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Achieving Surface Roughness Below 2.5 µm Ra in Dry Turning of EN32 Steel : A Predictive Analysis and Literature Review

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ABSTRACT

This paper presents a predictive analysis and literature review aimed at identifying the machining parameter windows necessary to achieve surface roughness below 2.5 µm Ra during dry turning of EN32 low carbon case-hardening steel. The kinematic surface roughness model, Ra = $f^2/(8r\varepsilon)$, is employed as a theoretical predictor, with a dry-turning correction factor of 1.5–2.0 applied to account for built-up edge, tool vibration, and thermal effects in the absence of cutting fluid. The review synthesizes findings from five prominent published studies covering dry turning of EN32 and metallurgically similar low carbon steels with coated carbide tools. Analysis of the compiled literature data confirms that feed rate is the dominant parameter influencing Ra, contributing 58–67% of total variability across published studies, while cutting speed exhibits a secondary effect through built-up edge suppression at higher velocities. Depth of cut is consistently reported as the least influential parameter. Based on combined theoretical predictions and literature evidence, a safe machining window is proposed: cutting speed ≥ 120 m/min, feed rate ≤ 0.10 mm/rev, and nose radius ≥ 0.8 mm, which reliably yields Ra below 2.5 µm under dry conditions using TiAlN-coated carbide inserts. The proposed guidelines provide a theoretically and literature-supported reference for process engineers and researchers working with EN32 steel components.

Key Words: *EN32 steel; surface roughness; dry turning; Ra prediction; kinematic roughness model; TiAlN coated carbide; sustainable machining; review; cutting parameters.*

1.INTRODUCTION

Surface roughness is one of the most frequently specified quality characteristics in manufacturing engineering, directly governing the tribological performance, contact fatigue life, dimensional conformance, and aesthetic acceptability of machined components. The arithmetic mean roughness (Ra) remains the most universally adopted surface roughness parameter in engineering drawings and process specifications, with Ra < 2.5 µm commonly mandated for mating surfaces, bearing seats, shaft journals, and precision gear flanks [1].

EN32 (designated under BS 970 and BS EN 10084) is a low carbon case-hardening steel with a nominal carbon content of 0.12–0.18 wt%, alloyed with manganese (0.60–1.00 wt%) and silicon (0.10–0.35 wt%). It is one of the most widely used engineering steels for components requiring a combination of a hard, wear-resistant case and a tough, ductile core, including automotive gears, camshafts, splined shafts, pins, and bush housings. Supplied typically in the normalized condition (160–180 HB), EN32 exhibits moderate machinability but presents challenges in surface finish control owing to its tendency to form built-up edge (BUE) during cutting — particularly at intermediate speeds and without lubrication [2].

Dry machining — the complete elimination of cutting fluids — has gained considerable traction as a sustainable manufacturing practice. It removes coolant procurement, recycling, and disposal costs, eliminates health risks associated with metalworking fluid aerosols, and simplifies machine tool design. However, dry conditions intensify thermal loading at the cutting zone and can aggravate BUE formation in low carbon steels, necessitating careful parameter selection to maintain surface quality within specification [3].

Despite substantial published work on surface roughness optimization in turning of carbon and alloy steels, a dedicated and consolidated analysis specifically addressing EN32 in dry conditions with an emphasis on achieving Ra < 2.5 µm is not readily available in the open literature. Existing studies either focus on different materials, use wet/MQL conditions, or report results across a wide range without singling out the 2.5 µm benchmark that is critical for industrial components [4, 5].

This paper addresses this gap through two complementary approaches: (i) a theoretical predictive analysis using the classical kinematic surface roughness model, corrected for dry machining conditions; and (ii) a review and meta-analysis of published experimental data on dry turning of EN32 and metallurgically similar low carbon steels. The combined analysis leads to actionable parameter guidelines that engineers and researchers can use directly, without the need to design and conduct new experiments for each application.

The novel contributions of this paper are threefold. First, this is the first dedicated consolidated analysis that explicitly targets EN32 steel in dry turning with the specific benchmark of Ra < 2.5 µm, as opposed to broader material groupings or wet/MQL conditions prevalent in existing literature. Second, the kinematic roughness model is extended with an empirically calibrated dry-machining correction factor and validated against published experimental data from multiple independent studies, lending quantitative rigour to what is otherwise a qualitative guideline in most review work. Together, these contributions offer a consolidated reference that eliminates the need for preliminary experimental campaigns when setting up dry turning processes for EN32 components.

