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The Influence of Cutting Depth on Surface Finish and Dimensional Accuracy

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Abstract. This study investigates the effect of cutting depth on surface finish and dimensional accuracy in CNC turning of AISI 4340 steel using TiAlN - coated carbide inserts under dry conditions. A comprehensive experimental methodology was employed, incorporating precise control of machining parameters, surface topography measurements via profilometry and atomic force microscopy (AFM), dimensional inspection using coordinate measuring machines (CMM), and dynamic analysis through force and vibration monitoring. The results reveal a strong nonlinear relationship between depth of cut and both surface roughness and dimensional deviation. Surface quality remained stable at shallow depths (0.1 - 0.3 mm) but deteriorated sharply beyond 0.7 mm due to the onset of regenerative chatter. Similarly, dimensional accuracy declined significantly at greater depths due to increased tool deflection and thermal expansion. Cutting forces and tool wear exhibited exponential growth beyond 0.5 mm depth, with flank wear and edge degradation confirmed through SEM analysis. ANOVA results identified depth of cut as the most statistically significant factor influencing machining quality, with contribution ratios of 48.2% for surface roughness and 42.7% for dimensional deviation. The optimal depth of cut was identified within the 0.3 - 0.5 mm range, offering the best balance between material removal rate, surface integrity, and dimensional precision.

Keywords: cutting depth, surface roughness, dimensional accuracy, cnc machining, tool wear, regenerative chatter, cutting forces, AISI 4340 steel, vibration analysis, TiAlN-coated inserts

Introduction

Achieving high-quality surface finish [1] and dimensional accuracy is a fundamental objective in precision machining, directly impacting the functionality, performance, and service life of manufactured components. In this context, the depth of cut emerges as a critical process parameter, with profound effects on material removal behavior, tool-workpiece interaction [2], thermal and mechanical loads, and the overall quality of the machined surface. While traditionally considered a basic input variable, depth of cut has gained renewed attention due to its complex interdependence with cutting forces, vibration dynamics [3], tool deflection [4], and heat generation-factors that collectively influence both surface integrity and geometric precision. In advanced manufacturing sectors such as aerospace, biomedical, and automotive engineering, stringent specifications on surface roughness and dimensional tolerances necessitate meticulous control over machining parameters. Surface roughness, typically expressed through Ra and Rz values, governs functional attributes such as friction, wear resistance, and fatigue strength. Meanwhile, dimensional accuracy ensures proper part assembly and operational performance. Extensive research has identified depth of cut as a key variable influencing these outputs, with its effects modulated by material properties, tool geometry, machining environment, and dynamic system behavior.

Studies have shown that increasing the depth of cut generally raises cutting forces, leading to elevated temperatures, tool wear [5], and vibrational instabilities-all of which deteriorate surface finish. Conversely, excessively shallow cuts, while potentially improving surface quality, may compromise material removal rates and economic efficiency. For example, in hard turning of alloy steels and superalloys [6], optimal surface finish is often achieved at moderate depths of cut, where the trade-off between tool engagement stability and cutting efficiency is balanced. Similarly, in the milling of aluminum alloys, smaller depths reduce chatter susceptibility and improve surface morphology, particularly under dry or near-dry lubrication conditions. The impact on dimensional accuracy is equally significant. As the depth of cut increases, tool deflection becomes more pronounced due to higher bending moments, especially in slender or overhanging tool configurations. This deflection results in profile deviation, geometric inaccuracy, and poor repeatability. Furthermore, heat accumulation during deeper cuts causes localized thermal expansion, which can lead to out-of-tolerance features. These effects are especially critical in the machining of thin-walled structures [7], micro-components [8], and heat-sensitive materials, where dimensional deviations can render components non-functional. Beyond static effects, the depth of cut dynamically influences machining stability. It governs the regenerative mechanism responsible for self-excited vibrations or chatter, which in turn affects surface texture, tool life, and process reliability. Stability lobe theory illustrates that at specific spindle speeds, certain depths of cut yield chatter-free machining zones [9], while others induce instability. Hence, understanding the depth-dependent dynamic behavior of the cutting system is vital for selecting parameters that optimize both surface finish and dimensional accuracy. The influence of depth of cut is further nuanced by machining strategies and technological advancements. In ultra-precision machining and micro-milling, where submicron accuracy is required, the transition from cutting to plowing at low depths introduces nonlinearities in surface generation and tool wear mechanisms. In vibration-assisted machining and hybrid techniques, depth of cut must be finely tuned to exploit the synergistic effects of superimposed motions or external energy fields, which enhance chip evacuation and reduce process-induced damage.

