

Effect of Milling Cutter Helix Angle and Cutting Parameters on Surface Roughness in Peripheral Milling: A Critical Review and Theoretical Framework

Ali Serhat Ersoyoğlu

Konya Technical University, Konya, Türkiye

Abstract

Surface roughness in peripheral milling results from the coupled effects of cutting conditions, tool geometry, machine–tool dynamics, tool condition, runout, and the kinematic envelope generated by successive cutting edges. Among cutter-geometry variables, helix angle is particularly important because it changes the axial phase distribution of the cutting edge, chip-thickness distribution, cutting-force components, and dynamic excitation. This paper presents a critical review and theoretical analysis of the influence of helix angle and cutting parameters on surface roughness in peripheral milling. No new experimental measurements are claimed. Instead, published experimental, analytical, numerical, and prediction studies are synthesized into a unified mechanistic framework linking helix angle to chip thickness, cutting force, dynamic response, surface topography, and roughness. The literature indicates that feed per tooth is generally a dominant geometric/process variable, whereas cutting speed and depth of cut affect roughness through coupled force, thermal, wear, and dynamic mechanisms. Helix angle should therefore not be treated as an isolated parameter or associated with a universal optimum value. Its effect depends on cutter diameter, tooth count, workpiece material, engagement, feed per tooth, cutting speed, tool stiffness, runout, and dynamic stability. The proposed framework is explicitly presented as a literature-derived theoretical structure and a basis for future experimental calibration and validation.

Keywords—peripheral milling; side milling; helix angle; surface roughness; feed per tooth; cutting force; milling stability; surface topography; theoretical framework.

Highlights

- Helix angle is interpreted as a coupled geometric, force-related, and dynamic variable in peripheral milling.
- A mechanistic chain linking helix angle, chip thickness, cutting force, dynamic response, and surface topography is proposed.
- Published studies are synthesized without claiming new experimental measurements.
- Thirty-three DOI-identified publications are used to establish the theoretical framework and research gaps.

Article type and scope. This manuscript is a critical review and theoretical framework paper. It does not report new experiments, new measured datasets, or experimentally calibrated universal coefficients. All quantitative relationships proposed below are mechanistic or conceptual and are intended to guide future experimental validation.

1. Introduction

The paper first establishes the geometric and mechanistic foundations of peripheral milling and then develops a literature-derived theoretical framework for future validation.

Peripheral milling is widely used for generating planar and contoured surfaces because it combines geometric flexibility with high material-removal capability. The final surface, however, is not determined by cutting speed or feed rate alone. It is the result of an interaction among cutter geometry, engagement conditions, cutting forces, tool/workpiece deformation, vibration, tool wear, runout, and the kinematic envelope generated by successive cutting edges.

Previous milling studies have established the importance of feed rate, spindle speed, depth of cut, tool wear, and vibration in surface-roughness prediction. Zhang et al. demonstrated the usefulness of Taguchi-based optimization of milling parameters, while Ozcelik and Bayramoglu developed statistical models that incorporated spindle speed, feed rate, depth of cut, step-over, and tool operating time. Brezocnik et al. further showed that feed rate and vibration can materially improve roughness prediction [1]–[3].

Tool geometry introduces an additional level of complexity. In particular, the helix angle changes the axial phase of the cutting edge. Buj-Corral et al. explicitly modeled side-milling surface topography as a function of feed, eccentricity, and helix angle [4]. Wan et al. subsequently provided an analytical treatment of the mechanism by which helix angle influences peak cutting forces [5]. Ozturk et al. and Kao et al. also incorporated helix angle into cutting-force coefficient prediction [6], [7].

The objective of this paper is therefore to integrate these findings into a single theoretical framework. The paper is deliberately positioned as a critical review and theoretical analysis rather than an experimental study. The equations introduced below are mechanistic or conceptual relationships; they are not presented as experimentally calibrated universal roughness laws.

Novelty and contribution. The novelty of this paper is not claimed to be a new experimentally calibrated roughness equation. Instead, the contribution is a unified mechanistic framework that explicitly connects helix-angle-induced axial phase variation to chip-thickness modulation, cutting-force redistribution, dynamic excitation, and surface-topography generation, while distinguishing established relationships from hypotheses that require experimental calibration. This synthesis is intended to identify the missing experimental links needed for quantitative prediction and to provide a reproducible basis for future DOE-based validation.

2. Review Methodology

A structured critical-review approach was used to identify and organize literature linking milling cutter helix angle, cutting parameters, cutting forces, milling dynamics, surface topography, and surface

roughness. The search was intentionally broader than a single material system because the objective is to establish a transferable mechanistic framework rather than a material-specific empirical correlation.

The literature search used combinations of the terms “helix angle”, “variable helix”, “peripheral milling”, “side milling”, “cutting force”, “surface roughness”, “surface topography”, “milling stability”, and “tool runout”. Publisher and indexing records from ScienceDirect, SpringerLink, MDPI, Taylor & Francis, Wiley, institutional repositories, and other scholarly databases were considered when bibliographic metadata and DOI information could be verified.

Studies were included when they addressed at least one of the following: (i) helix-angle or variable-helix effects on milling forces; (ii) helix-angle effects on surface roughness or topography; (iii) regenerative stability or dynamic effects of helix/pitch variation; or (iv) established roughness-prediction relationships involving milling process parameters. Studies were excluded from the mechanistic synthesis when they concerned unrelated machining processes or did not provide sufficient bibliographic information for verification.

The final reference set was then organized into four evidence streams: geometric surface-generation models, mechanistic cutting-force models, dynamic/stability models, and empirical/statistical roughness-prediction studies. Recent work published in 2025 was additionally examined to ensure that the framework reflects current developments in helix-dependent force modelling and surface-quality research [34], [35].

3. Fundamentals of Peripheral Milling

The principal geometric and process variables used throughout the analysis are illustrated in Fig. 1.