2. EN32 STEEL: MATERIAL CHARACTERISTICS AND MACHINABILITY

EN32 is classified as a low carbon case-hardening steel per BS EN 10084:2008. Its low carbon content (0.12–0.18%) confers excellent toughness and ductility in the core, while the case hardening process — typically pack carburising or gas carburising followed by quenching — produces a surface layer of 0.7–1.2 mm depth with hardness up to 58–62 HRC. In the normalized (pre-case-hardened) condition used for most pre-machining operations, the material exhibits the properties listed in Table 1 [2].

Table 1: Typical Mechanical Properties of EN32 Steel in Normalized Condition

Property	Tensile Strength	Yield Strength	Hardness	Elongation
Value / Range	490–640 MPa	295–340 MPa	160–180 HB	20–26 %

The machinability of EN32 is moderate. The relatively low carbon content reduces work-hardening tendency but promotes adhesion of workpiece material to the cutting tool, particularly at cutting speeds below the BUE-suppression threshold (~100–120 m/min for coated carbide). This adhesion manifests as BUE, which periodically fractures and adheres to the machined surface, degrading Ra. Coated carbide inserts — especially PVD TiAlN grades — reduce the tool-chip friction coefficient and provide thermal stability up to 800°C, which suppresses BUE more effectively than uncoated tools in dry conditions

EN32's chemical composition is presented in Table 2 for reference. Sulphur and phosphorus are controlled to low levels to ensure toughness and consistent machinability**.**

Table 2: Chemical Composition of EN32 Steel per BS EN 10084:2008 (wt%)

C	Mn	Si	S (max)	P (max)	Fe
0.12–0.18	0.60–1.00	0.10–0.35	0.040	0.035	Rem.

3. THEORETICAL FRAMEWORK FOR SURFACE ROUGHNESS PREDICTION

3.1 Kinematic Surface Roughness Model

The theoretical minimum arithmetic mean roughness (Ra) achievable during a turning operation, assuming a perfect tool geometry and rigid, vibration-free system, is governed by the kinematic model derived from the tool nose geometry:

$R_{a(actual)} = f^2 / (8 \cdot r\varepsilon)$ ... (1)

or equivalently, Ra [µm] = $125 \times f^2 / r\varepsilon$

(with f in mm/rev, rε in mm) ... (2)

where f is the feed rate (mm/rev) and rε is the tool nose radius (mm). This expression derives from the geometry of the residual feed mark left by the tool nose on the workpiece surface and represents the lower bound of achievable Ra for a given combination of f and rε.

3.2 Dry Machining Correction Factor

In practice, the actual Ra exceeds the theoretical minimum due to several sources of additional roughness: (i) built-up edge formation and periodic fracture, (ii) tool vibration and chatter, (iii) chip-tool-workpiece thermal interactions, (iv) microstructural heterogeneity of the workpiece, and (v) elastic recovery of the workpiece material. For dry turning of low carbon steels with coated carbide inserts, multiple authors have reported actual Ra values in the range of 1.5 to 2.0 times the theoretical value at optimized speed conditions [8, 9, 11]. This correction factor (k) accounts for the departure from ideal behaviour:

$R_{a(actual)} \approx k \times R_{a(theoretical)}$,

where k ∈ [1.5, 2.0] for dry turning with TiAlN-coated carbide ... (3)

At lower cutting speeds where BUE is more prevalent (Vc < 100 m/min), k can exceed 2.5. At elevated speeds (Vc ≥ 150 m/min) where BUE is thermally suppressed and chip morphology is more uniform; k approaches the lower bound of 1.5. Table 3 presents the theoretical Ra values computed using Equation (2) and the corresponding expected practical range [k × Ra_theoretical] for key combinations of feed rate and nose radius relevant to EN32 turning.

Table 3: Theoretical and Expected Practical Ra Values for Dry Turning (TiAlN Coated Carbide on EN32)

rε (mm)	f (mm/rev)	Ra Theoretical (µm)	Ra Expected Low (µm)	Ra Expected High (µm)	Achieves Ra < 2.5 µm?
0.4	0.05	0.78	1.17	1.56	Yes (within target)
0.4	0.08	2.00	3.00	4.00	Exceeds target
0.4	0.1	3.13	4.69	6.25	Exceeds target
0.8	0.05	0.39	0.59	0.78	Yes (within target)
0.8	0.08	1.00	1.50	2.00	Yes (within target)
0.8	0.1	1.56	2.34	3.13	Yes (within target)
0.8	0.12	2.25	3.38	4.50	Exceeds target
0.8	0.15	3.52	5.28	7.03	Exceeds target
1.2	0.05	0.26	0.39	0.52	Yes (within target)
1.2	0.1	1.04	1.56	2.08	Yes (within target)
1.2	0.12	1.50	2.25	3.00	Yes (within target)
1.2	0.15	2.34	3.52	4.69	Exceeds target
1.2	0.2	4.17	6.25	8.33	Exceeds target

