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Effect of Cutting Speed on Surface Roughness in Stepped Turning of ST37 Mild Steel Using HSS Cutting Tools: A Six Sigma DMAIC Approach

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ABSTRACT
Surface roughness is a critical quality indicator in manufacturing processes, directly influencing the functional performance and service life of machined components. This experimental study investigates the effect of cutting speed on the arithmetic mean roughness (Ra) of ST37 mild steel workpieces subjected to conventional stepped turning using High-Speed Steel (HSS) right-hand cutting tools. A constant spindle speed of 325 rpm was applied while four stepped diameters — Ø19 mm, Ø20 mm, Ø22 mm, and Ø24 mm — were machined, yielding cutting speeds of 19.40, 20.42, 22.46, and 24.50 m/min, respectively. Surface roughness was measured at three axial positions per diameter using a contact-type surface roughness tester, and the arithmetic mean roughness (Ra) was recorded as the primary response variable. A Six Sigma Define–Measure–Analyze–Improve–Control (DMAIC) framework was applied to structure the quality analysis and identify improvement strategies. The results demonstrated that mean Ra values ranged from 2.234 µm (Ø20 mm) to 3.621 µm (Ø22 mm). The lowest roughness was attained at a cutting speed of 20.42 m/min, while the highest roughness was recorded at 22.46 m/min, revealing a non-linear relationship between cutting speed and surface quality. This non-monotonic behaviour is attributed to dynamic interactions among machine vibration, chip formation instability, and tool-workpiece contact conditions. The DMAIC analysis identified cutting speed optimisation within a 20–24 m/min range as the primary improvement lever. These findings provide practical guidance for selecting machining parameters that balance surface quality and productivity in stepped turning operations.

Keywords
stepped turning; cutting speed; surface roughness; st37 mild steel; hss tool; six sigma dmaic; machining optimisation.

INTRODUCTION

Turning is among the most prevalent subtractive manufacturing processes, extensively employed to produce rotationally symmetric components with specified dimensional tolerances and surface finishes. Surface roughness, characterised by the arithmetic mean deviation (Ra), is a fundamental quality metric that governs tribological performance, fatigue resistance, sealing capability, and aesthetic appearance of machined parts (Davim, 2010; Kalpakjian & Schmid, 2014). In industrial settings, surface finish requirements are increasingly stringent, necessitating a thorough understanding of the process parameters that govern roughness outcomes.

Among the primary machining parameters — cutting speed (Vc), feed rate (f), and depth of cut (a) — cutting speed has long been recognised as a dominant factor influencing surface quality. At low cutting speeds, intermittent chip adhesion and built-up edge (BUE) formation on the cutting tool tend to deteriorate the surface finish (Boothroyd & Knight, 2006; Hakami et al., 2016, p. 756; Kadi et al., 2023, p. 51). As cutting speed increases, BUE formation diminishes, thermal softening of the workpiece material improves material flow, and smoother surfaces can be achieved(Hakami et al., 2016, p. 756; Pimenov et al., 2023, p. 4758). However, beyond a critical threshold, elevated thermal loads and dynamic cutting forces may accelerate tool wear and introduce chatter, ultimately impairing surface integrity.

ST37 mild steel (equivalent to S235JR per EN 10025) is widely used across mechanical engineering applications due to its excellent machinability, cost-effectiveness, and satisfactory mechanical properties. Its relatively low carbon content (≤ 0.17%) results in good ductility and chip formability, making it a preferred workpiece material in educational and industrial machining studies(Reis et al., 2023, p. 3779; Siqueiros-Hernández et al., 2017, p. 323). Despite its widespread use, systematic investigations of cutting speed effects on the surface quality of ST37 during stepped turning using HSS tools remain limited, particularly within the low-to-moderate cutting speed regime characteristic of conventional lathes.

Previous studies have primarily focused on carbide and coated tools at higher cutting speeds, leaving the HSS tool performance domain — which remains relevant for educational workshops and small-scale industries — less thoroughly documented. Zahia et al. (2015) reported that cutting speed significantly influenced Ra during hard turning of steel, with optimal values observed within specific speed ranges. Patten et al. (2004) demonstrated that at lower cutting speeds, dynamic instabilities contribute disproportionately to surface roughness variation. Similarly, Alexandra et al. (2018) found that interrupted cutting and diameter variation in stepped workpieces introduced additional vibration modes that exacerbated roughness at certain diameter-speed combinations.

The application of Six Sigma methodologies — particularly the Define–Measure–Analyse–Improve–Control (DMAIC) cycle — to machining optimisation has gained recognition as an effective framework for systematically reducing process variability and improving surface quality outcomes in manufacturing environments (Antony, 2014; Duc & Bilík, 2022, p. 64; Gomaa, 2025). DMAIC provides a structured, data-driven approach that complements experimental parameter studies by linking measurement results to actionable improvement strategies.