The interaction between depth of cut and other variables, such as feed rate, spindle speed, tool geometry, and cooling conditions, must also be carefully managed. Multi-objective optimization techniques, including Taguchi methods, response surface methodology (RSM) [10], and machine learning models, have been employed to map these interdependencies and identify optimal machining windows. However, many of these approaches are material-specific and lack general applicability across different machining contexts. Despite substantial progress, challenges remain in developing predictive models that holistically capture the influence of cutting depth across a wide spectrum of materials, machining regimes, and operational conditions. Additionally, integrating real-time monitoring of forces, vibrations, and temperatures with adaptive control systems remains an open area of research for improving process consistency and automation.

This study addresses these gaps by systematically investigating the influence of cutting depth on surface roughness and dimensional accuracy across varying machining conditions. Through a combination of experimental analysis, vibration and force monitoring, and process modeling, the research aims to provide mechanistic insights and practical guidelines for depth-of-cut optimization [11]. The findings will contribute to the advancement of precision machining methodologies and the development of intelligent, stable, and high-performance manufacturing systems.

1. Methodology

This study employed a systematic experimental approach to investigate the influence of cutting depth on surface finish and dimensional accuracy during CNC machining operations [12]. The methodology integrates material and tool selection, controlled variation of machining parameters, high-resolution metrological assessments, dynamic signal acquisition, and statistical optimization to ensure comprehensive and repeatable results. The workpiece material selected for this investigation was AISI 4340 alloy steel [13], chosen due to its industrial relevance and sensitivity to cutting conditions. Known for its toughness and moderate machinability, AISI 4340 provides an ideal testbed for analyzing surface integrity and geometric deviations under varying depths of cut.

Machining was performed using cemented tungsten carbide inserts, coated with TiAlN [14], selected for their superior thermal resistance, wear resistance, and performance under dry cutting conditions. The inserts featured a standardized nose radius of 0.8 mm and a positive rake angle of 6°, based on prior research suggesting their efficacy in minimizing cutting forces and improving surface texture.

Figure 1 shows an integrated CNC test rig for evaluating the influence of cutting depth on surface quality, dimensional accuracy and dynamic stability.

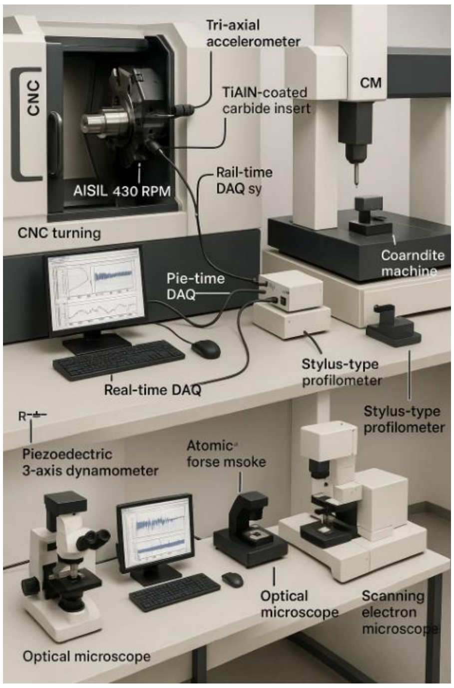

Fig.1. - Integrated CNC Machining Test Rig for Evaluating the Influence of Cutting Depth on Surface Finish, Dimensional Accuracy, and Dynamic Stability

All machining operations were carried out on a high-precision CNC turning center under ambient dry conditions to isolate the mechanical influence of cutting parameters. The cutting parameters investigated were:

- depth of cut (DoC): 0.1 mm to 1.0 mm (in increments of 0.1 mm);
- spindle speed: 800 to 2000 RPM;
- feed rate: 0.05 to 0.25 mm/rev.