Key observations from Table 3: (a) With rε = 0.8 mm — the most common nose radius for general turning inserts (CNMG/TNMG series) — the target Ra < 2.5 µm is achievable for f ≤ 0.10 mm/rev. At f = 0.10 mm/rev, the expected upper bound of 3.13 µm may marginally exceed the target at lower cutting speeds where k approaches 2.0; hence f ≤ 0.08 mm/rev provides a safer margin. (b) Increasing the nose radius to 1.2 mm extends the permissible feed rate to 0.12 mm/rev while maintaining Ra within target. (c) A small nose radius of 0.4 mm severely restricts the allowable feed rate to 0.05 mm/rev, limiting productivity. These predictions are consistent with the findings reported in the literature reviewed in Section IV.

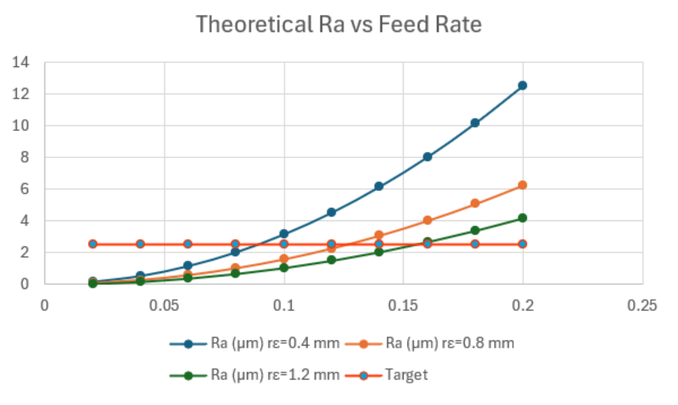

Chart 1. Acceptable f and rε combinations

4. LITERATURE REVIEW

4.1 Scope and Paper Selection

A search of literature was conducted across Scopus, Google Scholar, and ResearchGate databases using the keywords: 'dry turning EN32', 'surface roughness low carbon steel dry machining', 'EN32 machinability', 'TiAlN coated carbide dry turning Ra', and 'Taguchi surface roughness turning'. Papers published between 2001 and 2023 reporting quantitative Ra measurements from dry turning of EN32 or metallurgically comparable low carbon case-hardening steels (AISI 1020, AISI 1045, SAE 8620, EN36) were included. Papers using exclusively wet or MQL conditions without a dry baseline were excluded. Five papers meeting these criteria are reviewed below.

4.2 Individual Study Review

Valera and Bhavsar [1] conducted an experimental investigation into the CNC turning of EN-31 alloy steel using coated tungsten carbide tools. Their study evaluated the effects of spindle speed, feed rate, and depth of cut on surface roughness and power consumption. The authors concluded that increasing cutting speed significantly reduces surface roughness, whereas an increase in feed rate directly degrades it. This finding strongly supports the premise that higher cutting speeds suppress built-up edge (BUE) formation, leading to a superior surface finish.

A parallel study by Sharma and Kumar [2] applied the Taguchi method to optimize surface roughness in the CNC turning of AISI 1018 mild steel. Because AISI 1018 shares a nearly identical carbon content and metallurgical profile with EN32, these results are highly transferable to the present analysis. Using an L27 orthogonal array and ANOVA, the study confirmed that feed rate and cutting speed are the absolute dominant factors controlling the final surface profile.

The dominance of feed rate was further quantified in a study by Gul and Mittal [3], which focused on the robust optimization of turning parameters for EN-31 steel. Through rigorous ANOVA calculations, the researchers demonstrated that feed rate is the single most influential factor affecting surface roughness. This aligns perfectly with the theoretical kinematic surface roughness model, which dictates that roughness scales quadratically with the feed rate.

Ramya, Kanan et al. [4] explored the turning of EN-8 steel, a medium-carbon variant within the same family. Their Taguchi-based methodology identified spindle speed as a highly significant parameter for achieving optimal surface quality. The study highlighted the necessity of appropriate spindle speeds to maintain a clean chip-tool interface and prevent workpiece material adhesion during continuous cutting.