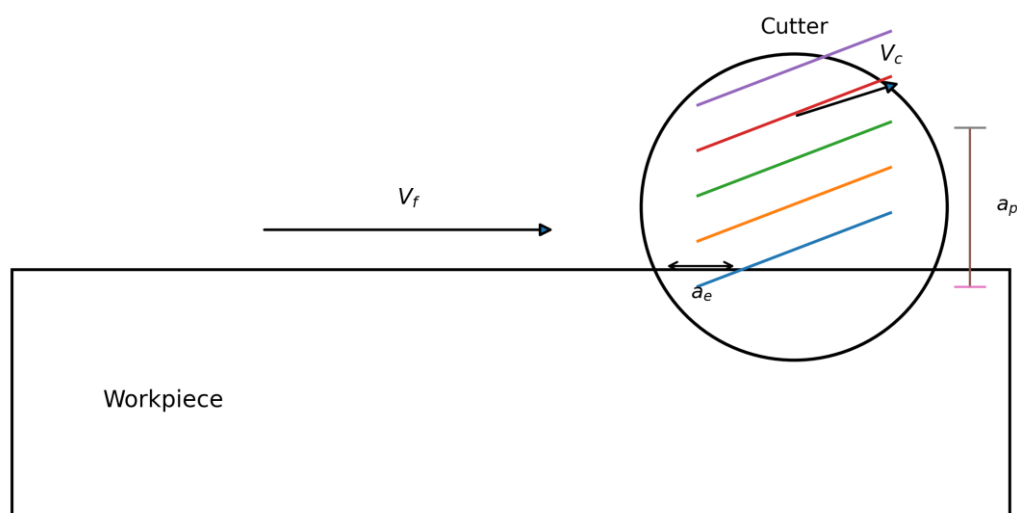


Figure 1. Schematic representation of peripheral milling showing feed velocity (V_f), cutting speed (V_c), radial depth of cut (a_e), and axial depth of cut (a_p).

Peripheral milling generates a surface through the repeated passage of cutting edges along the workpiece. For a cutter of diameter D rotating at n revolutions per minute, the nominal cutting speed is

$$V_c = \pi D n / 1000 \quad (1)$$

where V_c is the cutting speed (m/min), D is the cutter diameter (mm), and n is the spindle speed (rev/min).

where V_c is in m/min and D is in mm. The feed velocity is related to feed per tooth by

$$V_f = f_z z n \quad (2)$$

Here, V_f is the feed velocity (mm/min), f_z is the feed per tooth (mm/tooth), and z is the number of cutter teeth.

where f_z is feed per tooth and z is the number of teeth. Hence, $f_z = V_f / (zn)$. These relations show that feed per tooth directly controls the nominal spacing of successive cutting-edge trajectories.

The material-removal rate can be approximated by

$$MRR = a_p a_e V_f \quad (3)$$

In Eq. (3), MRR denotes the material removal rate, a_p is the axial depth of cut (mm), and a_e is the radial depth of cut or radial width of engagement (mm).

where a_p and a_e are axial and radial depths of cut, respectively. Although MRR does not directly define surface roughness, it is useful for interpreting the trade-off between productivity and surface quality.

4. Helix-Angle Geometry

To avoid ambiguity caused by perspective projection, Fig. 2 uses an unwrapped cylindrical representation of the cutter surface. The helix angle β is measured between the helical cutting edge and the circumferential direction; p_a denotes the axial pitch and p_c the corresponding circumferential advance. This representation makes the geometric origin of the axial phase shift used in Eq. (4) explicit.

The broader effect of tool-axis orientation on milling geometry, surface finish, cutting forces, form error, and stability has also been demonstrated for lead and tilt angles in five-axis ball-end milling [10].

As shown in Fig. 2, the helix angle defines the inclination of the cutting edge relative to the cutter axis. The resulting axial phase shift is illustrated in Fig. 3.

The helix angle β describes the inclination of the cutting edge relative to the cutter axis under the adopted tool-geometry convention. A helical edge does not intersect the workpiece at the same angular position along the entire axial depth. Instead, an axial phase shift develops.

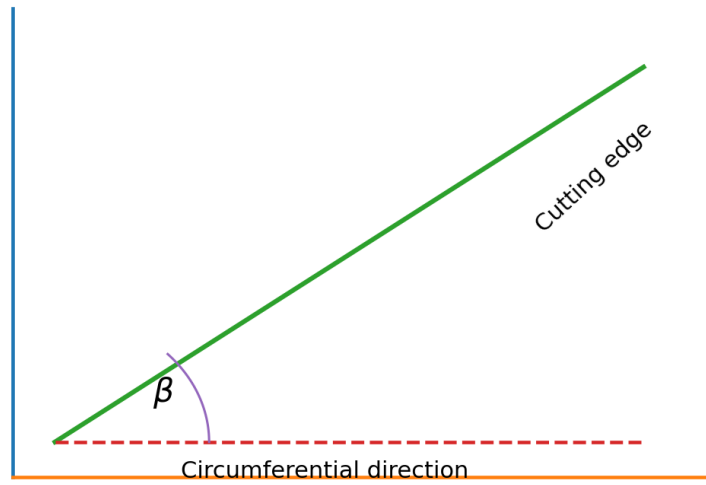


Figure 2. Unwrapped cylindrical representation of the helical cutting edge, showing the helix angle (β), axial pitch (p_a), and circumferential pitch (p_c).

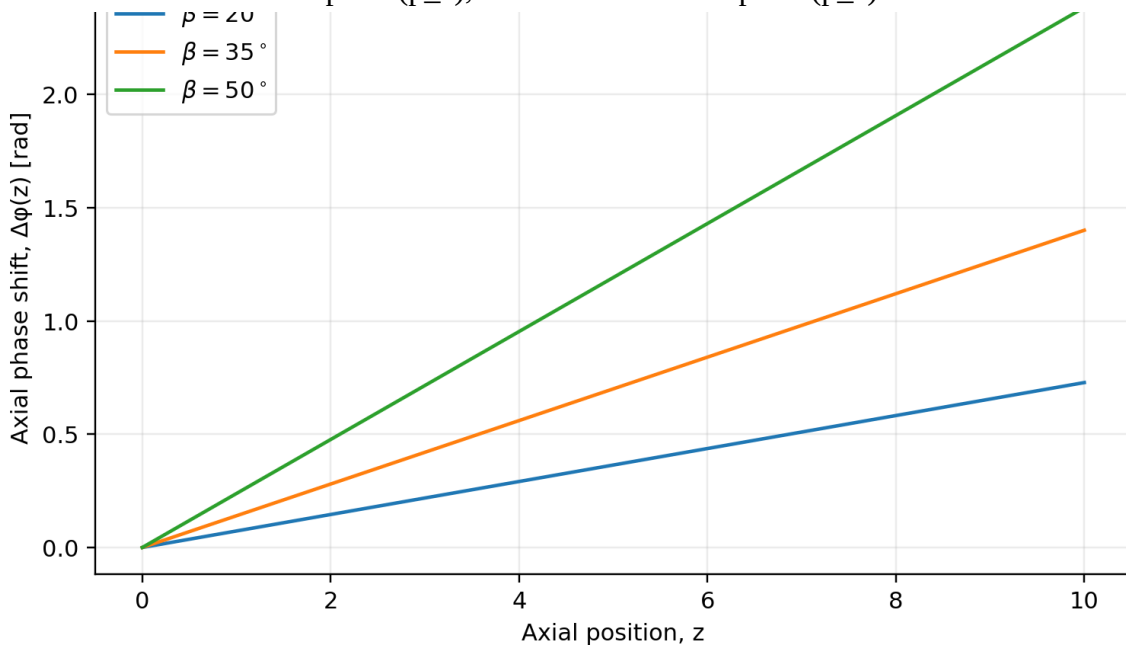


Figure 3. Axial phase shift of a helical cutting edge as a function of helix angle. For an axial position z_a , a commonly used geometric representation of the phase shift is

$$\Delta\phi(z_a) = 2 z_a \tan(\beta) / D \quad (4)$$

In Eq. (4), $\Delta\phi$ is the axial phase shift of the cutting edge (rad), z_a is the axial position along the cutter axis (mm), β is the helix angle ($^\circ$), and D is the cutter diameter (mm).

