UDC 621.91.01 **doi: 10.20998/2078-7405.2026.104.11**

COMPARATIVE STUDY OF SURFACE HEIGHT AND GRADIENT PARAMETERS IN TURNING OF 42CRMO4 AND X5CRNI18-10

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Received: 10 April 2026/ Revised: 19 April 2026/ Accepted: 29 April 2026 / Published: 15 May 2026

Abstract. *This study presents a comparative investigation of surface topography in turning of two engineering materials, 42CrMo4 alloy steel and X5CrNi18-10 austenitic stainless steel. A full factorial experimental design was applied to evaluate the effects of cutting speed, feed, depth of cut, and material type on selected areal surface roughness parameters. The analysis focused on* S_q*,* S_p*,* S_v*, and* S_{dq}*, representing surface height and gradient characteristics according to ISO 25178. The results show a strong dependence of surface topography on material properties. The 42CrMo4 steel exhibited significantly higher roughness and steeper surface features compared to the stainless steel under identical cutting conditions. Increasing cutting speed led to a consistent reduction in all evaluated parameters, while feed rate primarily influenced the amplitude-related characteristics. The* S_{dq} *parameter showed lower sensitivity to cutting conditions but highlighted clear differences in surface slopes between the materials. The findings demonstrate that the combined evaluation of height and gradient parameters provides an effective approach for characterizing machining-induced surface features and supports improved selection of cutting conditions.*

Keywords: *tangential turning; surface topography; roughness parameters; material comparison.*

1. Introduction

Surface quality is a critical aspect of machining performance, as it directly influences the functional behaviour, reliability, and service life of mechanical components [1,2]. In turning operations, the generated surface topography is controlled by a complex interaction between cutting parameters, tool geometry, and material properties [3]. While conventional surface characterization has long relied on profile-based parameters, the increasing availability of three-dimensional measurement techniques has led to a growing interest in areal surface roughness evaluation based on ISO 25178. These parameters provide a more comprehensive description of surface features, enabling improved interpretation of machining-induced surface characteristics.

Among the various groups of areal parameters, height-related metrics such as S_q, S_p, and S_v are widely used to quantify the amplitude of surface irregularities [4]. S_q represents the overall magnitude of surface deviations, while S_p and S_v describe the extreme peak and valley features, respectively. In addition to amplitude, the functional performance of a surface is also influenced by its local slopes and gradients [5,6]. The S_{dq} parameter, defined as the root mean square gradient, provides insight into the steepness of surface features and complements the information obtained from height parameters. The combined evaluation of these parameters enables a more complete understanding of surface formation mechanisms during machining.

The generation of surface topography in turning is strongly affected by technological parameters such as cutting speed, feed, and depth of cut. Feed rate is typically considered the dominant factor influencing surface roughness, as it directly determines the theoretical surface profile [7,8]. Cutting speed can modify the cutting process through thermal and tribological effects, often leading to improved surface finish at higher values [9]. Depth of cut, although generally less influential than feed, can affect process stability and material deformation behaviour [10]. However, the extent to which these parameters influence areal surface characteristics may vary depending on the material being machined.

Material properties play a particularly important role in surface generation. Differences in hardness, ductility, strain hardening behaviour, and thermal conductivity can lead to distinct chip formation mechanisms and tool-workpiece interactions [11-13]. For example, high-strength alloy steels typically exhibit more stable cutting behaviour but may generate pronounced surface irregularities due to their resistance to plastic deformation [14,15]. In contrast, austenitic stainless steels are characterized by high ductility and significant strain hardening, which can result in smoother surfaces but may also introduce phenomena such as material smearing or adhesion.

Despite the numerous research on machining-induced surface roughness, comparative studies focusing on the combined analysis of amplitude and gradient parameters for different materials under identical cutting conditions remain limited. There is a need for systematic investigations that evaluate how material-dependent behaviour influences not only the magnitude but also the morphology of surface features [16]. Such studies are essential for improving the understanding of surface generation mechanisms and for supporting the selection of appropriate machining parameters in industrial applications.

In this context, the present study aims to perform a comparative analysis of surface height and gradient parameters in turning of two widely used engineering materials: 42CrMo4 alloy steel and X5CrNi18-10 austenitic stainless steel. These materials were selected due to their distinctly different mechanical and physical properties, which are expected to result in different surface formation characteristics. A full factorial experimental design was applied, considering cutting speed, feed, depth of cut, and material type as input factors. The surface topography was evaluated using selected ISO 25178 parameters, namely S_q, S_p, S_v, and S_{dq}. This selection enables a focused yet comprehensive characterization of both amplitude and slope-related surface features. The study seeks to identify the dominant factors affecting these parameters and to quantify the differences between the two materials under identical machining conditions.