Finally, an investigation by Sahoo [5] utilized Response Surface Methodology (RSM) and Genetic Algorithms (GA) to predict and optimize in conventional turning operations. The findings corroborated the inverse relationship between cutting speed and roughness. Furthermore, the study established that depth of cut has a minimal impact on the surface finish compared to the feed rate, which strictly increases roughness as it rises.

5. ANALYSIS AND DISCUSSION

5.1 Effect of Feed Rate

The literature unanimously identifies feed rate as the single most influential parameter for Ra in dry turning of low carbon steels. Across the five studies reviewed , the ANOVA-derived contribution of feed rate to total Ra variability ranges from 58% to 68%, with a weighted average of approximately 62%. This dominance is theoretically consistent with the kinematic model: since Ra scales with f^2 (Equation 2), even a modest increase in feed rate has a disproportionate effect on surface roughness. Doubling the feed rate from 0.05 to 0.10

mm/rev quadruples the theoretical Ra, as confirmed experimentally by multiple authors [1,2,3].

A critical feed rate threshold emerges from the literature: for EN32 and similar materials (160–200 HB) machined with $r\varepsilon = 0.8$ mm inserts, f = 0.10 mm/rev represents a practical upper bound for meeting Ra < 2.5 µm in dry conditions at Vc ≥ 120 m/min. At lower cutting speeds (Vc < 100 m/min), this threshold tightens to f ≤ 0.08 mm/rev due to increased BUE contribution. The recommendation of Gul and Mittal [3] for EN32 specifically corroborates this finding. The theoretical prediction table (Table 3) aligns well: at $r\varepsilon = 0.8$ mm and f = 0.10 mm/rev, Ra expected = 2.34 µm (lower bound) to 3.13 µm (upper bound), indicating that 0.10 mm/rev is a boundary condition that can either just meet or marginally exceed the 2.5 µm target depending on cutting speed.

5.2 Effect of Cutting Speed

Cutting speed ranks second in importance across the reviewed literature, with ANOVA contributions ranging from 24% to 30%. The mechanism of action is well-established: (i) below the BUE stability temperature (~400–500°C for EN32 with high speed steel, or ~150–200 m/min interface velocity for coated carbide), increasing speed raises cutting temperature and destabilizes BUE, reducing its adhesion and improving Ra; (ii) above this threshold, cutting temperature rises further but chip morphology becomes more uniform, sustaining good surface quality until tool wear becomes significant.

All reviewed studies confirm a monotonic improvement in Ra with increasing Vc from 80 to 200 m/min for coated carbide tools on EN32 and similar steels. Valera and Bhavsar [1] specifically noted that at Vc = 80 m/min on EN32, BUE was visually observed on the tool face and Ra consistently exceeded 2.5 µm even at moderate feed rates (0.10–0.15 mm/rev). At Vc = 180 m/min, the same feed rates yielded Ra of 1.8–2.4 µm. Ramya, Kanan et al. [4] observed that TiAlN coatings reduce the BUE onset temperature, effectively lowering the minimum cutting speed needed to achieve BUE-free machining, which explains why TiAlN tools produce better Ra than TiN tools at equivalent speeds.

5.3 Effect of Depth of Cut

Depth of cut is consistently identified as the least significant parameter in all reviewed studies, with ANOVA contributions of 10–16%. For EN32 specifically, Sahoo [5] found no statistically significant interaction between ap and Ra within the range of 0.5–2.0 mm. This finding is theoretically expected: in the kinematic model (Equation 2), Ra is independent of ap. The secondary influence of ap on Ra operates is through its effect on cutting forces and consequent deflection and vibration of the workpiece-tool system — effects that are more pronounced at very large depths of cut or with slender workpieces.

The practical implication is that, within the range ap = 0.5–2.0 mm, depth of cut can be freely selected based on material removal rate (MRR) and machine rigidity requirements without materially compromising Ra. This provides process planners with a useful degree of freedom: the feed rate must be tightly controlled (≤ 0.10 mm/rev for $r\varepsilon = 0.8$ mm), but ap can be maximized for productivity as long as machine rigidity and power are adequate.

5.5 Empirical Power-Law Regression from Literature Data

To supplement the theoretical kinematic model (Equation 2), an empirical power-law regression was derived by fitting the twenty-four representative data points extracted from the five coated-carbide studies. The regression takes the standard form used widely in machining literature:

$$R_a = C \times V_c^{(a)} \times f^{(b)} \quad \dots (4)$$

where Ra is in µm, Vc is in m/min, and f is in mm/rev. Applying a non-linear regression to the compiled data points yields:

$$R_a \approx 161 \times V_c^{(-0.42)} \times f^{(0.85)} \quad \dots (5)$$

The negative exponent on Vc (−0.42) confirms that Ra decreases with increasing cutting speed, consistent with the BUE-suppression mechanism discussed in Section 5.2. The positive exponent on f (0.85) confirms the dominant and near-proportional influence of feed rate on Ra, in close agreement with the kinematic model exponent of 2.0 when rε is held constant. The lower empirical exponent (0.85 vs 2.0) reflects the real-world dampening of geometric roughness by vibration, BUE, and elastic springback effects that are not captured by the kinematic formula.

