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ASSESSMENT OF THE ROOT MEAN SQUARE DEVIATION ON SURFACES MACHINED BY HIGH-FEED TANGENTIAL TURNING

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Abstract. *Recent advancements in machining focus on precision, efficiency, and handling harder materials, driven by sectors like aerospace and automotive. Hard machining, or processing materials over 45 HRC, presents challenges such as rapid tool wear, intense heat, and maintaining dimensional accuracy. Innovations in cutting tool materials and CNC technology have improved these processes, but tool degradation and high forces still complicate machining hardened materials. Surface roughness is a key quality metric, impacting performance factors like wear resistance and fatigue life. By optimizing cutting parameters, manufacturers aim to achieve consistent surface finishes, essential for durability in demanding applications. In this paper, the effect of the input parameters (depth of cut, feed, and cutting speed) are analysed on selected surface roughness parameters. The setup parameters were selected according to the full factorial design of experiment method. The results showed that higher feed rates resulted in rougher finishes, leading to greater spacing between profile elements and steeper surface profiles in the studied range.*

Keywords: *design of experiments; mean spacing of profile; root mean square deviation; root mean square slope; surface roughness; tangential turning.*

1. Introduction

In recent years, the field of machining has undergone significant advancements due to the increasing demand for precision, efficiency, and cost-effectiveness in manufacturing processes [1, 2]. Development trends in machining are largely driven by innovations in material science, tool design, and automation. Modern machining procedures have evolved to handle not only traditional soft and medium-hard materials but also a range of harder materials, such as hardened steels, superalloys, and composites [3–5]. This shift is driven by industries like aerospace, automotive, and medical manufacturing, which require components with high wear resistance and structural integrity. As a result, machining processes have adapted to achieve these demanding specifications through innovations in cutting tools, machining centres, and process control systems [7–9]. The development of advanced tooling materials, such as carbide, cermet, ceramic, and cubic boron nitride (CBN), The development of advanced tooling materials, such as carbide, cermet, ceramic, and cubic boron nitride (CBN), has significantly enhanced the machinability of hard materials. In addition, high-speed machining, adaptive control, and computer numerical control (CNC) technologies allow for greater precision and reduced cycle times, improving productivity. The integration of digital technologies, including real-time monitoring and data analytics [10, 11], further refines these processes, enabling manufacturers to predict tool wear, optimize cutting parameters, and minimize downtime. However, despite these technological advancements, hard machining remains a challenging area due to the inherent difficulties associated with processing hardened materials.

Hard machining, specifically the machining of materials with a hardness level exceeding 45 HRC, poses several challenges. The primary difficulty is the increased wear and failure rate of cutting tools [12, 13], which leads to frequent tool replacements and higher production costs. The elevated hardness of materials generates intense heat and cutting forces during the machining process, resulting in rapid tool degradation. Heat dissipation in hard machining is also problematic; as cutting temperatures rise, tool wear accelerates, impacting surface finish and dimensional accuracy [14, 15]. Additionally, achieving desired geometrical tolerances and surface finishes in hard materials requires precise control over cutting parameters, including feed rate, depth of cut, and cutting speed. The presence of hard carbides and other abrasive constituents within these materials can further complicate the machining process, making it challenging to achieve consistent results.

Surface roughness is a critical quality parameter in machining [16–18] and is particularly important in the context of hard machining. Surface roughness affects the functional performance of machined components, influencing properties such as fatigue resistance, friction, wear, and corrosion resistance [19, 20]. In applications where components must withstand high stress or operate in harsh environments, a smooth and consistent surface finish is essential. Consequently, evaluating and controlling surface roughness has become a central aspect of machining research. Surface roughness evaluation typically involves measuring parameters like the Average Roughness (R_a), Root Mean Square Roughness (R_q), and Mean Spacing of Profile elements (R_{ms}), which provide insights into the micro-topography of the machined surface [21, 22]. Various methods are used to assess surface roughness, including contact and non-contact measurement techniques [23]. Contact methods, such as stylus profilometers, physically trace the surface to record roughness values, while non-contact methods, such as optical and laser-based systems, offer faster measurements with less risk of damaging the surface. Advanced software tools and three-dimensional surface analysis have made it possible to obtain detailed topographical information, enabling engineers to better understand the effects of machining parameters on surface quality. With these methods, researchers can optimize machining processes by examining the impact of cutting speed, feed, depth of cut, and tool geometry on surface roughness. By improving control over surface quality in hard machining, manufacturers can enhance the reliability, durability, and performance of critical components.