The results of this work contribute to a better understanding of material-dependent surface generation in tangential turning and provide practical insights for the optimization of cutting conditions when surface quality is of primary importance.

2. Experimental conditions and methods

Machining tests were performed using a CNC turning centre (EMAG VSC 400 DS) under stable operating conditions. A tangential turning approach was applied, where the cutting edge is oriented at an inclination angle relative to the workpiece surface (S117.0032.00 insert mounted in an H117.2530.4132 tool holder). This configuration alters the mechanics of material removal compared to conventional turning processes. Cutting was carried out under dry conditions using an uncoated cemented carbide insert. The tool geometry was kept constant throughout the experiments, and the cutting edge condition was controlled by regularly replacing inserts to avoid the influence of tool wear.

The experimental investigation was carried out on two metallic materials with significantly different mechanical behaviour in machining. The first material was 42CrMo4 alloy steel in quenched and tempered condition, exhibiting a hardness of approximately 410 HV10. The second material was X5CrNi18-10 austenitic stainless steel with a hardness of around 300 HV10. While the alloy steel represents a relatively stable cutting material, the stainless steel is characterized by higher ductility and strain hardening, which can affect chip formation and surface generation.

Surface characterization was conducted using a three-dimensional optical measurement system (AltiSurf 520). For each machined sample, a 4 mm × 4 mm area was analysed in the steady-state region of the cut, excluding entry and exit zones. The acquired topography data were evaluated in accordance with ISO 25178. To maintain a focused analysis, four areal surface parameters were selected:

- S_q - root mean square height, representing the overall surface height variation;
- S_p - maximum peak height, indicating the highest point above the mean plane;
- S_v - maximum pit depth, corresponding to the deepest valley below the mean plane;
- S_{dq} - root mean square gradient, describing the average slope of the surface.

These parameters jointly characterize both amplitude and gradient features of the machined surface.

The experimental plan was based on a full factorial design including cutting speed, feed, depth of cut, and material type. Each numerical factor was examined at two levels: cutting speed of 100 and 200 m/min, feed of 0.3 and 0.6 mm/rev, and depth of cut of 0.1 and 0.2 mm. Together with the two material types, this resulted in 16 distinct machining conditions, which are summarized in Table 1.

Table 1 – Experimental setups

Setup	1	2	3	4	5	6	7	8
v_c [m/min]	100	100	100	100	200	200	200	200
f [mm]	0.3	0.3	0.6	0.6	0.3	0.3	0.6	0.6
a [mm]	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.2

3. Experimental results

The measured surface topography parameters obtained from the full factorial experiments are summarized in Tables 2 and 3 for X5CrNi18-10 and 42CrMo4, respectively. The results clearly indicate substantial differences in both magnitude and variability of the evaluated parameters (S_q, S_p, S_v, S_{dq}) between the two materials, as well as notable dependencies on the applied cutting conditions.

Table 2 – Experimental results – X5CrNi18-10

Setup	1	2	3	4	5	6	7	8
S_q [µm]	0.50	0.40	0.53	0.61	0.29	0.30	0.49	0.58
S_p [µm]	3.29	5.45	3.97	5.43	3.03	1.81	1.94	2.40
S_v [µm]	3.44	5.81	3.20	5.50	1.59	1.76	1.95	2.50
S_{dq} [–]	0.14	0.16	0.13	0.15	0.16	0.13	0.16	0.13

For X5CrNi18-10, the S_q values range from 0.288 µm to 0.605 µm. The lowest S_q value is observed at the higher cutting speed (200 m/min) combined with low feed (0.3 mm/rev) and low depth of cut (0.1 mm), while the highest S_q occurs at lower cutting speed (100 m/min) and higher feed (0.6 mm/rev) with increased depth of cut. In general, S_q values remain within a relatively narrow band, indicating a stable surface generation process across the investigated parameter space. The S_p parameter for X5CrNi18-10 varies between 1.805 µm and 5.453 µm. The highest peak values are associated with lower cutting speed and higher depth of cut, whereas increasing cutting speed tends to reduce peak height. A similar tendency is observed for S_v, where values range from 1.594 µm to 5.812 µm. The highest valley depths occur at lower cutting speed and higher depth of cut, while reduced values are observed at higher cutting speeds. The S_{dq} parameter for X5CrNi18-10 shows limited variation, with values between 0.127 and 0.163. No extreme deviations are observed, suggesting relatively uniform surface slopes across all cutting conditions.