The precise sign and angular convention depend on the coordinate system, but the physical interpretation is invariant: increasing β increases the phase difference between axial sections of the same cutting edge.

Helix-angle convention. Throughout this paper, β is defined on the developed cylindrical cutter surface as the angle between the helical cutting edge and the circumferential reference direction. With this convention, Eq. (4) expresses the axial phase shift between two axial sections of the same cutting edge; changing the angular convention would alter the algebraic form but not the underlying physical interpretation.

This distributed engagement is central to the present theoretical framework because it couples cutter geometry to both surface generation and cutting-force distribution.

5. Chip Thickness and Cutting-Force Mechanism

Figure 4 illustrates how changing the helix angle changes the phase of instantaneous chip-thickness generation along the axial direction. The corresponding redistribution of cutting-force components is shown in Fig. 5.

Figure 4 illustrates how changing the helix angle changes the phase of instantaneous chip-thickness generation along the axial direction. The corresponding conceptual redistribution of cutting-force components is shown in Fig. 5.

For a simplified tooth-position description, instantaneous chip thickness can be represented as

$$h(\phi, z_a) \approx f_z \sin[\phi + \Delta\phi(z_a)] \quad (5)$$

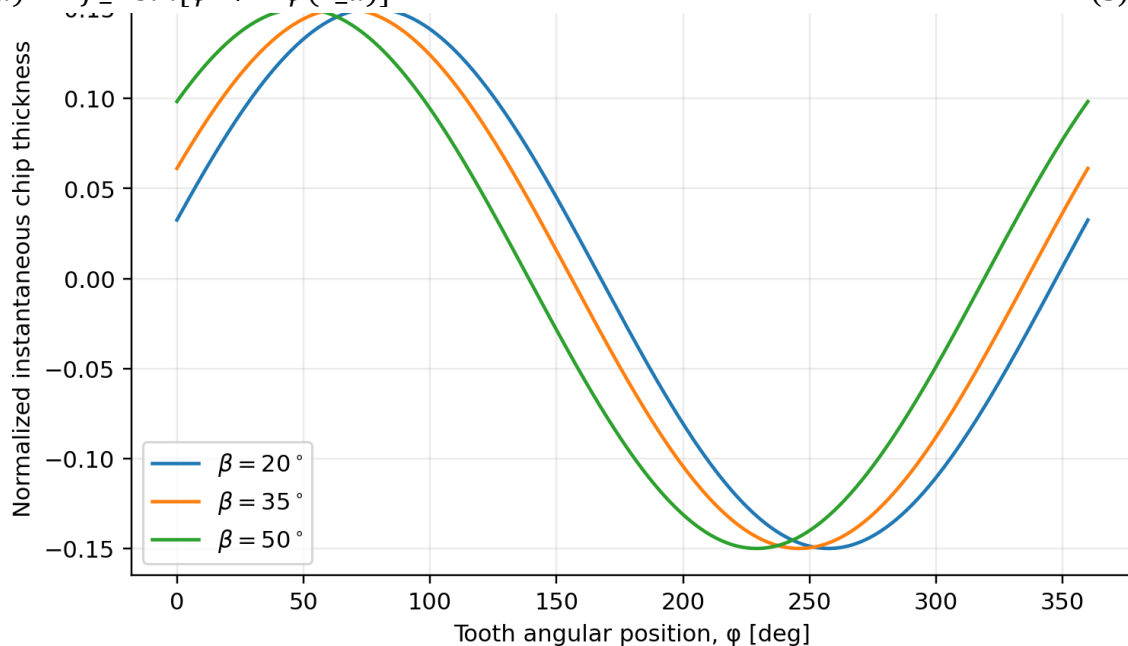


Figure 4. Schematic effect of helix angle on instantaneous chip-thickness phase.

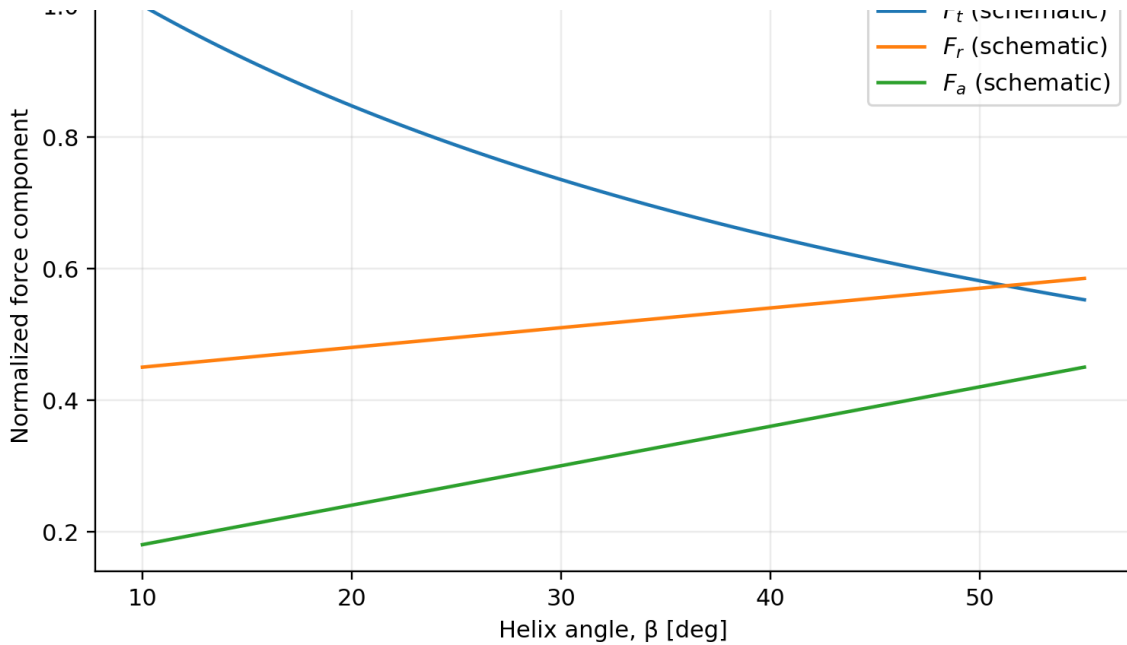


Figure 5. Conceptual influence of helix angle on cutting-force distribution.