In summary, while advancements in machining technology have enabled significant progress in processing hard materials, challenges remain. The optimization of surface roughness through careful selection and control of cutting parameters is essential for achieving high-quality finishes in hard machining applications. In this paper, an innovative machining procedure (tangential turning) is studied, which could provide solutions for the challenges of hard machining. The surface roughness of the machined workpieces was assessed by the evaluation of Mean Spacing of Profile, Root Mean Square Deviation, Root Mean Square Slope roughness parameters. The study aims to find connections between the input technological parameters (feed, depth of cut, cutting speed), and the selected roughness parameters.

2. Experimental conditions and methods

In this study, the tangential turning process was performed using a specialized tool designed for precision and durability. The tool setup included a SANDVIK Coromant CNMG 12 04 12-PM 4314 cutting insert for initial turning, followed by a tangential turning tool from HORN Cutting Tools Ltd., with a 45° inclination angle. The tangential tool assembly consisted of an S117.0032.00 insert and an H117.2530.4132 holder. The cutting edge used for tangential turning was an uncoated carbide insert of MG12 grade, selected for its ability to maintain sharpness under demanding cutting conditions.

The study focused on three primary technological parameters: cutting speed (v_c), feed per revolution (f), and depth of cut (a). A 2^3 factorial design was employed to systematically vary these parameters and analyse their effects on cutting forces. For each parameter, two levels were defined. Cutting speed was set at 200 m/min as the lower level and 250 m/min as the upper level. Feed rates were chosen at 0.6 mm and 0.8 mm, while the depth of cut was varied between 0.1 mm and 0.2 mm. In total, eight different parameter setups were tested, as shown in Table 1. These ranges allowed for a comprehensive assessment of the analysed parameters.

Table 1 – Experimental setups

Setup	1	2	3	4	5	6	7	8
f [mm]	0.6	0.8	0.6	0.8	0.6	0.8	0.6	0.8
v_c [m/min]	200	200	250	250	200	200	250	250
a	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2

[mm]								

The workpiece material selected for these experiments was 42CrMo4 alloyed steel, which was heat-treated to a hardness of 410 HV10 to replicate typical conditions encountered in hard machining applications. Cylindrical workpieces with an outer diameter of 65 mm were prepared for the tests, providing a consistent geometry for evaluating the surface roughness.

All experiments were conducted on an EMAG VSC 400 DS hard machining centre. This advanced machining centre enabled precise control of parameters and consistent conditions across each setup, ensuring accurate and reliable data collection for the analysis.

An AltiSurf 520 3D topography instrument equipped with a confocal chromatic probe was used for measurements following the machining tests. Measurement parameters were chosen in accordance with ISO 21920:2021 standards. Roughness profiles for each surface were recorded along three generatrix lines and subsequently analysed with AltiMap Premium 6.2.7487 surface analysis software.

The evaluated 2D surface texture parameters [X] were the following (ISO 21920:2021):

- R_q – Root Mean Square Deviation of the assessed profile corresponds to the standard deviation of the height distribution on the sampling length. [µm]
- R_{sm} – Mean Spacing of profile elements, defined on the evaluation length. This parameter is interesting on surfaces having periodic or pseudo-periodic motifs, such as turned or structured surfaces, where this parameter approximates their spacing. [mm]
- R_{dq} – Root Mean Square Slope of the assessed profile, defined on the sampling length. A low value is found on smooth surfaces while higher values can be found on rough surfaces with microroughness. [°]