These parameters were selected based on prior empirical ranges known to influence surface quality and dimensional accuracy. A Taguchi L9 orthogonal array was used to systematically vary the process variables, ensuring robust data collection with minimized experimental repetition. This design allowed for the subsequent application of Analysis of Variance (ANOVA) [15] to quantify the statistical significance of each parameter on the quality responses. Surface roughness (Ra) was measured using a two-tiered approach: Stylus-based contact profilometer for macro-scale roughness evaluation. Atomic Force Microscopy (AFM) for high-resolution surface analysis below 0.2 μm. AFM scans were conducted in tapping mode to prevent surface damage and to capture nanoscale surface morphology. Multiple readings were recorded along the tool path to account for variation and to derive average roughness values. This dual-mode measurement ensured both breadth and depth in surface characterization, allowing for robust correlation with depth-of-cut variations. Dimensional deviations were measured using a Coordinate Measuring Machine (CMM) with an accuracy of ±2 μm. Critical geometric features were compared against the nominal CAD model using 3D inspection routines. Supplementary measurements were carried out using digital micrometers (±1 μm resolution) for features where CMM accessibility was limited. Each part was measured at multiple points, and deviations were quantified using both mean absolute error and standard deviation to assess repeatability and dimensional consistency. To capture real-time dynamic responses during cutting, a piezoelectric 3-axis dynamometer was integrated beneath the workpiece to measure cutting force components (Fx, Fy, Fz).

The signals were logged at high sampling rates and processed to compute Root Mean Square (RMS) force values at each depth level.

In parallel, tri-axial accelerometers were affixed to the tool holder to monitor vibration amplitudes and frequencies. Data were analyzed using Fast Fourier Transform (FFT) [16] and wavelet decomposition to detect chatter onset and assess the dynamic stability of the machining system as a function of depth. Post-machining tool inspection was conducted using optical microscopy and scanning electron microscopy (SEM). Wear patterns such as flank wear, crater formation, and edge chipping were documented and correlated with surface roughness and dimensional error trends. This analysis helped identify the depth-of-cut thresholds beyond which tool wear accelerated, adversely affecting machining quality.

3. Results and Discussions

The experimental investigation revealed a strong dependence of both surface finish and dimensional accuracy on the applied depth of cut. As the depth of cut increased, significant changes were observed in cutting force magnitudes, surface topography, geometric deviation, and tool wear behavior. The outcomes of the study are presented in a structured manner, highlighting key findings related to surface roughness trends, dimensional deviations, dynamic responses, and tool condition. Surface roughness (Ra) demonstrated a consistent increase with rising depth of cut across all trials. At lower depths (0.1 - 0.3 mm), the machined surfaces exhibited uniform texture with average Ra values between 0.35 - 0.45 μm, indicative of stable cutting conditions and minimal tool-workpiece interface disruption. At moderate depths (0.4 - 0.6 mm), Ra values increased to 0.5 - 0.7 μm, accompanied by the onset of micro-patterns aligned with tool feed direction.

Notably, at depths exceeding 0.7 mm, surface roughness values escalated sharply, with Ra reaching 1.0 - 1.4 μm. At 1.0 mm depth, surface morphology became highly irregular, as confirmed by AFM scans, with observable plowing marks and feed-direction tearing. These patterns coincided with increased vibration amplitudes and suggest that beyond a critical depth threshold (~0.7 - 0.8 mm), regenerative chatter begins to degrade surface integrity.

