting speed. Increasing the feed rate from 0.3 mm/rev to 0.8 mm/rev caused a significant rise in F_c at both depth levels. For the lower depth of cut (a = 0.1 mm), F_c increased from 197.9 N to 421.1 N at 200 m/min cutting speed, and from 204.0 N to 406.7 N at 250 m/min.

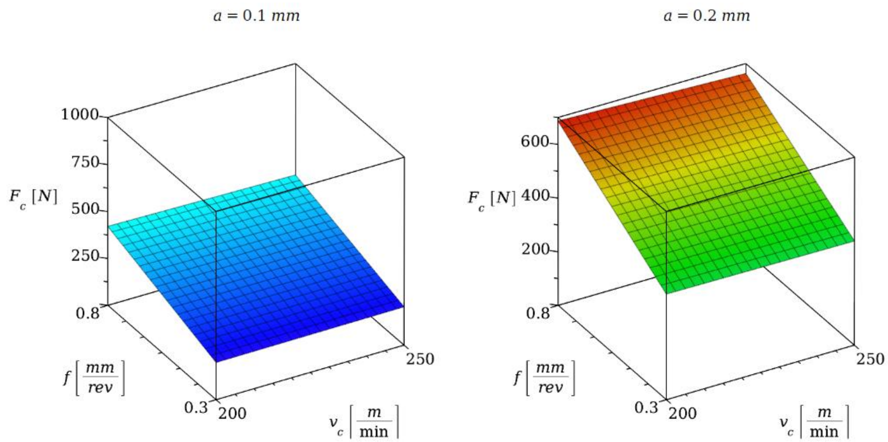

Figure 1 – Alteration of the F_c in the studied range

A similar trend is observed at the higher depth of cut (*a* = 0.2 mm), where the force increased from 393.1 *N* to 687.2 *N* at 200 m/min, and from 388.2 *N* to 663.3 *N* at 250 m/min. The increase in cutting speed generally led to a slight decrease or stabilization of F_c values for the same feed and depth of cut, especially at higher material removal rates. This indicates that higher cutting speeds slightly reduce cutting resistance, potentially due to thermal softening or reduced contact stresses at the tool-workpiece interface. The results confirm that feed rate and depth of cut have a dominant influence on the main cutting force, while the cutting speed plays a secondary, stabilizing role.

The feed force (Figure 2) showed a strong dependence primarily on feed rate and depth of cut, while cutting speed had a less pronounced but still observable effect. When the feed rate increased from 0.3 mm/rev to 0.8 mm/rev at a depth of 0.1 mm, F_f rose from 61.1 *N* to 172.4 *N* at 200 m/min, and from 72.9 *N* to 177.9 *N* at 250 m/min. For the larger depth of cut (*a* = 0.2 mm), F_f increased more steeply, reaching 328.0 *N* and 348.1 *N* at 200 m/min and 250 m/min, respectively. The cutting speed slightly increased the feed force at lower feed rates, but its influence diminished as both feed and depth of cut increased. The high sensitivity of F_f to the feed rate is expected, as feed directly affects the chip thickness and thus the resistance experienced by the tool in the feed direction. The relatively smaller effect of cutting speed on F_f suggests that chip formation mechanics in the feed direction are more strongly controlled by chip load than by thermal or frictional effects that cutting speed influences.