Polynomial equations were also developed to calculate and represent the factors under study according to the design of experiments method, as shown in Equation 1. This equation incorporates variables (f, v_c, a_p) and their interactions, with constants (k_i) representing the influence of each factor. In this study, roughness parameters are expressed as the function $y(f, v_c, a_p)$. These equations provide a quantitative and visual means to assess the effects of each factor, offering a structured approach to optimize machining processes for enhanced dimensional accuracy and surface quality.

$$y(v_c, f, a) = \mathrm{k}_0 + \mathrm{k}_1 v_c + \mathrm{k}_2 f + \mathrm{k}_3 a + \mathrm{k}_{12} v_c f + \mathrm{k}_{13} v_c a + \mathrm{k}_{23} f a + \mathrm{k}_{123} v_c f a \qquad (1)$$

3. Experimental results

The experiments were carried out and the selected surface roughness parameters are measured for each setup three times on three separate directrix of the workpiece. The measurement results than averaged for each setup for the evaluation. The values of Root Mean Square Deviation are shown in Table 2, the results of Mean Spacing are presented in Table 3, and Table 4 contains the data of Root Mean Square slope. Equation 2-4 present the deducted calculation formulas of the previously declared roughness parameters, which are determined in the form of Equation 1 based on the design of experiments methodology.

$$R_q(f, v_c, a) = -0.0412fv_ca + 0.00661fv_c + 4.55fa + 0.877f + 0.0402v_ca - 0.00569v_c -6.09a + 0.388 \tag{2}$$

$$R_{sm}(f, v_c, a) = -0.00463fv_ca + 0.000480fv_c + 1.17fa - 0.0967f + 0.00297v_ca - 0.00035v_c - 0.773a + 0.119 \tag{3}$$

$$R_{dq}(f, v_c, a) = -2.19fv_ca + 0.017fv_c + 380.3fa + 28.3f + 1.57v_ca + 0.005v_c - 272.6a -6.70 \tag{4}$$

Table 2 – Measurement results of the Root Mean Square Deviation

R_q [µm]	Setup							
No.	1	2	3	4	5	6	7	8
1	0.55	0.89	0.55	0.92	0.52	0.82	0.57	0.81
2	0.53	0.90	0.54	0.95	0.52	0.83	0.58	0.87
3	0.55	0.93	0.52	0.91	0.52	0.79	0.62	0.91
Avg.	0.54	0.91	0.54	0.93	0.52	0.81	0.59	0.86

Table 3 – Measurement results of the Mean Spacing

R_{sm} [mm]	Setup							
No.	1	2	3	4	5	6	7	8
1	0.0452	0.0510	0.0440	0.0480	0.0428	0.0510	0.0440	0.0470
2	0.0452	0.0460	0.0450	0.0460	0.0428	0.0520	0.0390	0.0460
3	0.0471	0.0550	0.0420	0.0520	0.0430	0.0550	0.0420	0.0480
Avg.	0.0458	0.0507	0.0437	0.0487	0.0429	0.0527	0.0417	0.0470

Table 4 – Measurement results of the Root Mean Square Slope

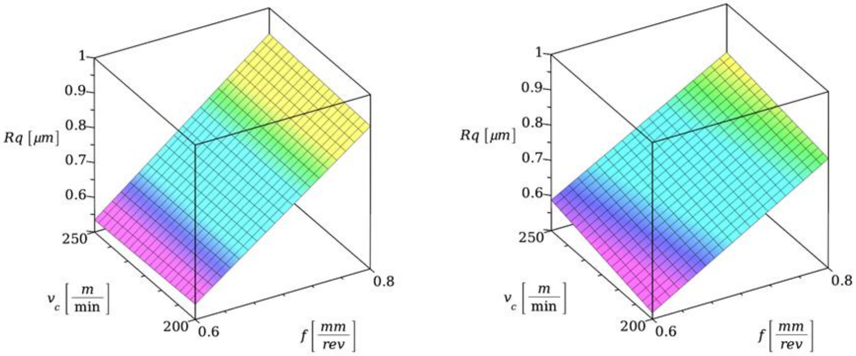
R_{dq} [°]	Setup							
No.	1	2	3	4	5	6	7	8