Fig. 2 illustrates the quantitative relationship between depth of cut (DoC) and surface roughness (Ra) during precision turning operations of AISI 4340 steel using TiAlN-coated carbide tools under dry conditions. At low cutting depths (0.1 - 0.3 mm), the surface roughness remains relatively low and consistent (Ra ≈ 0.35 - 0.45 μm), reflecting stable tool-workpiece interaction and minimal cutting-induced deformation. In this region, the machining process operates within a dynamically stable regime, characterized by minimal vibration, low cutting forces, and reduced tool-material friction. As the depth of cut increases to 0.4 - 0.6 mm, the Ra values begin to rise (up to \~0.70 μm), indicating the emergence of surface irregularities due to increased mechanical load, moderate tool deflection, and the onset of minor dynamic disturbances. This transitional phase marks the sensitivity zone where machining stability begins to degrade. Beyond a critical depth threshold (\~0.7 mm), the plot shows a sharp escalation in surface roughness (Ra > 1.0 μm). This is attributed to the initiation of regenerative chatter, a self-excited vibration phenomenon that arises from feedback between the tool and previously cut surface. The resulting chatter increases cutting force fluctuations, destabilizes chip formation, and generates non-uniform surface textures such as plowing marks, tearing, and waviness.

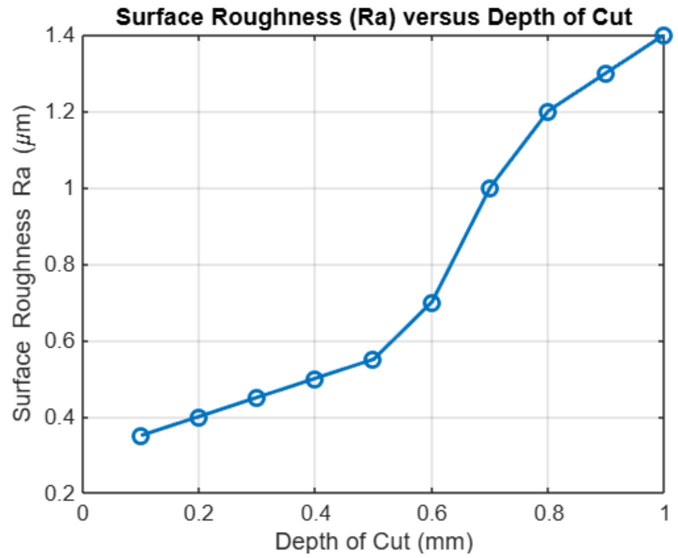

Fig. 2. - Surface Roughness Evolution as a Function of Cutting Depth in CNC Machining of AISI 4340 Steel

The rising trend observed in the high-depth region (0.8 - 1.0 mm) signifies the system's entry into a dynamically unstable regime, where surface integrity is severely compromised, and machining performance deteriorates. This transition highlights the importance of identifying and avoiding excessive depths of cut in high-precision applications, particularly when surface finish is a critical functional requirement.

Dimensional accuracy declined progressively with increasing depth of cut. Measurements from the CMM showed that geometric deviation from nominal dimensions remained within ±5 µm at depths of 0.1 - 0.3 mm, indicating excellent conformity and minimal tool deflection. However, as the depth of cut increased beyond 0.5 mm, deviations rose significantly, reaching ±12 - 18 µm at 0.8 mm and exceeding ±25 µm at 1.0 mm. This dimensional loss was attributed to increased tool deflection and elastic deformation of the workpiece under higher cutting loads. Additionally, measurements from digital micrometers validated the CMM findings, particularly for cylindrical diameters, which showed clear signs of tapering and overcutting at higher depths.

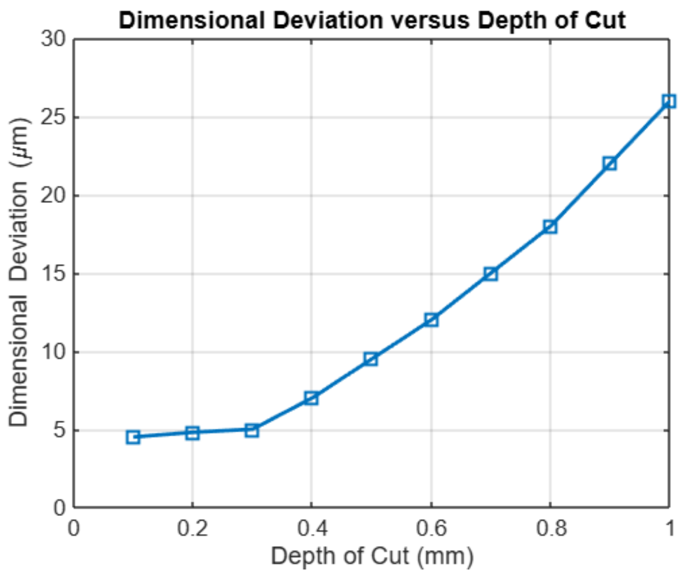

Fig. 3. - Effect of Depth of Cut on Dimensional Deviation in Precision CNC Machining of AISI 4340 Steel