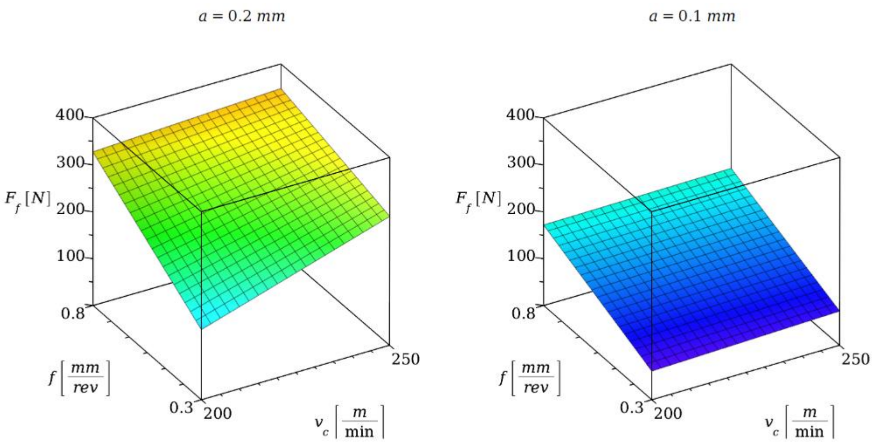

Figure 2 – Alteration of the F_f in the studied range

The passive force (Figure 3), which acts perpendicular to both feed and cutting directions, was strongly influenced by all three cutting parameters. Increasing the feed rate from 0.3 mm/rev to 0.8 mm/rev at a constant depth of 0.1 mm resulted in a considerable increase of F_p from 205.9 N to 503.8 N at 200 m/min, and from 279.4 N to 531.9 N at 250 m/min. At the higher depth of cut (0.2 mm), the passive force further increased, reaching 627.8 N at 200 m/min and 755.1 N at 250 m/min under the highest material removal conditions. Unlike F_c and F_f, F_p appears to be more sensitive to cutting speed, especially at higher depths of cut and feeds, where thermal and dynamic effects may amplify side loading on the cutting edge. The higher values of passive force may indicate elevated radial loading, potentially affecting dimensional accuracy and tool deflection during tangential turning. These results show the need to control feed rate and depth of cut carefully to minimize side loading, especially in high-speed tangential turning

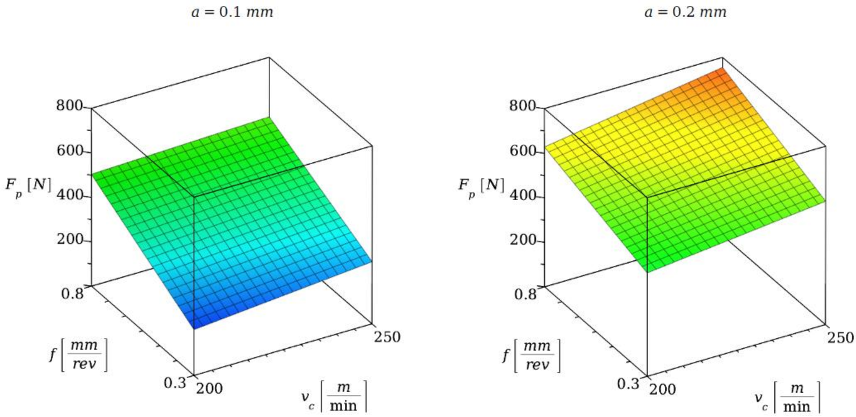

Figure 3 – Alteration of the F_p in the studied range

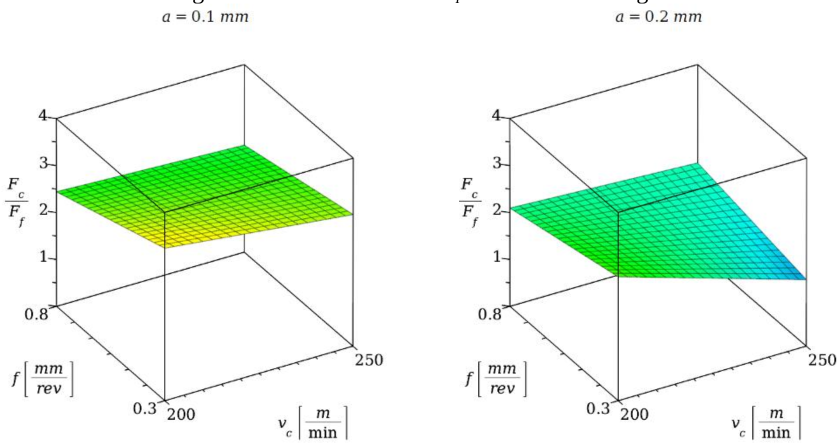

Figure 4 – The ratio of F_c and F_f in the studied range

The ratio of main cutting force to feed force (F_c / F_f) varied notably across the tested parameter combinations (Figure 4). At lower feed rates (0.3 mm/rev), the ratio ranged between 0.96 and 1.62, while at higher feeds (0.8 mm/rev), the ratio generally stabilized around 1.31 to 1.62. At lower depth of cut (0.1 mm), increasing cutting speed caused an increase in F_c / F_f, for example from 0.96 to 1.62 at 200 to 250 m/min when f = 0.3 mm/rev. However, at a = 0.2 mm, the ratio remained more stable, with values mostly around 1.62 regardless of cutting speed or feed. These results indicate that at higher chip loads, the increase in feed force tends to proportionally follow the increase in main cutting force, leading to more balanced force components. At lower depths and feeds, the cutting speed exerts more influence on this ratio, likely due to combined effects of thermal softening and cutting edge engagement dynamics. The stability of F_c / F_f at higher depths may suggest a more predictable force relationship under productive machining conditions.