In Eq. (5), h is the instantaneous uncut chip thickness (mm), φ is the instantaneous angular position of the tooth (rad), z_a is the axial position along the cutting edge (mm), f_z is the feed per tooth (mm/tooth), and $\Delta\varphi$ is the helix-induced axial phase shift (rad).

Substitution of Eq. (4) gives

$$h(\varphi, z_a) \approx f_z \sin[\varphi + 2 z_a \tan(\beta) / D] \quad (6)$$

Equation (6) uses the same variables as Eq. (5); β denotes the helix angle and D the cutter diameter.

Equation (6) is a mechanistic representation rather than a complete milling-force model. It shows directly how helix angle changes the phase of chip-thickness generation along the axial direction.

A differential tangential-force relation may then be written as

$$dF_t = K_t h(\varphi, z_a) dz_a \quad (7)$$

Here, dF_t is the differential tangential cutting force (N), K_t is the tangential cutting-force coefficient (N/mm²), h is the instantaneous chip thickness (mm), and dz_a is an infinitesimal axial element of the engaged cutting edge (mm).

and similarly for the radial component, $dF_r = K_r h(\varphi, z_a) dz_a$. Integrating over the engaged axial interval gives the total force. Wan et al. showed analytically that helix angle affects peak cutting forces in peripheral milling, while Ozturk et al. and Kao et al. demonstrated that helix angle should be incorporated into force-coefficient prediction [5]–[7].

This force-to-displacement pathway is consistent with established mechanistic milling-force formulations based on orthogonal cutting data and helical-tooth force models [21]–[24]. Budak et al. specifically established force-coefficient prediction from orthogonal cutting data [22], while Armarego and Deshpande developed force-prediction models for helical-tooth milling [23]. Lamikiz et al. further

addressed specific cutting coefficients and geometric aspects relevant to sculptured-surface machining [24].

The implication is important: helix angle affects surface roughness indirectly as well as directly. A change in force magnitude or phase can alter elastic deflection and vibration, thereby changing the actual tool trajectory.

6. Dynamic Response and Milling Stability

A simplified linear representation of the machining system is

$$M \ddot{x}(t) + C \dot{x}(t) + K x(t) = F(t) \quad (8)$$

In Eq. (8), M , C , and K represent the equivalent mass, damping, and stiffness of the machine-tool-workpiece dynamic system, respectively; $x(t)$ is the dynamic displacement, and $F(t)$ is the time-dependent milling-force excitation.

where M , C , and K are equivalent mass, damping, and stiffness matrices. The force $F(t)$ contains tooth-passing and regeneration-related components. The tooth-passing frequency is

$$f_{tp} = z n / 60 \quad (9)$$

In Eq. (9), f_{tp} is the tooth-passing frequency (Hz), z is the number of cutter teeth, and n is the spindle speed (rev/min).

when n is expressed in revolutions per minute.

Variable-pitch and variable-helix milling studies demonstrate that changes in pitch and helix geometry modify regenerative phase relationships and can alter chatter stability [8], [9], [14], [15]. Sims et al. showed that variable-helix cutters can alter chatter stability, while Jin et al. developed a frequency-domain stability solution for variable-helix cutters [8], [9]. Yusoff and Sims optimized variable-helix geometry for regenerative chatter mitigation [14], and Niu et al. analyzed variable-pitch/variable-helix stability while accounting for runout [15].

Because chatter produces a dynamically modulated tool path, its contribution to roughness cannot be represented by ideal feed geometry alone.

7. Geometrical and Process-Induced Surface Roughness

Figures 6 and 7 summarize the proposed mechanistic pathway and the resulting geometrical and dynamic contributions to surface topography.

The measured roughness can be conceptually decomposed into several contributions. This interpretation is consistent with surface-generation models that account for tool runout, displacement, cutting-force-induced motion, and process stochasticity [11]–[13], [32]:



Figure 6. Mechanistic pathway from helix angle to surface roughness.

$$R_a \approx R_{a,g} + R_{a,d} + R_{a,w} + R_{a,e} \quad (10)$$

Here, R_a is the measured arithmetic average surface roughness, $R_{a,g}$ is the geometrical contribution, $R_{a,d}$ is the dynamic contribution, $R_{a,w}$ is the tool-wear contribution, and $R_{a,e}$ represents eccentricity, runout, and other geometrical-error effects.

where $R_{a,g}$ is the geometrical contribution, $R_{a,d}$ the dynamic contribution, $R_{a,w}$ the tool-wear contribution, and $R_{a,e}$ the contribution of eccentricity, runout, and related geometrical errors.

The decomposition is conceptual rather than a strict additive physical law. Its purpose is to distinguish mechanisms that are often mixed together when only R_a is reported.

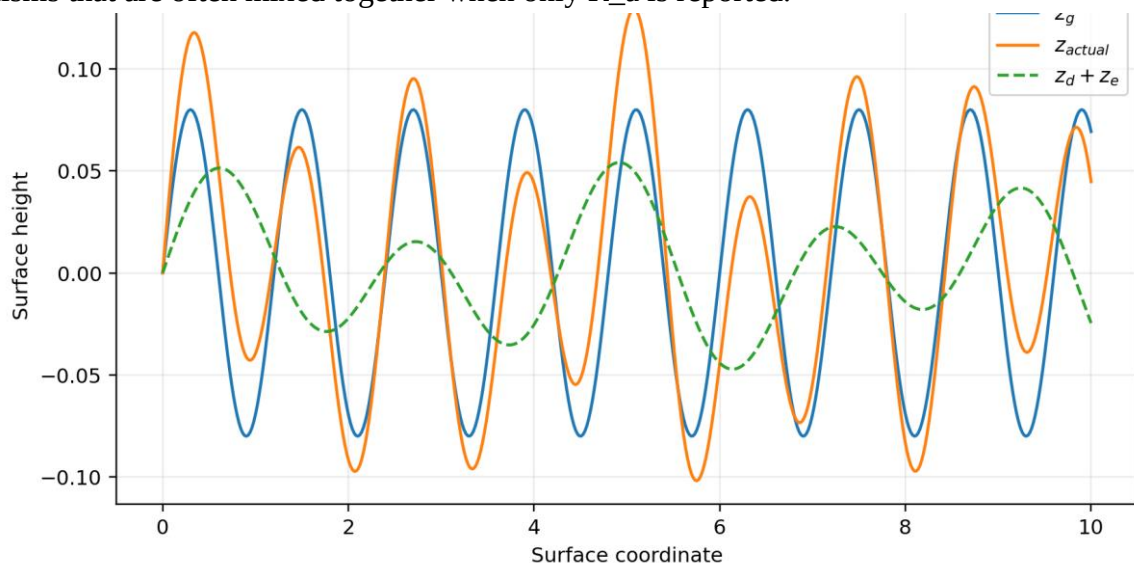


Figure 7. Geometrical and dynamic contributions to the generated surface topography.