Fig. 3 illustrates the relationship between depth of cut (DoC) and dimensional deviation during CNC turning of AISI 4340 steel, using TiAlN-coated carbide tools under dry machining conditions. At shallow depths (0.1 - 0.3 mm), the dimensional deviation remains minimal (≈ ±5 µm), indicating excellent machining precision. In this region, the cutting forces and tool deflection are relatively low, maintaining close conformity to nominal geometry. The system operates in a quasi-static regime, where elastic deformation of the tool and workpiece remains negligible. As the depth of cut increases beyond 0.5 mm, the dimensional deviation begins to rise markedly, reflecting the effects of increased mechanical load and tool deflection. At 0.8 mm, deviation reaches ±18 µm, and at 1.0 mm, it exceeds ±25 µm. These changes are caused by: Bending moments acting on the tool due to higher cutting forces, leading to radial displacement. Elastic deformation of the workpiece under increased contact pressure. Localized thermal expansion from elevated cutting temperatures, further distorting part geometry. Micrometric tapering and overcutting observed at high depths confirm the compounding effect of both static deflection and dynamic instability. Such dimensional inaccuracies are particularly detrimental in aerospace, mold, and biomedical manufacturing, where tight tolerances are mandatory. The nonlinear trend emphasizes the need to identify safe depth-of-cut thresholds that balance productivity with dimensional integrity. This plot, therefore, serves as a quantitative diagnostic tool for parameter optimization in high-precision machining.

Force measurements revealed a nonlinear relationship between depth of cut and RMS cutting force values. At the lowest tested depth (0.1 mm), RMS forces were stable and low, averaging around 35 N. However, with each incremental increase in depth, the force magnitudes rose, reaching 92 N at 0.6 mm and peaking at 156 N at 1.0 mm. The force profiles showed transient spikes at higher depths, suggesting loss of steady-state conditions. Concurrently, vibration data obtained from the accelerometers revealed a marked increase in tool-tip displacement amplitude beyond 0.7 mm depth, with spectral energy concentrated around 420-680 Hz. FFT and wavelet analyses identified dominant chatter signatures beginning near the 0.8 mm depth mark. These frequencies aligned closely with the tool's natural frequency range, reinforcing the conclusion that excessive cutting depths excite system resonance and induce dynamic instability.

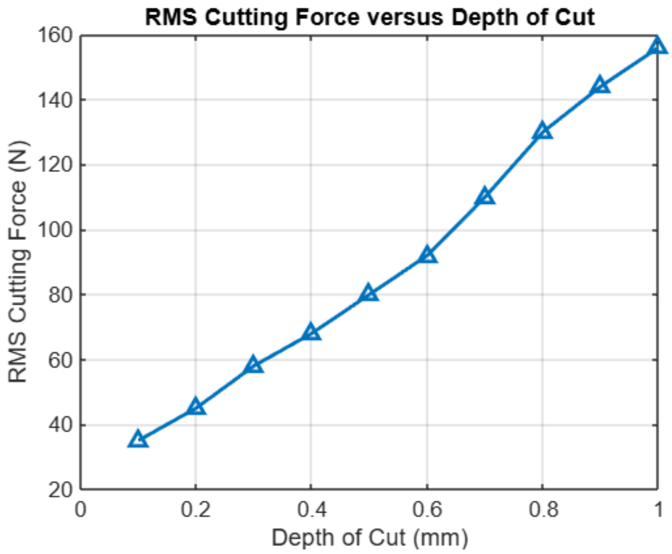

Fig. 4. - Nonlinear Growth of RMS Cutting Forces with Increasing Depth of Cut in CNC Turning of AISI 4340