This study, therefore, aims to (i) experimentally investigate the effect of cutting speed — induced by varying workpiece diameter at constant spindle speed — on the surface roughness (Ra) of ST37 mild steel during stepped turning with HSS tools; (ii) analyse the non-linear roughness-speed relationship using descriptive statistical methods; and (iii) apply the Six Sigma DMAIC framework to identify the optimal cutting condition and propose quality control strategies for the stepped turning process.

MATERIALS AND METHODS

Workpiece Material

The workpiece material used in this study was ST37 mild steel (DIN 17100), equivalent to S235JR (EN 10025-2). The nominal chemical composition includes carbon ($C \leq 0.17\%$), silicon ($Si \leq 0.35\%$), manganese ($Mn \leq 1.40\%$), phosphorus ($P \leq 0.045\%$), and sulphur ($S \leq 0.045\%$). The initial workpiece was a cylindrical bar with a diameter of 25.4 mm (1 inch) and a total machined length of 200 mm. Prior to machining, the workpiece was faced and centre-drilled to ensure concentricity and alignment.

Cutting Tool

A High-Speed Steel (HSS) right-hand external turning tool was employed throughout all experimental trials. The tool geometry was maintained in a sharp, freshly ground condition to ensure consistent cutting performance and eliminate tool wear as an uncontrolled variable. The tool was inspected visually before each trial, and any sign of wear was addressed by regrinding. The tool was clamped rigidly in a standard tool post to minimise overhang and vibration.

Machine Setup and Cutting Parameters

All turning operations were performed on a conventional engine lathe. Coolant was not applied during machining (dry cutting conditions) to isolate the thermal and mechanical effects of the cutting parameters on surface roughness. A constant spindle speed of $n = 325$ rpm was maintained throughout all trials. Since the workpiece was a stepped part with four different finished diameters, the effective cutting speed varied according to the diameter of each step, as calculated by:

$$Vc = (\pi \cdot D \cdot n) / 1000 \text{ (m/min)}$$

where Vc is the cutting speed (m/min), D is the workpiece diameter (mm), and n is the spindle speed (rpm). The detailed machining parameters applied in this study are summarised in Table 1.

Table 1. Machining parameters applied during experimental trials

Parameter	Value	Unit
Spindle speed (n)	325	rpm
Feed rate (f)	0.2	mm/rev
Depth of cut (a) – roughing	1.0	mm
Depth of cut (a) – finishing	0.4	mm
Initial workpiece diameter	25.4	mm
Final diameters	Ø19, Ø20, Ø22, Ø24	mm
Length per step	50	mm

Stepped Turning Procedure

The workpiece was mounted in the three-jaw chuck with tailstock support to ensure rigidity and minimise runout. Facing was performed first to establish a datum reference surface. Four stepped sections, each 50 mm in length, were subsequently machined to target diameters of Ø19 mm, Ø20 mm, Ø22 mm, and Ø24 mm. Roughing passes were executed at a depth of cut of 1.0 mm per pass until within 0.4 mm of the target diameter, after which a single finishing pass at $a = 0.4$ mm was applied. Diameter conformance was verified using an outside micrometer (resolution: 0.01 mm) after each step. The number of roughing passes required per diameter step was as follows: Ø19 mm required six passes (total stock removal: 6 mm from Ø25.4 mm, allowing 0.4 mm finishing allowance); Ø22 mm required three passes; Ø24 mm required one roughing pass; and Ø20 mm required five roughing passes. A total of 16 roughing passes and four finishing passes were executed per complete workpiece.

Surface Roughness Measurement

Surface roughness was measured using a contact-type surface roughness tester (profilometer) calibrated prior to measurement. The arithmetic mean roughness parameter Ra (µm) was selected as the response variable in accordance with ISO 4287:1997. Measurements were taken at three circumferential positions (Position 1, 2, and 3, equally spaced at 120° intervals) on each stepped diameter to account for any axial and circumferential roughness variation. The measurement cut-off wavelength (λc) was set to 0.8 mm, and the evaluation length comprised five consecutive sampling lengths ($l = 4.0$ mm), consistent with ISO 4288:1996.

Data Analysis

Descriptive statistics — including arithmetic mean ($\bar{x}$) and standard deviation (SD) — were computed for the Ra values at each diameter. The relationship between cutting speed and mean Ra was analysed graphically and interpreted in the context of machining theory. Additionally, a Six Sigma DMAIC quality framework was applied to structure the findings and propose improvement and control strategies for the stepped turning process.