Table 3 – Experimental results – 42CrMo4

Setup	1	2	3	4	5	6	7	8
S_q [µm]	2.91	1.90	1.27	3.56	0.58	0.36	0.54	0.51
S_p [µm]	9.39	7.07	8.50	12.31	3.77	3.16	4.18	3.20
S_v [µm]	14.29	8.81	7.00	13.32	4.13	4.23	2.30	2.15
S_{dq} [–]	0.40	0.32	0.25	0.40	0.23	0.21	0.24	0.25

In contrast, significantly higher values are observed for 42CrMo4. The S_q parameter ranges from 0.360 µm to 3.556 µm, with the highest values occurring at lower cutting speed and higher depth of cut. A pronounced reduction in S_q is observed when increasing cutting speed from 100 m/min to 200 m/min. The S_p values for 42CrMo4 range from 3.164 µm to 12.312 µm, while S_v varies between 2.145 µm and 14.29 µm. These values are substantially higher than those measured for X5CrNi18-10, indicating more pronounced peak and valley formation. The highest S_p and S_v values are consistently associated with low cutting speed and high depth of cut. The S_{dq} parameter for 42CrMo4 ranges from 0.209 to 0.404, showing considerably higher values compared to the stainless steel. This indicates steeper surface gradients and more irregular surface features.

Overall, the results demonstrate a strong material dependency of all investigated surface parameters, as well as consistent trends with respect to cutting speed, feed, and depth of cut.

4. Discussion

The experimental results reveal clear and systematic differences in surface topography between X5CrNi18-10 and 42CrMo4, which can be interpreted by considering both the machining parameters and the intrinsic material properties.

As shown in Figure 1, a comparison of S_q values indicates that the surfaces generated on 42CrMo4 exhibit significantly higher roughness levels than those on X5CrNi18-10. At a cutting speed of 100 m/min, S_q values for 42CrMo4 reach up to 3.556 µm, whereas the corresponding maximum for X5CrNi18-10 remains below 0.61 µm. This represents a difference of more than a factor of five. When the cutting speed is increased to 200 m/min, S_q values decrease markedly for both materials, but the relative difference remains substantial. This behaviour may be attributed to the higher hardness and lower ductility of 42CrMo4, which can promote more brittle-like material removal and the formation of irregular surface features. In contrast, the more ductile X5CrNi18-10 likely undergoes greater plastic deformation, leading to smoother surface profiles. Feed rate exhibits a strong influence on S_q for both materials. Increasing the feed from 0.3 mm/rev to 0.6 mm/rev generally leads to higher S_q values. This effect is particularly pronounced for 42CrMo4 at low cutting speed, where S_q increases from approximately 1.265 µm to 3.556 µm. This trend is consistent with the increased uncut chip thickness, which directly affects the resulting surface geometry.

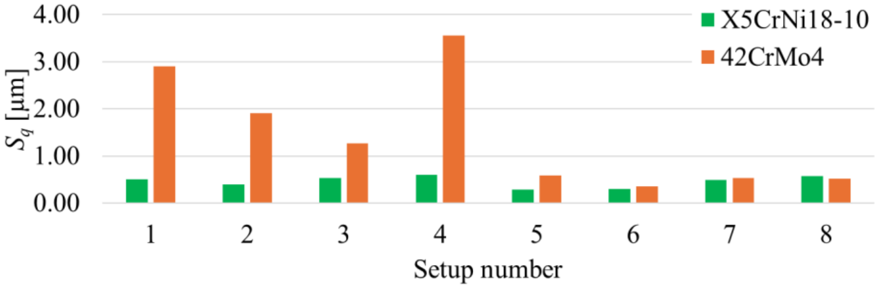

Figure 1 – Alteration of the S_q in the studied range

The analysis of S_p and S_v provides further insight into the asymmetry of surface features (Figure 2 and 3). For X5CrNi18-10, S_p and S_v values are relatively balanced, typically remaining within a similar range. In contrast, 42CrMo4 often exhibits higher S_v values than S_p, particularly at lower cutting speeds, where S_v reaches 14.29 µm compared to S_p of 9.39 µm. This indicates the presence of deeper valleys relative to peak heights. Such behaviour may be related to material fracture and localized material pull-out, which can generate deeper surface defects. For X5CrNi18-10, the more homogeneous deformation behaviour appears to limit the formation of extreme valleys. Cutting speed has a consistently beneficial effect on both S_p and S_v. Increasing the cutting speed from 100 m/min to 200 m/min results in a significant reduction in both peak and valley magnitudes for both materials. For example, in

42CrMo4, S_v decreases from 14.29 µm to approximately 4 µm or lower at higher cutting speed. This suggests improved surface formation stability at elevated speeds.