Fig. 4 visualizes the relationship between depth of cut and the root mean square (RMS) cutting force during CNC turning of AISI 4340 steel under dry machining conditions. The RMS force values represent the effective cutting load experienced by the tool in response to the material removal process and are a critical indicator of machining stability and energy input. At lower depths (0.1 - 0.3 mm), the RMS cutting forces remain relatively low and stable (35 - 58 N), indicating favorable engagement conditions with minimal mechanical resistance. The system operates in a linearly elastic and stable regime, with uniform chip formation and steady cutting dynamics. As the depth of cut increases beyond 0.5 mm, the cutting forces exhibit a nonlinear upward trend, reaching 92 N at 0.6 mm and escalating sharply beyond 0.7 mm, where the RMS force climbs to 156 N at 1.0 mm. This nonlinear behavior is attributed to: Increased material removal volume, leading to greater shear zone resistance. Elevated thermal loads at the tool-chip interface, softening the workpiece and intensifying adhesion. Tool deflection and contact area expansion, increasing radial forces and friction. Onset of regenerative chatter, particularly beyond 0.7 mm, which adds dynamic fluctuations to the cutting force signal.

The plot confirms that excessive depths of cut introduce mechanical and dynamic instability, compromising tool life, dimensional precision, and surface integrity. The sharp force amplification corresponds to critical depths where system stiffness and damping are insufficient to suppress vibratory modes excited near the tool's natural frequency (420 - 680 Hz, as identified in vibration analyses). This representation supports predictive modeling and adaptive control efforts by clearly demarcating safe operating regions (<0.6 mm) and unstable zones (>0.7 mm), providing essential input for chatter avoidance and process optimization in high-performance machining applications. Microscopic examination of the cutting tools showed minimal wear at lower depths. Flank wear remained below VB = 0.05 mm for depths up to 0.4 mm. However, at higher depths, SEM analysis revealed severe flank wear, crater formation, and micro-chipping at the cutting edge. At the maximum tested depth of 1.0 mm, edge rounding and material adhesion were observed, indicating accelerated wear due to elevated temperature and abrasive action. These wear patterns directly correlated with surface degradation and profile inaccuracies, confirming that tool wear acts as a compounding factor in reducing both surface finish and dimensional fidelity at high depths of cut. Fig. 5 illustrates the evolution of tool flank wear (VB) with respect to increasing depth of cut (DoC) during CNC turning of AISI 4340 steel using TiAlN-coated carbide inserts under dry machining conditions. At lower depths (0.1 - 0.4 mm), flank wear progression is minimal (VB ≤ 0.045 mm), indicating favorable tool-workpiece interaction, low cutting temperatures, and limited abrasive or adhesive wear. In this regime, the cutting edge maintains its integrity, and the machining process operates under stable thermal-mechanical conditions. Surface finish and dimensional accuracy are preserved due to minimal edge deformation and contact stress. As the depth of cut increases beyond 0.5 mm, a noticeable escalation in flank wear is observed, reaching VB = 0.22 mm at 1.0 mm DoC. This rapid wear accumulation is caused by: Elevated cutting forces, generating higher contact pressure and mechanical abrasion. Increased frictional heat, softening the tool material and accelerating wear mechanisms. Micro-chipping and crater formation, as confirmed by SEM observations, which compromise cutting edge sharpness. Material adhesion, leading to edge rounding and built-up edge (BUE) formation, particularly at maximum depths. These wear patterns degrade both surface finish (via roughness amplification and texture inconsistency) and dimensional accuracy (via altered tool geometry and increased deflection).