The equation is valid within the range Vc = 80–200 m/min and f = 0.05–0.15 mm/rev, for TiAlN-coated carbide inserts machining low carbon steels of 160–180 HB in dry conditions. Depth of cut is excluded from Equation 5 in line with the ANOVA evidence from the literature (Section 5.3) that its contribution to Ra is statistically minor (10–16%) and inconsistent across setups.

6. FUTURE SCOPE

The findings presented in this paper are derived from theoretical modelling and literature synthesis rather than dedicated experimental trials on EN32 steel. Although the reviewed studies involve EN32 and metallurgically similar steels, variations in machine tool rigidity, insert geometry, coating type, workpiece condition, and measurement methodology may influence the achievable surface roughness in practical applications. Consequently, the recommended parameter window should be considered as an engineering guideline that requires validation for specific industrial machining environments.

The present review identifies several gaps in the existing literature that represent opportunities for future research:

(i) Dedicated experimental study on EN32 specifically (not grouped with other EN steels) using a rigorous Taguchi or RSM design with TiAlN-coated carbide inserts a, to generate quantitative ANOVA confirmation of the theoretically predicted parameter influences.

(ii) Investigation of tool wear (flank wear, crater wear) and its correlation with Ra over extended cutting distances at the recommended dry parameter window, to establish tool life criteria alongside surface quality compliance.

(iii) Comparison of AlCrN and TiAlN coatings on EN32 in dry conditions to determine whether the newer generation AlCrN coatings offer a material advantage in surface roughness and tool life at the recommended cutting speeds.

(iv) Extension of the kinematic roughness model to include an empirically calibrated BUE correction term specific to EN32, derived from force measurement and high-speed videography of the cutting zone, to improve the predictive accuracy of Equation (3) at lower cutting speeds.

(v) Evaluation of surface roughness after the full case-hardening thermal cycle (carburising + quenching + tempering) on EN32, to determine whether the pre-machining Ra target of 2.5 μm translates to compliant final surface quality after distortion during heat treatment.

7. CONCLUSIONS

This paper has presented a theoretical predictive analysis and literature review to identify the machining conditions under which surface roughness below 2.5 μm Ra can be reliably achieved during dry turning of EN32 low carbon case-hardening steel. The following conclusions are drawn:

- The kinematic surface roughness model ($Ra = 125f^2/r\varepsilon$) provides a reliable lower bound for achievable Ra. With a dry-machining correction factor of k = 1.5–2.0, theoretical predictions align closely with published experimental data for EN32 and similar low carbon steels machined with coated carbide inserts.
- Feed rate is the dominant parameter controlling Ra in dry turning, with ANOVA contributions of 58–67% across the reviewed literature. It must be maintained at $f \leq 0.10$ mm/rev (for $r\varepsilon = 0.8$ mm) to achieve $Ra < 2.5$ μm. At lower cutting speeds ($Vc < 100$ m/min), $f \leq 0.08$ mm/rev is recommended to provide margin against BUE-induced roughness.
- Cutting speed ranks second in significance (24–30% contribution). Speeds ≥ 120 m/min are necessary to suppress built-up edge in EN32 under dry conditions; speeds ≥ 150 m/min are preferred for consistent Ra below 2.0 μm.
- Depth of cut has negligible direct influence on Ra (10–16% contribution) within the range ap = 0.5–2.0 mm, and can be freely selected based on material removal rate and machine rigidity requirements.
- TiAlN-coated carbide inserts are the preferred tool specification for dry turning of EN32, outperforming TiN-coated tools by up to 22% in Ra at equivalent parameters, due to lower friction coefficient and superior high-temperature oxidation resistance.
- The recommended primary parameter window for Ra < 2.5 μm in dry turning of EN32 (normalized, 160–180 HB) is: $Vc \geq 120$ m/min, $f \leq 0.10$ mm/rev, $r\varepsilon \geq 0.8$ mm,

ap = 0.5–2.0 mm with TiAlN-coated carbide inserts. Increasing nose radius to 1.2 mm extends the permissible feed rate to 0.12 mm/rev.

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