Buj-Corral et al. showed that feed, eccentricity, and helix angle alter side-milling surface topography [4]. Their model is particularly relevant because it treats surface generation geometrically and shows that helix angle changes the heightwise distribution of the roughness profile. Additional studies show that tool runout can create heterogeneity bands in the machined topography [11], while tool displacement and measured cutting forces can be used to reconstruct or predict the generated surface [12], [13].

Runout-correction studies further show that dynamic/geometrical error sources can alter the effective tool trajectory and the resulting milled surface [16].

Dynamic displacement may be represented as $x_d(t)$, so that

$$x_{actual}(t) = x_{ideal}(t) + x_d(t) \quad (11)$$

In Eq. (11), $x_{actual}(t)$ is the actual tool/workpiece relative displacement, $x_{ideal}(t)$ is the ideal kinematic displacement, and $x_d(t)$ is the additional dynamic displacement caused by vibration and deformation.

This relationship provides the bridge between cutting-force/dynamic models and measured surface texture.

8. Effect of Feed per Tooth

Feed per tooth is generally one of the most influential variables in milling surface generation because it controls chip thickness and the spacing between consecutive cutting-edge trajectories. Experimental and modelling studies have repeatedly identified feed and other process variables as important predictors of surface roughness [1]–[3], [25]–[31]. A generalized empirical relationship may be written as

$$R_a \propto f_z^m \quad (12)$$

In Eq. (12), R_a is the arithmetic average surface roughness, f_z is the feed per tooth, and m is a process-dependent empirical exponent describing the sensitivity of roughness to feed per tooth. where m is process-dependent.

Brezocnik et al. found feed rate to be a major variable in end-milling roughness prediction, with vibration improving model accuracy [3]. Zhang et al. also showed that feed rate, spindle speed, and depth of cut can be optimized statistically for surface quality [1]. Subsequent studies using grey-fuzzy, intelligent, machine-vision, hybrid, and Bayesian approaches likewise demonstrate that feed, cutting speed, depth of cut, tool condition, and dynamic information can improve roughness prediction [25]–[30]. Sharkawy compared intelligent-system approaches for end-milling roughness prediction [27]; Palani and Natarajan used machine vision with an artificial neural network for CNC end-milling roughness prediction [28]; and Beruvides et al. proposed a hybrid incremental model for coping with nonlinear complexity in milling roughness prediction [29].

The key implication for helix-angle studies is that the effect of β should not be interpreted without specifying f_z . A helix angle that is favorable at one feed per tooth may not be equally favorable at another because the phase-shift mechanism acts on a different chip-thickness level.

9. Effect of Cutting Speed

Cutting speed affects roughness through cutting temperature, material deformation, built-up-edge behavior, tool wear, and dynamic response. Therefore, its effect is not necessarily monotonic.

The relationship can be expressed generically as

$$R_a = F(V_c) \quad (13)$$

Here, V_c is the cutting speed and $F(\cdot)$ denotes a general, potentially nonlinear functional relationship between cutting speed and surface roughness.

with F potentially nonlinear. Ozcelik and Bayramoglu found that surface roughness models in high-speed flat end milling are improved when process variables and tool operating time are considered [2]. More recent prediction studies likewise use heterogeneous process data, micro-milling surface-quality descriptors, and simulation-based kinematic/stochastic modelling to capture nonlinear roughness behaviour [30]–[32].

In a helix-angle-aware framework, V_c also changes tooth-passing frequency and therefore the relationship between the excitation spectrum and the structural modes of the machining system.

10. Effect of Axial and Radial Depth of Cut

Axial and radial engagement affect the length of cutting edge in contact with the workpiece and therefore influence force magnitude, heat generation, and stability. Their influence on roughness is process-dependent; experimental optimization studies explicitly include depth of cut among the variables affecting cutting force and surface quality [1], [25], [26].

Importantly, the geometric component of surface roughness does not necessarily depend directly on cutting speed or axial depth under idealized cylindrical side milling. Buj-Corral et al. showed that the geometric roughness generated in their side-milling model was governed primarily by feed, tool geometry, eccentricity, and helix angle [4]. The same distinction between ideal kinematic geometry and additional process-induced effects is supported by surface-topography reconstruction and simulation studies [11]–[13], [32].

However, once force-induced deformation, wear, and vibration are included, a_p and a_e can affect measured roughness indirectly through the dynamic and mechanical terms in Eq. (10).

11. Critical Review of Helix-Angle Studies

Zagórski et al. experimentally investigated carbide tools with different cutting-edge helix angles in finish milling of AZ31B and AZ91D magnesium alloys. The study varied cutting speed, feed per tooth, axial depth, and radial depth and measured several surface-roughness parameters [18].

Sur et al. investigated fixed- and variable-helix tools in peripheral milling of Ti6Al4V and considered cutting force and surface roughness simultaneously [19]. Their results support the interpretation that helix angle can influence both force and surface quality, while variable-helix tools can additionally modify dynamic behaviour.

Hu et al. examined a variable-helical end mill in titanium-alloy milling and discussed its influence on cutting force, stability, and machining performance [20]. Yang and Liu also showed that variable-pitch geometry can affect surface plastic deformation and surface topography in peripheral milling [17]. The broader variable-helix literature indicates that helix variation changes regenerative phase relationships and can therefore alter chatter stability [8], [9], [14], [15].

These studies collectively support a coupled interpretation: helix angle is neither a purely geometric parameter nor a purely dynamic parameter. It affects both.

Recent developments reinforce the need for this distinction. Ding et al. (2025) proposed a helix-angle-differentiation method for cutting-force modelling of gradient-helix-edge end mills and validated the resulting model against numerical and experimental comparisons [34]. Sönmez (2025) reported experimentally that helix angle, cutting conditions, and tool wear are coupled with surface roughness in helical plunge milling of AISI 1045 [35]. These studies extend the literature beyond fixed-helix force models and further motivate a framework that separates geometric, force, dynamic, and wear contributions.