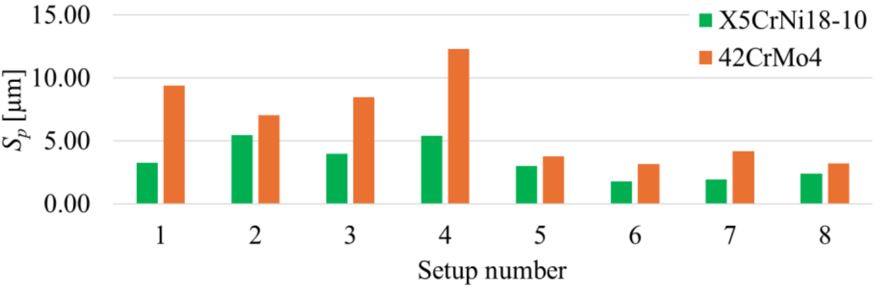

Figure 2 – Alteration of the S_p in the studied range

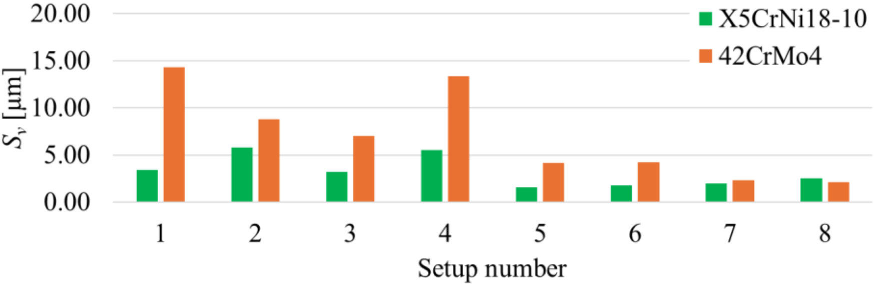

Figure 3 – Alteration of the S_v in the studied range

The S_{dq} parameter provides additional insight into surface slope characteristics (Figure 4). The results show that S_{dq} values for 42CrMo4 are approximately 1.5 to 3 times higher than those for X5CrNi18-10. For instance, maximum S_{dq} values reach 0.404 for 42CrMo4, compared to approximately 0.16 for the stainless steel. This indicates that surfaces produced on 42CrMo4 are not only rougher in terms of amplitude but also exhibit significantly steeper gradients. From a functional perspective, this may have implications for contact behaviour, friction, and wear performance. The influence of cutting parameters on S_{dq} is less pronounced than for S_q, S_p, and S_v, particularly in the case of X5CrNi18-10, where S_{dq} remains within a narrow range across all conditions. However, for 42CrMo4, higher S_{dq} values are observed at lower cutting speeds and higher feeds, indicating that aggressive cutting conditions promote sharper surface features.

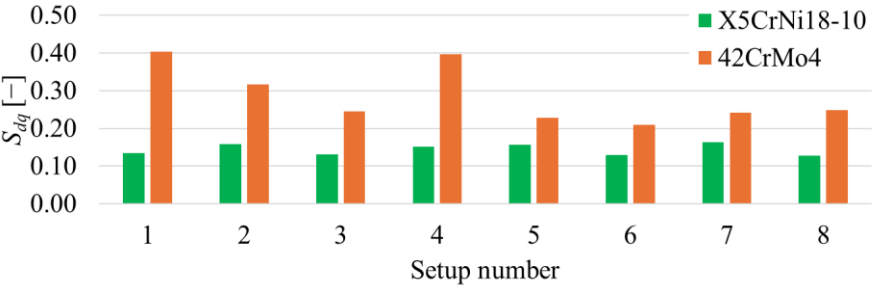

Figure 4 – Alteration of the S_{dq} in the studied range

A combined interpretation of S_q and S_{dq} highlights an important aspect of surface characterization. While S_q describes the overall magnitude of surface deviations, S_{dq} reflects the local steepness of these features. The results show that high S_q values are generally accompanied by high S_{dq} values for 42CrMo4, indicating that rougher surfaces are also steeper. In contrast, X5CrNi18-10 maintains relatively low S_{dq} values even when S_q increases, suggesting smoother transitions between peaks and valleys. From a practical standpoint, the results suggest that cutting speed is the most effective parameter for improving surface quality for both materials. Increasing cutting speed consistently reduces S_q, S_p, and S_v, and also contributes to lower S_{dq} values. Feed rate remains a dominant factor influencing surface amplitude, while depth of cut shows a secondary but still noticeable effect.

Finally, the observed differences between the two materials emphasize the importance of material-specific parameter selection in turning operations. Identical cutting conditions do not yield comparable surface characteristics, and the choice of parameters must consider the underlying material behaviour.