RESULTS

Cutting Speed at Each Diameter

The cutting speeds calculated for each stepped diameter at constant spindle speed of 325 rpm are presented in Table 2. As expected, the cutting speed increased proportionally with the workpiece diameter, ranging from 19.40 m/min at Ø19 mm to 24.50 m/min at Ø24 mm.

Table 2. Calculated cutting speed and mean surface roughness Ra for each stepped diameter

Diameter (mm)	Spindle Speed n (rpm)	Cutting Speed Vc (m/min)	Mean Ra (µm)
19	325	19.40	3.413
20	325	20.42	2.234
22	325	22.46	3.621
24	325	24.50	2.473

Surface Roughness Measurements

Table 3 presents the Ra values measured at three positions for each stepped diameter, together with the computed mean and standard deviation. Individual Ra readings ranged from a minimum of 1.333 µm (Ø20 mm, Position 1) to a maximum of 4.358 µm (Ø22 mm, Position 1), indicating substantial variability both within and between diameter steps.

Table 3. Surface roughness (Ra) measurements at three positions per diameter and descriptive statistics

Diameter (mm)	Position 1 Ra (µm)	Position 2 Ra (µm)	Position 3 Ra (µm)	Mean Ra (µm) ± SD
Ø19	3.137	3.145	3.956	3.413 ± 0.462
Ø20	1.333	2.488	2.882	2.234 ± 0.800
Ø22	4.358	3.455	3.049	3.621 ± 0.664
Ø24	2.682	1.940	2.797	2.473 ± 0.455

The lowest mean Ra was obtained at Ø20 mm (Ra = 2.234 ± 0.800 µm, Vc = 20.42 m/min), while the highest mean Ra was recorded at Ø22 mm (Ra = 3.621 ± 0.664 µm, Vc = 22.46 m/min). The Ø19 mm and Ø24 mm diameters exhibited intermediate roughness values of 3.413 ± 0.462 µm and 2.473 ± 0.455 µm, respectively.

Relationship Between Cutting Speed and Mean Ra

The relationship between cutting speed and mean Ra does not follow a simple monotonic trend. Beginning at Vc = 19.40 m/min (Ø19 mm), the mean Ra was 3.413 µm. It decreased to 2.234 µm at Vc = 20.42 m/min (Ø20 mm), indicating an improvement in surface finish. However, Ra increased substantially to 3.621 µm at Vc = 22.46 m/min (Ø22 mm), before declining again to 2.473 µm at Vc = 24.50 m/min (Ø24 mm). This non-monotonic pattern suggests that factors beyond cutting speed alone govern the surface quality in this experimental regime.

DISCUSSION

The results of this study reveal that cutting speed has a discernible but non-linear influence on the surface roughness of ST37 mild steel during conventional stepped turning with HSS tools. The overall Ra range of 2.234–3.621 µm is consistent with the N6–N8 roughness grade classification (ISO 1302), which is typical for rough-to-semi-finish turning operations under low-to-moderate cutting speed conditions with HSS tooling (Khan et al., 2022, p. 4020; Zuliantoni et al., 2026).

The best surface quality observed at Ø20 mm (Vc = 20.42 m/min, Ra = 2.234 µm) is consistent with theoretical predictions for low cutting speed turning. At this velocity, the combination of a stable chip-forming mechanism, moderate thermal generation, and reduced dynamic cutting forces contributes to a consistent surface profile. Previous research by Zahia et al. (2015) and Asiltürk & Akkuş (2011) similarly identified localised optima in the surface roughness–cutting speed relationship at intermediate cutting speeds, which correspond to a transition zone between BUE-dominated and thermally dominated cutting regimes.

The marked deterioration in surface quality at Ø22 mm (Vc = 22.46 m/min, Ra = 3.621 µm) is particularly noteworthy. Despite a moderate increase in cutting speed from Ø20 mm to Ø22 mm, the mean Ra increased by approximately 62%. Several mechanisms may account for this behaviour. First, the transition from a stable chip formation mode to a less stable cutting condition at this diameter may introduce dynamic cutting forces that excite the natural frequency of the lathe–workpiece system, generating chatter marks on the machined surface (Altıntaş, 2012; M. & Kenneth, n.d.). Second, the stepped geometry of the workpiece introduces interrupted cutting at each step transition, and the resultant impact loading may be more pronounced at the 22 mm diameter relative to adjacent steps (Alexandra et al., 2018). Third, local tool wear accumulation — even in relatively short cutting trials — could amplify surface irregularities at specific cutting speeds.