The ratio between the main cutting force and passive force (Figure 5) was generally below 1.0 for most cutting conditions, indicating that the passive force was comparable to or exceeded the main cutting force.

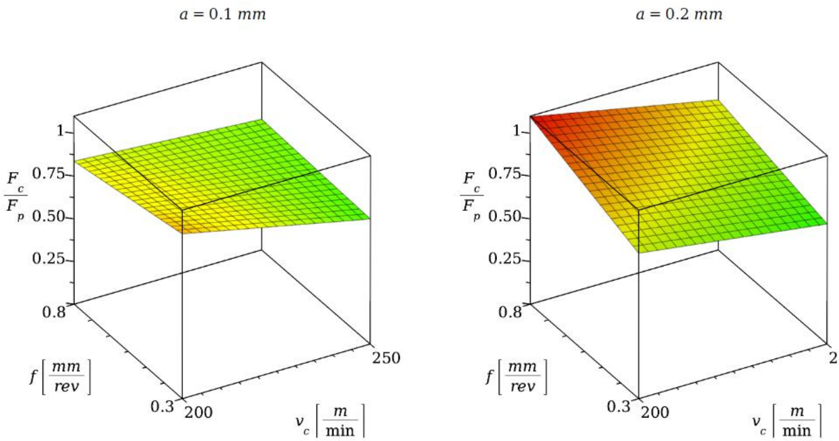

Figure 5 – The ratio of F_c and F_p in the studied range

At low feed and low depth of cut (f = 0.3 mm/rev, a = 0.1 mm), the ratio was near unity (0.96 at 200 m/min) but decreased to 0.73 at 250 m/min. At higher feeds (0.8 mm/rev), F_c / F_p remained below 1.0 for most conditions, with values ranging between 0.70 and 0.84 at lower depth, and reaching 1.09 and 0.88 at higher depth of cut (a = 0.2 mm). This shows that increasing feed and depth of cut both increase passive force more aggressively than the main cutting force. The decrease of F_c / F_p

with cutting speed also suggests that thermal effects at higher speeds may disproportionately elevate radial forces. These results highlight the particular significance of passive forces in tangential turning and their potential role in influencing tool deflection, surface waviness, and stability.

The passive-to-feed force ratio (Figure 6) showed a decreasing trend as feed rate and depth of cut increased. At the lowest feed and depth (f = 0.3 mm/rev, a = 0.1 mm), the ratio was relatively high, reaching 3.37 at 200 m/min and 3.83 at 250 m/min, indicating that at light cutting conditions, the passive force dominates over feed force. However, as feed increased to 0.8 mm/rev, F_p / F_f reduced to values between 2.92 and 2.99 at lower depth, and further decreased to around 1.91–2.17 at a = 0.2 mm. This suggests that increasing material removal rate leads to a more balanced distribution between passive and feed forces, as feed force grows more rapidly than passive force. The cutting speed had a minor effect on this ratio, with slightly higher values observed at 250 m/min for the lowest feeds. These results imply that at heavier cutting conditions, radial loading becomes less dominant relative to feed resistance, contributing to improved process stability but potentially increasing tool wear in the feed direction.