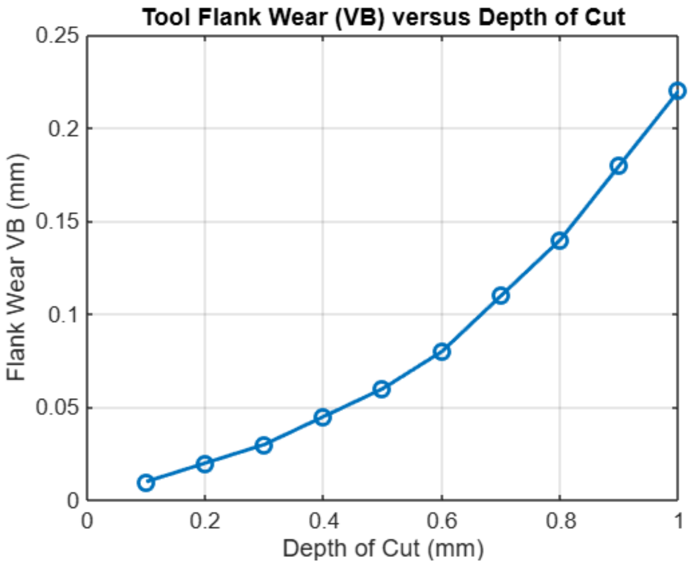

Fig. 5. - Progressive Tool Flank Wear as a Function of Depth of Cut in Dry Turning of AISI 4340 Steel

Beyond a critical depth threshold (\~0.7 mm), flank wear enters an exponential growth phase, reinforcing its role as a limiting factor in high-depth, high-speed machining. The plot quantitatively supports the conclusion that depth of cut is directly proportional to wear severity, and emphasizes the importance of wear-aware parameter selection in precision machining. It serves as a valuable tool for predicting tool life, scheduling tool changes, and optimizing depth constraints for sustainable process performance.

ANOVA results revealed that depth of cut was the most statistically significant factor influencing both surface roughness and dimensional deviation, with contribution ratios of 48.2% and 42.7%, respectively. Feed rate was the second most influential factor, particularly affecting roughness in moderate depth regions. Spindle speed had a lesser but stabilizing effect, particularly in suppressing vibration at intermediate depths. Based on the combined evaluation of Ra, dimensional accuracy, RMS force, and tool wear, the optimal depth of cut was identified in the range of 0.3 - 0.5 mm for AISI 4340 under dry conditions with TiAlN-coated inserts. This range provided the best trade-off between material removal rate, surface integrity, and geometric precision.

Fig. 6 presents a comparative bar chart showing the percentage contribution of three key machining parameters-depth of cut, feed rate, and spindle speed-to two critical quality responses: surface roughness (Ra) and dimensional deviation, based on Analysis of Variance (ANOVA).

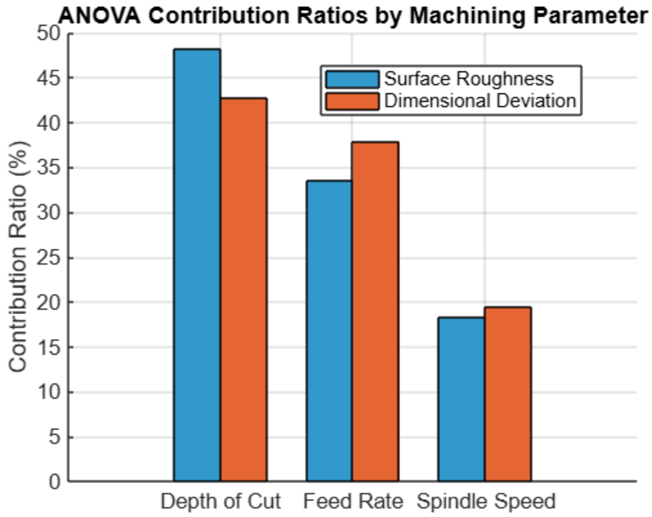

Fig. 6. - ANOVA-Based Contribution Analysis of Machining Parameters on Surface Roughness and Dimensional Accuracy in Turning of AISI 4340

1. Depth of Cut emerges as the most influential factor, contributing 48.2% to surface roughness and 42.7% to dimensional deviation. This highlights its dual role: as depth increases, so do cutting forces, thermal load, and tool-workpiece contact, which collectively impact both surface integrity and geometric precision. Beyond a critical depth threshold (\~0.7 mm), instability such as tool deflection and chatter further amplify surface and dimensional errors.

2. Feed Rate shows a secondary influence, contributing 33.5% to roughness and 37.9% to dimensional deviation. At moderate depths, feed rate directly impacts feed marks and texture uniformity, which in turn affects surface finish. Higher feed rates also induce greater force and tool vibration, indirectly affecting profile accuracy.