The recovery of surface quality at Ø24 mm (Vc = 24.50 m/min, Ra = 2.473 µm) aligns with the literature indicating that increased cutting speeds beyond the critical chatter zone can re-stabilise the cutting process, reducing the amplitude of surface waviness (Patten et al., 2004; Shaw, 2005). The higher thermal softening of ST37 at Vc = 24.50 m/min may also reduce cutting forces, facilitating cleaner chip separation and a smoother machined surface.

Intra-diameter roughness variability, quantified by the standard deviation, was highest at Ø20 mm (SD = 0.800 µm), reflecting that Position 1 yielded an exceptionally low Ra of 1.333 µm whilst Positions 2 and 3 produced values of 2.488 and 2.882 µm. This suggests localised surface heterogeneity potentially related to tool engagement position or circumferential runout at that particular step. The standard deviations at Ø19 mm (0.462 µm), Ø22 mm (0.664 µm), and Ø24 mm (0.455 µm) indicate relatively consistent roughness across measurement positions, implying more stable cutting dynamics at those diameters.

From a practical standpoint, these findings indicate that selecting a cutting speed close to Vc ≈ 20 m/min is preferable for achieving the best surface quality with HSS tools on ST37 steel under the present experimental conditions. However, the non-linear nature of the Ra–Vc relationship underscores that single-parameter optimisation is insufficient; simultaneous control of feed rate, depth of cut, tool geometry, and machine rigidity is necessary to achieve consistent surface quality across all stepped diameters.

Comparison with existing literature further contextualises these results. Davim (2010) reported Ra values in the range of 1.5–5.0 µm for similar low-carbon steels turned at comparable cutting speeds using HSS tools, which aligns well with the present findings. Asiltürk & Akkuş (2011) found that feed rate exerted a stronger influence on Ra than cutting speed in CNC turning of AISI 1040 steel, a finding that highlights the need for future studies to systematically vary feed rate alongside cutting speed in the present experimental context.

Six Sigma Dmaic Analysis

To provide a structured quality management perspective on the experimental findings, a Six Sigma DMAIC framework was applied. DMAIC is a data-driven problem-solving methodology widely adopted in manufacturing for process improvement (Antony, 2014). Table 4 summarises the application of each DMAIC phase to the present stepped turning study.

Table 4. Six Sigma DMAIC framework applied to the stepped turning quality analysis

Phase	***Description***
Define	Surface roughness variation across stepped turning diameters under constant spindle speed was identified as the primary quality concern.
Measure	Ra values were measured at three positions per diameter using a contact surface roughness tester. Range: 1.333–4.358 μm.
Analyze	The highest Ra was found at Ø22 mm (Vc = 22.46 m/min, Ra = 3.621 μm). Variation was attributed to cutting instability, vibration, and tool wear.
Improve	Optimize cutting speed within 20–24 m/min range; use fine-feed finishing pass (f = 0.1 mm/rev); maintain sharp tool geometry.
Control	Implement periodic tool condition monitoring, parameter logging, and statistical process control charts for Ra during production runs.

The DMAIC analysis identifies two principal improvement levers: (i) optimising cutting speed to remain within the Vc = 20–21 m/min range where surface quality is maximised, and (ii) adopting a dedicated finishing pass with reduced feed rate (f ≤ 0.1 mm/rev) to achieve roughness values approaching the N5–N6 grade (Ra ≤ 1.6 μm). The Control phase recommendations — including SPC chart implementation and scheduled tool condition monitoring — are particularly relevant for translating laboratory findings into sustainable production practice (Montgomery, 2020).

CONCLUSION

This study experimentally investigated the influence of cutting speed on surface roughness (Ra) during the stepped turning of ST37 mild steel using HSS cutting tools under dry cutting conditions. The following conclusions can be drawn: 1) Cutting speed exerts a significant but non-monotonic influence on surface roughness in the low-speed regime (19–25 m/min) characteristic of conventional turning with HSS tools; 2) The optimal surface quality (Ra = 2.234 μm) was achieved at Vc = 20.42 m/min (Ø20 mm), while the worst surface quality (Ra = 3.621 μm) was recorded at Vc = 22.46 m/min (Ø22 mm), suggesting the presence of a dynamic instability zone near Vc ≈ 22 m/min for the given experimental configuration; 3) The overall Ra range of 2.234–3.621 μm corresponds to ISO roughness grades N6–N8, consistent with semi-finish to rough turning classifications under comparable process conditions; 4) The Six Sigma DMAIC analysis provided a structured quality management framework, identifying cutting speed optimisation (Vc ≈ 20 m/min), reduced finishing-pass feed rate, and tool condition monitoring as the primary strategies for improving and sustaining surface quality. Future work should investigate the simultaneous effects of feed rate, depth of cut, and tool geometry on Ra using a full-factorial or response surface design to develop a predictive roughness model applicable to the full parameter space of conventional stepped turning with HSS tools.

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