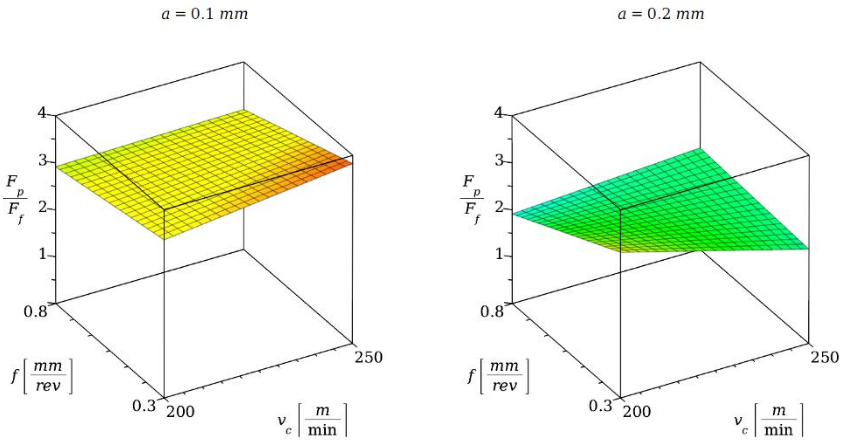

Figure 6 – The ratio of F_p and F_f in the studied range

4. Conclusions

In this study, cutting force components were analysed in tangential turning under varying cutting conditions. The experiments were conducted on 42CrMo4 alloy steel workpieces using a tangential turning tool with a 45° inclination angle. The tested cutting parameters included two cutting speeds (200 and 250 m/min), two feed rates (0.3 and 0.8 mm/rev), and two depths of cut (0.1 and 0.2 mm), resulting in a full factorial experimental design with eight unique setups. The major cutting force, feed force, and passive (thrust) force were measured for each combination using a three-component dynamometer. Additionally, the ratios between the force components were calculated to further characterize the cutting process. The experimental results revealed several important findings.

1. Both feed and depth of cut had a dominant influence on all force components, with higher values leading to significant increases in F_c, F_f, and F_p.
2. The cutting speed mainly influenced the passive force, especially at higher material removal rates, where the increased speed led to higher radial forces.
3. The ratio analyses showed that at higher feeds and depths of cut, the F_c/F_f ratio stabilized around 1.6, indicating a more balanced relationship between cutting and feed forces under productive conditions.
4. Finally, the passive-to-feed force ratio (F_p/F_f) decreased as feed and depth of cut increased, suggesting that under heavier cutting conditions, the feed force grew more rapidly than the passive force, reducing radial load dominance and potentially improving process stability.

These findings contribute to a deeper understanding of the force distribution in tangential turning at high cutting speeds and high feed rates, supporting better parameter selection for stable and efficient machining.

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РОЗПОДІЛ ЗУСИЛЛЯ РІЗАННЯ ПРИ ТАНГЕНЦІАЛЬНІЙ ТОКАРНІЙ ОБРОБЦІ ЛЕГОВАНОЇ СТАЛІ 42CRMO4: ВПЛИВ ВИСОКИХ ШВИДКОСТЕЙ РІЗАННЯ ТА ВЕЛИКИХ ЗНАЧЕНЬ ПОДАЧІ

Анотація. *У цьому дослідженні були проаналізовані складові сили різання при тангенціальному точінні при різних умовах різання. Експерименти проводилися на заготовках з легованої сталі 42CrMo4 з використанням тангенціального токарного інструменту з кутом нахилу 45°. Перевірені параметри різання включали дві швидкості різання (200 і 250 м/хв), дві швидкості подачі (0,3 і 0,8 мм/об) і дві глибини різання (0,1 і 0,2 мм), що дозволило отримати повний факторіальний експериментальний дизайн з вісьмома унікальними установками. Основна сила різання, сила подачі та пасивна (тяга) сила вимірювалися для кожної комбінації за допомогою* *трикомпонентного динамометра. Крім того, співвідношення між силовими складовими були розраховані для подальшої характеристики процесу різання. Результати експериментів виявили кілька важливих висновків. Як подача, так і глибина різання мали домінуючий вплив на всі складові сили, причому більш високі значення призводили до значного збільшення Fc, Ff і Fp. Швидкість різання в основному впливала на пасивну силу, особливо при більш високих швидкостях зняття матеріалу, де підвищена швидкість призводила до більш високих радіальних сил. Аналіз співвідношення показав, що при більш високих подачах і глибині різання співвідношення Fc/Ff стабілізувалося близько 1,6, що вказує на більш збалансоване співвідношення між силами різання і подачі в продуктивних умовах. Нарешті, відношення сили пасивності до подачі (Fp/Ff) зменшувалося зі збільшенням подачі та глибини різання, що свідчить про те, що в більш важких умовах різання сила подачі зростала швидше, ніж пасивна сила, зменшуючи домінування радіального навантаження та потенційно покращуючи стабільність процесу. Ці результати сприяють глибшому розумінню розподілу зусиль при тангенціальному точінні при високих швидкостях різання та високій швидкості подачі, що сприяє кращому вибору параметрів для стабільної та ефективної обробки.*

Ключові слова: *планування експериментів; сила різання; експеримент; тангенціальне точіння.*