1	14.5	18.6	15.9	19.1	14.6	18.4	17.7	17.5
2	14.3	20.3	16.9	20.6	14.7	19.7	18.8	18.1
3	13.7	19.2	15.9	18.6	15.3	18.5	18.3	18.5
Avg.	14.2	19.3	16.2	19.4	14.9	18.9	18.2	18.0

4. Discussion

The paper continues with the analysis of the experimental results and the deducted equations. The three surface roughness parameter will be evaluated separately based on surface graphs based on Equation 2-4.

Figure 1 shows the alteration of the Root Mean Square Deviation in the studied range. When the feed rate increases from 0.6 mm to 0.8 mm, we observe an overall increase in Root Mean Square Deviation values, suggesting a rougher surface finish. For example, in the setups with a cutting speed of 200 m/min and depth of cut of 0.1 mm (Setups 1 and 2), the average pf Root Mean Square Deviation rises from 0.54 µm to 0.91 µm as the feed increases from 0.6 mm to 0.8 mm. This trend is consistent across different combinations of cutting speed and depth of cut, indicating that higher feed rates contribute to greater surface roughness due to the increased material removal rate per revolution, which results in more pronounced feed marks on the surface.



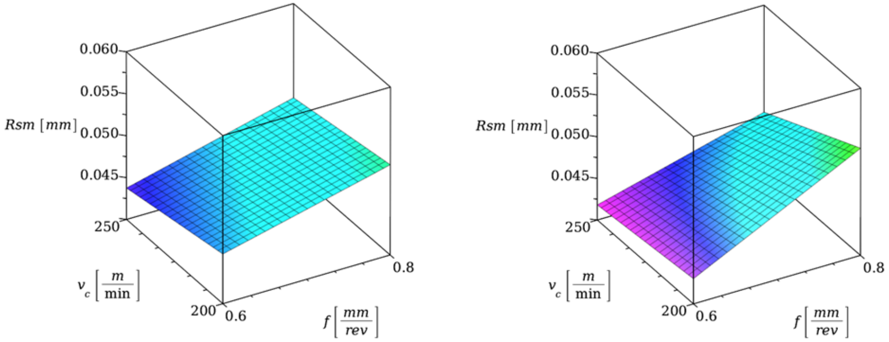
a_p = 0.1 mm a_p = 0.2 mm

Figure 1 – Alteration of the R_q in the studied range

The influence of cutting speed on surface finish is less straightforward, with variations in effect depending on feed and depth of cut. In cases where the feed is 0.6 mm, increasing cutting speed from 200 m/min to 250 m/min (for example Setups 1 to 3 and 5 to 7) leads to a minor decrease in Root Mean Square Deviation, suggesting a slight improvement in surface quality. However, for experiments where the feed rate is 0.8 mm, a similar increase in cutting speed results in only a slight reduction in Root Mean Square Deviation. This suggests that higher cutting speeds may reduce surface roughness, likely due to reduced tool vibration and heat generation, although the effect is moderated by the feed rate.

The impact of depth of cut on Root Mean Square Deviation appears significant. In both feed rate conditions, increasing the depth of cut from 0.1 mm to 0.2 mm generally leads to a reduction in Root Mean Square Deviation. For instance, at a cutting speed of 200 m/min and feed rate of 0.8 mm, the Root Mean Square Deviation drops from 0.91 µm (Setup 2) to 0.81 µm (Setup 6) when the depth of cut is increased. This could be due to the deeper cut stabilizing the tool's engagement with the material, thereby reducing the Root Mean Square Deviation.

The change in the measurement results of Mean Spacing of the profile elements can be seen in Figure 2. The depth of cut has a noticeable impact on Mean Spacing values, particularly at higher feed rates. For instance, at a feed rate of 0.8 mm and a cutting speed of 200 m/min, increasing the depth of cut from 0.1 mm (Setup 2) to 0.2 mm (Setup 6) results in an increase in MSP from 0.0507 µm to 0.0527 µm. This suggests that a deeper cut creates a more pronounced surface profile with wider spacing between elements, potentially due to increased material removal per pass, which emphasizes surface features.