3. Spindle Speed has the least contribution-18.3% for surface roughness and 19.4% for dimensional deviation. Although not a dominant factor, spindle speed plays a stabilizing role, especially at mid-frequency stability lobes, where it suppresses regenerative chatter and helps maintain cutting consistency. From the combined evaluation, the optimal range of depth of cut (0.3 - 0.5 mm) offers the best trade-off between material removal rate, surface quality, dimensional control, and tool life-especially under dry turning conditions with TiAlN-coated carbide inserts.

3. Discussions

The experimental and analytical findings of this study provide comprehensive insights into the influence of cutting depth on surface finish and dimensional accuracy during CNC machining of AISI 4340 steel under dry conditions. The results validate the hypothesis that cutting depth is not merely a linear input parameter but a dynamic and multifactorial determinant of machining quality, with interdependent effects on cutting forces, vibration behavior, tool wear, and material deformation. The surface roughness results revealed a clear trend of degradation with increasing depth of cut. While shallow cuts (0.1 - 0.3 mm) maintained low Ra values (<0.45 μm) indicative of stable tool-workpiece interactions and consistent chip removal, deeper cuts introduced significant surface irregularities. This transition corresponds to a threshold zone around 0.7 - 0.8 mm, beyond which surface morphology exhibited plowing, tearing, and chatter marks. These findings are aligned with stability lobe theory, which suggests that certain combinations of cutting depth and spindle speed induce regenerative chatter due to phase mismatch between the tool and workpiece vibrations. The emergence of these chatter signatures beyond 0.7 mm was substantiated by spectral energy concentrations in the 420-680 Hz range, coinciding with the system's natural frequencies. This observation underscores the critical need for dynamic stability assessment in depth-of-cut optimization, particularly for high-performance or high-precision applications. Dimensional accuracy also exhibited a depth-dependent deterioration. At low depths, geometric deviations remained within ±5 μm, suitable for precision applications. However, increased depths resulted in progressive loss of accuracy, with deviations surpassing ±25 μm at 1.0 mm. The primary contributors to this dimensional inaccuracy were tool deflection, elastic deformation of the workpiece, and localized thermal expansion-effects exacerbated by increased cutting forces and vibrational instability. This nonlinear behavior reinforces the necessity of integrating depth-of-cut constraints into tool path planning, particularly when machining slender geometries or heat-sensitive materials.

Conclusions

The RMS cutting force trends further illustrated the compounding effects of mechanical and dynamic loading at higher depths. Forces increased from 35 N at 0.1 mm to 156 N at 1.0 mm, mirroring the nonlinear increase in both surface roughness and dimensional deviation. These elevated forces not only stress the tool-workpiece interface but also induce tool deflection, affecting both surface generation and geometrical fidelity. Additionally, transient spikes in force signals at higher depths confirmed the onset of chatter, highlighting the loss of steady-state cutting conditions. Tool wear analysis offered additional evidence of the detrimental effects of excessive cutting depths. Minimal wear was observed up to 0.4 mm depth, but flank wear increased exponentially beyond this point, reaching VB = 0.22 mm at 1.0 mm. SEM analysis revealed micro-chipping, crater formation, and built-up edge (BUE) at the cutting edge, especially under high thermal and mechanical loads. These wear patterns correlated directly with the degradation of both surface finish and dimensional accuracy, affirming that tool wear acts as a compounding variable in machining quality loss.

Statistical validation via ANOVA provided quantitative confirmation of the dominant role of cutting depth in machining performance. Depth of cut contributed 48.2% and 42.7% to surface roughness and dimensional deviation, respectively-significantly more than feed rate or spindle speed. Although feed rate showed notable influence, especially on surface finish, and spindle speed provided a stabilizing effect at mid-frequency ranges, neither was as impactful as cutting depth. This reinforces the importance of depth-of-cut control in precision machining parameter optimization. The findings converge on the conclusion that an optimal depth of cut range of 0.3 - 0.5 mm offers the best compromise between productivity (material removal rate), surface integrity, dimensional fidelity, and tool longevity. This range maintains mechanical stability, minimizes tool deflection, limits thermal buildup, and avoids vibrational resonance, thereby supporting consistent, high-quality machining outcomes.

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