12. Proposed Theoretical Framework

The complete theoretical framework proposed in this study is presented in Fig. 8.

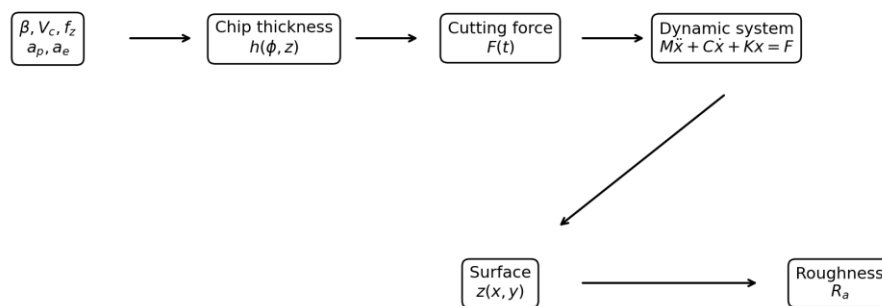


Figure 8. Proposed theoretical framework for helix-angle-dependent surface roughness.

The complete mathematical framework is summarized in Fig. 8. Figures 6 and 7, introduced earlier, provide the mechanistic pathway and surface-topography interpretation underlying this framework.

The central functional representation proposed in this review is

$$R_a = F(\beta, V_c, f_z, a_p, a_e, D, z, F_c, x_d, W, E) \quad (14)$$

In Eq. (14), β is the helix angle, V_c is the cutting speed, f_z is the feed per tooth, a_p and a_e are the axial and radial depths of cut, D is the cutter diameter, z is the number of teeth, F_c represents the cutting-force response, x_d is the dynamic displacement, W represents the tool-wear state, and E represents geometrical errors such as runout or eccentricity.

where β is helix angle, V_c is cutting speed, f_z is feed per tooth, a_p and a_e are axial and radial depths of cut, D is cutter diameter, z is tooth count, F_c represents cutting-force behavior, x_d dynamic displacement, W tool-wear state, and E geometrical errors.

A useful hierarchical form is

$$R_a = R_{a,g} + R_{a,d} + R_{a,w} + R_{a,e} \quad (15)$$

The terms in Eq. (15) have the same meanings as those defined for Eq. (10): geometrical, dynamic, tool-wear, and geometrical-error contributions.

The additive decomposition in Eq. (15) is a conceptual superposition used to organize the mechanisms. It is not assumed here that the four contributions are strictly independent or linearly additive under all

cutting conditions; interaction terms are expected and are explicitly retained in the proposed response-surface formulation of Eq. (20).

with

$$R_{a,g} = f(f_z, D, z, a_e, \beta) \quad (16)$$

Here, $R_{a,g}$ is the geometrical component of surface roughness and is expressed as a function of f_z , D , z , a_e , and β .

$$R_{a,d} = f(F_c, \beta, M, C, K) \quad (17)$$

In Eq. (17), $R_{a,d}$ is the dynamic roughness contribution; F_c is the cutting-force response, β is the helix angle, and M , C , and K are the equivalent mass, damping, and stiffness parameters.

$$R_{a,w} = f(V_c, f_z, t) \quad (18)$$

Here, $R_{a,w}$ is the roughness contribution associated with tool wear, V_c is cutting speed, f_z is feed per tooth, and t is the machining or tool-operating time.

$$R_{a,e} = f(e, \beta) \quad (19)$$

In Eq. (19), $R_{a,e}$ is the roughness contribution associated with geometrical error, e denotes cutter eccentricity or runout magnitude, and β is the helix angle.

Equations (14)–(19) are intended as a structured theoretical framework. They define a causal hierarchy that a future calibrated predictive model should follow; they do not claim universal numerical coefficients or predictive accuracy without experimental calibration.

A second-order response-surface representation for future experimental validation could be written as

$$R_a = b_0 + \sum b_i X_i + \sum b_{ii} X_i^2 + \sum b_{ij} X_i X_j \quad (20)$$

In Eq. (20), b_0 is the intercept, b_i are the linear-effect coefficients, b_{ii} are the quadratic-effect coefficients, b_{ij} are the interaction coefficients, and X_i and X_j are coded experimental factors such as helix angle, cutting speed, feed per tooth, and depth of cut.

with β included as one of the coded variables X_i . The interaction terms $\beta \times f_z$ and $\beta \times V_c$ are particularly important because they represent the coupled influence of tool geometry and process conditions.

13. Literature Comparison

The literature can be grouped into four complementary streams: (i) geometric surface-topography modeling, (ii) mechanistic cutting-force modeling, (iii) milling-stability and variable-helix dynamics, and (iv) empirical/statistical roughness prediction.

Geometric models explain how helix angle changes the generated surface pattern [4], while runout and displacement models explain additional topographic deviations [11]–[13]. Force models explain how helix angle modifies cutting-force coefficients and peak force [5]–[7], with foundational force-coefficient formulations provided by [21]–[24]. Stability models explain how variable helix and pitch alter regenerative phase relationships and chatter boundaries [8], [9], [14], [15]. Experimental and

statistical studies show that cutting parameters, tool geometry, tool condition, and material can affect surface roughness [1]–[3], [18]–[20], [25]–[33].

The proposed framework combines these streams rather than treating them as separate topics.

14. Research Gaps

Several gaps remain. First, many roughness studies optimize cutting parameters while keeping tool geometry fixed, whereas helix angle is rarely treated as a primary factor together with feed, cutting speed, and engagement. Second, helix-angle studies often use a limited range of materials, cutter diameters, tooth counts, and engagement conditions, making direct transfer of an optimum helix angle difficult. Third, the literature frequently reduces surface quality to a single scalar parameter such as R_a , although helix angle can alter directional texture, height distribution, and three-dimensional topography. Fourth, geometric, force, dynamic, runout, and wear mechanisms are often investigated separately, leaving the causal chain between helix angle and measured roughness insufficiently integrated. Finally, recent helix-dependent force modelling [34] and helical-milling surface-quality experiments [35] indicate that current research is moving toward coupled geometry–force–surface descriptions, but a broadly calibrated framework remains unavailable.

Future studies should combine helix angle, feed per tooth, cutting speed, axial depth, radial depth, cutter diameter, tooth count, cutting force, vibration, runout, and tool wear in a single experimental design. Three-dimensional texture parameters such as S_a and S_z should be measured together with R_a and R_z .

15. Proposed Experimental Validation

The framework is not experimentally validated in the present paper. This distinction is essential: the equations define a mechanistic hierarchy, while the numerical coefficients and functional forms required for predictive use must be identified from controlled experiments.