5. Conclusions

This study presented a comparative experimental investigation of surface topography generated during turning of 42CrMo4 and X5CrNi18-10, based on selected ISO 25178 areal parameters (S_q, S_p, S_v, S_{dq}). The applied full factorial design enabled a systematic evaluation of the effects of cutting speed, feed, depth of cut, and material type on both amplitude- and gradient-related surface characteristics. The results clearly demonstrate that both machining parameters and material properties play a decisive role in surface formation. Significant differences were observed not only in the magnitude of the measured parameters, but also in their sensitivity to changes in cutting conditions. While similar trends were identified for certain parameters, the extent of these effects varied considerably between the two materials. The main findings of the study can be summarized as follows:

1. The material type has a dominant influence on surface topography. The 42CrMo4 alloy steel consistently exhibited higher values of the analysed parameters compared to X5CrNi18-10, indicating rougher and steeper surface profiles. In contrast, the austenitic stainless steel produced smoother and more uniform surfaces under identical cutting conditions.
2. Cutting speed proved to be an influential technological parameter in improving surface quality. Increasing the cutting speed from 100 m/min to 200 m/min resulted in a significant reduction in all evaluated parameters for both materials, particularly in the case of 42CrMo4, where substantial decreases in peak and valley magnitudes were observed.
3. Feed rate primarily affected the amplitude-related parameters (S_q, S_p, S_v), with higher feed values leading to increased surface roughness. The S_{dq} parameter showed lower sensitivity overall, but higher values were associated with more aggressive cutting conditions, especially for 42CrMo4.

In summary, the findings highlight that identical machining conditions can lead to markedly different surface characteristics depending on the workpiece material. The combined evaluation of height and gradient parameters proved to be an effective approach for capturing these differences. The results provide a useful basis for selecting appropriate cutting conditions in practical turning operations where surface quality is a critical requirement.

6. Acknowledgement

Supported by the University Research Scholarship Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund. Contract identifier: TNI/1834-39/2025. Scholarship identifier: EKÖP-25-4-II/35.

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ПОРІВНЯЛЬНЕ ДОСЛІДЖЕННЯ ПОВЕРХНЕВОЇ ТОПОГРАФІЇ ТА ГРАДІЄНТА ПАРАМЕТРІВ ОБРОБКИ ПРИ ТОЧІННІ СТАЛЕЙ 42CRMO4 ТА X5CRNI18-10

Анотація. *У цьому дослідженні представлено порівняльне дослідження поверхневої топографії при токарній обробці двох інженерних матеріалів — легованої сталі 42CrMo4 та аустенітної нержавіючої сталі X5CrNi18-10. Було застосовано повний факторіальний експериментальний дизайн для оцінки впливу швидкості різання, подачі, глибини розрізу та типу матеріалу на вибрані параметри шорсткості поверхні. Аналіз був зосереджений на Sq, Sp, Sv та Sdq, що відображають висоту нерівностей поверхні та характеристики градієнта відповідно до ISO 25178. Результати показують сильну залежність топографії поверхні від властивостей матеріалу. Сталь 42CrMo4 демонструвала значно вищу шорсткість і крутішу поверхню порівняно з нержавіючою сталлю за однакових умов різання. Збільшення швидкості різання призводило до послідовного зниження всіх* *оцінюваних параметрів, тоді як величина подачі головним чином впливала на амплітудні характеристики. Параметр* S_{dq} *показав нижчу чутливість до умов різання, але чітко підкреслив відмінності у нахилах поверхні між матеріалами. Тип матеріалу має домінуючий вплив на поверхневий рельєф. Легована сталь 42CrMo4 стабільно демонструвала вищі значення аналізованих параметрів порівняно з X5CrNi18-10, що свідчить про більш шорсткі та крутіші поверхневі профілі. Натомість аустенітна нержавіюча сталь забезпечувала більш гладкі та однорідні поверхні за однакових умов різання. Швидкість різання виявилася важливим технологічним параметром для покращення якості поверхні. Збільшення швидкості різання з 100 м/хв до 200 м/хв призвело до значного зниження всіх оцінюваних параметрів для обох матеріалів, особливо у випадку 42CrMo4, де спостерігалося значне зниження пікових і долинних магнітуд. Результати показують, що комбінована оцінка параметрів висоти та градієнта забезпечує ефективний підхід до характеристики поверхонь, викликаних механічною обробкою, і сприяє кращому вибору умов різання.*

Ключові слова: *тангенціальне обточування; топографія поверхні; параметри шорсткості; порівняння матеріалів.*