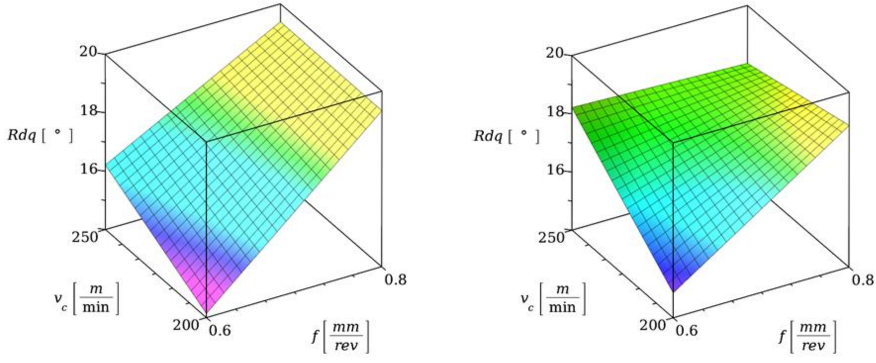
a_p = 0.1 mm a_p = 0.2 mm

Figure 2 – Alteration of the R_{sm} in the studied range

An increase in feed rate from 0.6 mm to 0.8 mm generally results in higher Mean Spacing values, indicating greater spacing between surface profile elements. For instance, in experiments with a cutting speed of 200 m/min and a depth of cut of 0.1 mm (Setup 1 and Setup 2), the MSP average increases from 0.0458 µm to 0.0507 µm as the feed increases. Similarly, under a cutting speed of 250 m/min and a depth of cut of 0.2 mm (Setup 7 and Setup 8), Mean Spacing increases from 0.0417 µm to 0.047 µm with the higher feed rate. This pattern suggests that as feed increases, the distance between profile peaks on the surface also grows, which is likely due to the larger increments in material removed per revolution, creating more distinct peaks and valleys.

The effect of cutting speed on Mean Spacing is less pronounced than that of feed, but some trends can be observed. When the feed rate is held constant at 0.6 mm, increasing the cutting speed from 200 m/min to 250 m/min results in a slight decrease in Mean Spacing. For example, in Setups 1 and 3, Mean Spacing drops from 0.0458 µm to 0.0437 µm. This reduction could be attributed to higher speeds improving tool stability, leading to a finer and more closely spaced surface profile. However, when the feed is increased to 0.8 mm, the effect of cutting speed is less consistent, suggesting that the interaction between cutting speed and feed rate influences Mean Spacing more complexly.

The last analysed roughness parameter (Root Mean Square Slope) is presented in Figure 3. The cutting speed also influences Root Mean Square Slope but to a lesser extent than feed rate. When the feed is held constant, increasing the cutting speed from 200 m/min to 250 m/min generally causes a slight increase in Root Mean Square Slope. For instance, in Setups 1 and 3, with a feed rate of 0.6 mm and depth of cut of 0.1 mm, the Root Mean Square Slope increases from 14.2 µm to 16.2 µm with a higher cutting speed. This suggests that higher speeds can contribute to steeper surface profiles, potentially due to the increased energy in the cutting process, which may amplify surface irregularities.



a_p = 0.1 mm a_p = 0.2 mm

Figure 3 – Alteration of the R_{dq} in the studied range

Increasing the feed rate from 0.6 mm to 0.8 mm generally results in a higher Root Mean Square Slope, indicating steeper surface features. For example, in Setups 1 and 2, where the cutting speed is 200 m/min and the depth of cut is 0.1 mm, the RMS Slope increases from an average of 14.2 µm to 19.3 µm as the feed rate is raised from 0.6 mm to 0.8 mm. This trend is consistent across different cutting speeds and depths of cut, suggesting that higher feed rates lead to sharper surface peaks and valleys due to the increased volume of material removed per revolution.