No experimental data are presented in this paper. A future validation study should use multiple helix-angle levels, for example $\beta = 20^\circ$, 35° , and 50° , together with at least three levels of feed per tooth and cutting speed. The exact levels should be selected from the manufacturer's recommended cutting range for the chosen tool/workpiece combination.

Cutting force and vibration should be recorded simultaneously with surface roughness and three-dimensional texture parameters such as S_a and S_z . Tool runout and tool wear should also be measured or independently characterized. This design would allow the proposed geometric, force, dynamic, wear, and error contributions to be separated rather than inferred from R_a alone.

ANOVA and response-surface methodology can then be used to quantify the main effects and interactions. A confirmation experiment should be conducted at the predicted optimum conditions.

16. Conclusions

This critical review and theoretical analysis examined the influence of milling cutter helix angle and cutting parameters on surface roughness in peripheral milling. The conclusions below are literature-

derived and define hypotheses for future experimental validation rather than experimentally validated universal laws.

- 1) Helix angle changes the axial phase distribution of a helical cutting edge and therefore modifies chip-thickness distribution and cutting-force behavior.
- 2) Feed per tooth is a dominant variable in the geometric generation of milling surfaces and should always be interpreted together with helix angle.
- 3) Cutting speed and depth of cut influence roughness through coupled thermal, force, wear, and dynamic mechanisms rather than through a universal monotonic relationship.
- 4) Helix angle can influence surface roughness indirectly through cutting-force redistribution and dynamic stability, in addition to its direct geometric effect.
- 5) Variable-helix literature demonstrates that tool geometry can modify regenerative delay and chatter stability, providing a mechanistic link between helix angle and dynamic surface generation.
- 6) No universal optimum helix angle can be established independently of material, cutter diameter, tooth count, engagement, feed per tooth, tool stiffness, runout, and cutting speed.
- 7) The proposed framework links β , cutting parameters, chip thickness, cutting forces, dynamic response, surface topography, and R_a and provides a basis for future experimental validation.

Table 1. Selected literature on helix angle, surface quality, force, and stability

Mechanistic cutting-force models [21]–[24], process-parameter optimization and roughness-prediction studies [25]–[30], surface-quality and simulation studies [31], [32], and recent helix-angle investigations [18]–[20], [33] collectively support the proposed theoretical framework.

Study	Focus	Variables	Contribution
Buj-Corral et al. [4]	Side milling	feed, eccentricity, helix	Surface-topography model
Wan et al. [5]	Peripheral milling	helix, force	Analytical force mechanism
Ozturk et al. [6]	Force coefficients	helix	Tool-design prediction
Kao et al. [7]	Flat-end milling	helix, geometry	Virtual force model
Sims et al. [8]	Stability	variable pitch/helix	Chatter prediction
Niu et al. [15]	Stability	helix, pitch, runout	Multi-regenerative model
Zagórski et al. [18]	Finish milling	helix, V_c , f_z , a_p , a_e	Experimental roughness study
Sur et al. [19]	Peripheral milling	helix, V_c , feed	Force/roughness optimization
Kowalczyk & Tomczyk [33]	Milling NiTi	helix, coating, feed	Recent force/roughness study
Ding et al. [34]	Force modelling	gradient helix, helix angle	Helix-angle-differentiated force model
Sönmez [35]	Helical plunge milling	helix, cutting	Surface roughness and

		conditions, wear	tool-wear evidence
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Notation. Unless otherwise stated, β denotes helix angle, V_c cutting speed, V_f feed velocity, f_z feed per tooth, a_p axial depth of cut, a_e radial depth of cut, D cutter diameter, z number of teeth, and R_a arithmetic average surface roughness. The symbols M , C , and K denote the equivalent dynamic mass, damping, and stiffness of the machining system.

[34] M. Ding, C. Yue, R. Zhen, X. Liu, S. Sun, S.Y. Liang, L. Wang, Cutting force modeling of the gradient helix edge end mill based on helix angle differentiation, *Thin-Walled Structures* 215 (2025) 113537. doi:10.1016/j.tws.2025.113537.

[35] F. Sönmez, Investigation of surface roughness and tool wear in helical plunge milling of AISI 1045 material, *Gazi University Journal of Science* 38 (2025) 2107–2116. doi:10.35378/gujs.1597747.

References

1. J.Z. Zhang, J.C. Chen, E.D. Kirby, Surface roughness optimization in an end-milling operation using the Taguchi design method, *J. Mater. Process. Technol.* 184 (2007) 233–239. doi:10.1016/j.jmatprotec.2006.11.029.
2. B. Ozcelik, M. Bayramoglu, The statistical modeling of surface roughness in high-speed flat end milling, *Int. J. Mach. Tools Manuf.* 46 (2006) 1395–1402. doi:10.1016/j.ijmachtools.2005.10.005.
3. M. Brezocnik, M. Kovacic, M. Ficko, Prediction of surface roughness with genetic programming, *J. Mater. Process. Technol.* 157–158 (2004) 28–36. doi:10.1016/j.jmatprotec.2004.09.004.
4. I. Buj-Corral, J. Vivancos-Calvet, A. Domínguez-Fernández, R. Casado-López, Influence of feed, eccentricity and helix angle on topography obtained in side milling processes, *Int. J. Mach. Tools Manuf.* 51 (2011) 889–897. doi:10.1016/j.ijmachtools.2011.08.001.
5. M. Wan, J. Feng, W.-H. Zhang, Y. Yang, Y.-C. Ma, Working mechanism of helix angle on peak cutting forces together with its design theory for peripheral milling tools, *J. Mater. Process. Technol.* 249 (2017) 570–580. doi:10.1016/j.jmatprotec.2017.06.030.
6. E. Ozturk, O. Ozkirimli, T. Gibbons, M. Saibi, S. Turner, Prediction of effect of helix angle on cutting force coefficients for design of new tools, *CIRP Ann.* 65 (2016). doi:10.1016/j.cirp.2016.04.042.
7. Y.-C. Kao, N.-T. Nguyen, M.-S. Chen, S.-T. Su, A prediction method of cutting force coefficients with helix angle of flat-end cutter and its application in a virtual three-axis milling simulation system, *Int. J. Adv. Manuf. Technol.* 77 (2015) 1793–1809. doi:10.1007/s00170-014-6550-8.
8. N.D. Sims, B. Mann, S. Huyanan, Analytical prediction of chatter stability for variable pitch and variable helix milling tools, *J. Sound Vib.* 317 (2008) 664–686. doi:10.1016/j.jsv.2008.03.045.
9. G. Jin, Q. Zhang, H. Qi, B. Yan, A frequency-domain solution for efficient stability prediction of variable helix cutters milling, *Proc. Inst. Mech. Eng. C* 228 (2014) 2702–2710. doi:10.1177/0954406214522614.