The depth of cut appears to have a moderate impact on the Root Mean Square Slope values. In both feed rate conditions, increasing the depth of cut from 0.1 mm to 0.2 mm leads to a general increase in Root Mean Square Slope. For example, at a feed rate of 0.6 mm and a cutting speed of 200 m/min, the Root Mean Square Slope rises from 14.2 μm (Setup 1) to 14.9 μm (Setup 5) with a deeper cut. This effect is more noticeable at higher feed rates, as seen in Setups 2 and 6, where the Root Mean Square Slope increases from 19.3 μm to 18.9 μm. A deeper cut likely results in more pronounced surface features due to the larger material removal.

5. Conclusions

The development of machining procedures requires the assessment of the produced surfaces in the point of view of geometric errors among many things. Surface roughness is a widely studied characteristic of the cutting processes, since the machined surface should meet the strict requirements of the product design. The surface quality could be improved by the application procedures with unusual kinematics, from which the tangential turning is studied in this paper. Three selected roughness parameters (Root Mean Square Deviation, the Mean Spacing of Profile Elements and the Root mean Square Slope) were measured on workpieces machined by this technique. The full factorial design of experiment method is applied in the selection of input parameters and in the determination of calculation formulas.

In summary, the following conclusions can be highlighted from the study:

- Feed has the most direct impact on the Root Mean Square Deviation, the Mean Spacing of Profile Elements and the Root mean Square Slope.
- with higher feed rates resulting in rougher finishes, leading to greater spacing between profile elements and steeper surface profiles.
- Cutting speed and depth of cut have more subtle and less consistent effects, although higher speeds and depths generally contribute to more distinct surface textures.

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ОЦІНКА СЕРЕДНЬОКВАДРАТИЧНОГО ВІДХИЛЕННЯ НА ПОВЕРХНЯХ, ОБРОБЛЕНИХ ТАНГЕНЦІЙНОЮ ТОКАРНОЮ ОБРОБКОЮ З ВИСОКОЮ ПОДАЧЕЮ

Анотація. *Нещодавні досягнення в галузі обробки зосереджені на точності, ефективності та обробці твердих матеріалів, що обумовлено такими секторами, як аерокосмічна та автомобільна промисловість. Жорстка обробка або обробка матеріалів понад 45 HRC пов'язана з такими проблемами, як швидкий знос інструменту, інтенсивне нагрівання та збереження точності розмірів. Інновації в різанні інструментальних матеріалів і технології ЧПУ покращили ці процеси, але деградація інструменту і високі зусилля все ще ускладнюють обробку загартованих матеріалів. Шорсткість поверхні є ключовим показником якості, що впливає на такі фактори продуктивності, як зносостійкість і термін служби. Оптимізуючи параметри різання, виробники прагнуть досягти стабільної обробки поверхні, необхідної для довговічності в складних умовах. У даній роботі аналізується вплив вхідних параметрів (глибина різання, подача і швидкість різання) на вибрані параметри шорсткості поверхні. Параметри установки вибиралися відповідно до повного факторіального дизайну методу експерименту. Результати показали, що вища швидкість подачі призвела до більш грубої обробки, що призвело до більшої відстані між профільними елементами та більш крутими профілями поверхні в досліджуваному діапазоні. Подача має найбезпосередніший вплив на середньоквадратичне відхилення, середнє значення відстані між елементами профілю та середньоквадратичний нахил. Більш висока швидкість подачі призводить до більш грубої обробки, що призводить до більшої відстані між елементами профілю та більш крутими профілями поверхні. Швидкість різання та глибина різання мають більш тонкий і менш стабільний ефект, хоча вищі швидкості та глибина зазвичай сприяють більш чіткій текстурі поверхні.*

Ключові слова: *планування експериментів; середня відстань між профілями; середньоквадратичне відхилення; середньоквадратичний нахил; шорсткість поверхні; тангенціальне точіння.*