10. E. Ozturk, L.T. Tunc, E. Budak, Investigation of lead and tilt angle effects in 5-axis ball-end milling processes, *Int. J. Mach. Tools Manuf.* 49 (2009) 1053–1062. doi:10.1016/j.ijmachtools.2009.07.013.
11. M. Arizmendi, J. Fernández, A. Gil, F. Veiga, Model for the prediction of heterogeneity bands in the topography of surfaces machined by peripheral milling considering tool runout, *Int. J. Mach. Tools Manuf.* 50 (2010) 51–64. doi:10.1016/j.ijmachtools.2009.09.007.
12. J.-P. Costes, V. Moreau, Surface roughness prediction in milling based on tool displacements, *J. Manuf. Process.* 13 (2011) 133–140. doi:10.1016/j.jmapro.2011.02.003.
13. B. Denkena, M. Krüger, D. Bachrathy, G. Stépán, Model based reconstruction of milled surface topography from measured cutting forces, *Int. J. Mach. Tools Manuf.* 54–55 (2012) 25–33. doi:10.1016/j.ijmachtools.2011.12.007.
14. A.R. Yusoff, N.D. Sims, Optimisation of variable helix tool geometry for regenerative chatter mitigation, *Int. J. Mach. Tools Manuf.* 51 (2011) 133–141. doi:10.1016/j.ijmachtools.2010.10.004.
15. J. Niu, Y. Ding, L. Zhu, H. Ding, Mechanics and multi-regenerative stability of variable pitch and variable helix milling tools considering runout, *Int. J. Mach. Tools Manuf.* 123 (2017) 129–145. doi:10.1016/j.ijmachtools.2017.08.006.
16. E. Diez Cifuentes, H. Pérez García, M. Guzmán Villaseñor, A. Vizán Idoipe, Dynamic analysis of runout correction in milling, *Int. J. Mach. Tools Manuf.* 50 (2010) 709–717. doi:10.1016/j.ijmachtools.2010.04.010.
17. D. Yang, Z. Liu, Surface plastic deformation and surface topography prediction in peripheral milling with variable pitch end mill, *Int. J. Mach. Tools Manuf.* 91 (2015) 43–53. doi:10.1016/j.ijmachtools.2014.11.009.
18. I. Zagórski, A. Szczepaniak, M. Kulisz, J. Korpysa, Influence of the tool cutting edge helix angle on the surface roughness after finish milling of magnesium alloys, *Materials* 15 (2022) 3184. doi:10.3390/ma15093184.
19. G. Sur, A.R. Motorcu, S. Nohutçu, Single and multi-objective optimization for cutting force and surface roughness in peripheral milling of Ti6Al4V using fixed and variable helix angle tools, *J. Manuf. Process.* 80 (2022) 529–545. doi:10.1016/j.jmapro.2022.06.016.
20. X. Hu, H. Qiao, M. Yang, Y. Zhang, Research on milling characteristics of titanium alloy TC4 with variable helical end milling cutter, *Machines* 10 (2022) 537. doi:10.3390/machines10070537.
21. P. Lee, Y. Altintas, Prediction of ball-end milling forces from orthogonal cutting data, *Int. J. Mach. Tools Manuf.* 36 (1996) 1059–1072. doi:10.1016/0890-6955(95)00081-X.
22. E. Budak, Y. Altintas, E.J.A. Armarego, Prediction of milling force coefficients from orthogonal cutting data, *J. Manuf. Sci. Eng.* 118 (1996) 216–224. doi:10.1115/1.2831014.
23. E.J.A. Armarego, N.P. Deshpande, Force prediction models and CAD/CAM software for helical tooth milling processes. I. Basic approach and cutting analyses, *Int. J. Prod. Res.* 31 (1993) 1991–2009. doi:10.1080/00207549308956836.
24. A. Lamikiz, L.N. Lopez de Lacalle, J.A. Sanchez, U. Bravo, Calculation of the specific cutting coefficients and geometrical aspects in sculptured surface machining, *Mach. Sci. Technol.* 9 (2005) 411–436. doi:10.1080/15321790500226614.

25. N. Masmiati, A.A.D. Sarhan, M.A.N. Hassan, M. Hamdi, Optimization of cutting conditions for minimum residual stress, cutting force and surface roughness in end milling of S50C medium carbon steel, *Measurement* 86 (2016) 253–265. doi:10.1016/j.measurement.2016.02.049.
26. N. Tamiloli, J. Venkatesan, V. Ramnath, A grey-fuzzy modeling for evaluating surface roughness and material removal rate of coated end milling insert, *Measurement* 84 (2016) 68–82. doi:10.1016/j.measurement.2016.02.008.
27. A.B. Sharkawy, Prediction of surface roughness in end milling process using intelligent systems: a comparative study, *Appl. Comput. Intell. Soft Comput.* 2011 (2011) 183764. doi:10.1155/2011/183764.
28. S. Palani, U. Natarajan, Prediction of surface roughness in CNC end milling by machine vision system using artificial neural network based on 2D Fourier transform, *Int. J. Adv. Manuf. Technol.* 54 (2011) 1033–1042. doi:10.1007/s00170-010-3018-3.
29. G. Beruvides, F. Castaño, R.E. Haber, Coping with complexity when predicting surface roughness in milling processes: hybrid incremental model with optimal parametrization, *Complexity* 2017 (2017) 7317254. doi:10.1155/2017/7317254.
30. W.-C. Liu, P. Wang, Y. You, Surface roughness prediction using multi-source heterogeneous data and Bayesian quantile regression in milling process, *J. Manuf. Process.* 95 (2023) 446–460. doi:10.1016/j.jmapro.2023.04.038.
31. X. Wu, Z. Chen, W. Ke, F. Jiang, M. Zhao, J. Shen, L. Zhu, Investigation on surface quality in micro milling of additive manufactured Ti6Al4V titanium alloy, *J. Manuf. Process.* 101 (2023) 446–457. doi:10.1016/j.jmapro.2023.05.110.
32. B. Denkena, M.-A. Dittrich, J. Huuk, Simulation-based surface roughness modelling in end milling, *Procedia CIRP* 99 (2021) 151–156. doi:10.1016/j.procir.2021.03.096.
33. M. Kowalczyk, K. Tomczyk, Quality of machined surface and cutting force when milling NiTi alloys, *Materials* 17 (2024) 6122. doi:10.3390/ma17246122.