International Journal of Science, Strategic Management and Technology
Volume **02** Issue **05** May-**2026** | ISSN: **3108-1762 (Online)** | Impact Factor: 3.8
An International, Peer-Reviewed, Open Access Scholarly Journal Indexed in recognized academic databases

Analytical Study of Rake Angle and Tool–Chip Friction Behaviour in Orthogonal Metal Cutting

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https://doi.org/10.55041/ijsmt.v2i5.379

Cite this Article: Anoop, C. (2026). Analytical Study of Rake Angle and Tool–Chip Friction Behaviour in Orthogonal Metal Cutting. International Journal of Science, Strategic Management and Technology, *02*(05). https://doi.org/10.55041/ijsmt.v2i5.379

Abstract: The friction generated between the cutting tool and the work piece is a critical area of study in machining research, as metal cutting involves three major deformation zones: the primary shear zone responsible for chip formation, the secondary shear zone on the rake face where complex tool work piece interaction occurs, and the tertiary zone associated with ploughing and flank contact. Although various analytical, semi-analytical, and numerical models have been developed to study machining behavior, accurate material model parameters and the friction coefficient between the tool and work piece remain essential inputs. Based on literature studies, the friction behavior in metal cutting operations was analyzed using a thermo-mechanical cutting model that considers both sticking and sliding regions on the rake face. The study quantitatively examined the relationship between sliding friction and apparent friction coefficients, identified sliding friction coefficients for different tool work piece combinations through cutting experiments, and investigated the influence of total, sticking, and sliding contact lengths on cutting mechanics. The effects of varying cutting conditions on friction coefficients and contact lengths were also evaluated. In this work, uncoated carbide and coated carbide cutting tools were used to machine aluminum work pieces at cutting speeds ranging from 600 m/min to 1200 m/min with a constant depth of cut of 2 mm. Furthermore, the experimental results related to rake angle and friction behavior during turning operations were optimized using the Taguchi method, where an appropriate orthogonal array was selected to minimize the number of experiments, and the significance of process parameters was analyzed using Minitab software.

Keywords: Friction Coefficient, Thermo-Mechanical Cutting Model, Rake Angle, Taguchi Method, Minitab Software.

I. INTRODUCTION

Metal cutting is a complex machining process in which material is removed as chips to obtain the required dimensional accuracy and surface quality. During this highly non-linear thermo-mechanical process, heat is generated within a small cutting region due to plastic deformation during chip formation and friction between the tool, workpiece, and chip. Chip formation mainly occurs in the primary deformation zone, also known as the shear zone, where the work material bends along the rake face of the cutting tool and experiences high strain and strain rates. The secondary deformation zone involves interaction between the chip and tool through sticking friction, where the chip adheres to the rake face, and sliding friction, where the chip moves across the tool surface. The tertiary deformation zone exists between the clearance face of the tool and the machined surface, primarily due to cutting edge roundness or the formation of a built-up edge.

Machining operations such as turning, milling, boring, and drilling are among the most significant techniques used in discrete part manufacturing. For over a century, researchers have extensively investigated machining processes to achieve a deeper understanding and to develop more advanced manufacturing technologies. Although the study of turning has continued for more than a hundred years, it still receives considerable research attention because turning remains one of the most widely employed machining operations in modern manufacturing industries.

Metal cutting tools are available in a wide variety of shapes, each defined by specific angles and geometries that serve particular purposes in machining operations. The main objective of machining is the efficient removal of chips from the workpiece, making the selection of an appropriate cutting tool geometry highly important. Chip formation is influenced by several factors, including the workpiece material, cutting tool material, machine power and speed, and process conditions such as heat and vibration. In turning operations, insert shape selection involves balancing strength and versatility; larger point angles provide greater strength, as seen in round inserts used for contouring and square inserts for roughing and finishing, while smaller angles such as 35° and 55° offer greater versatility for intricate machining tasks. Several important angles influence how the cutting edge engages with the rotating workpiece, including the angle of inclination, rake angle, effective rake angle, lead or entry angle, and tool nose radius. The angle of inclination refers to the orientation of the insert seat or pocket in the tool holder and may be positive, negative, or neutral. Similarly, the rake angle, defined as the angle between the cutting edge and the cut, can also be positive, negative, or neutral, while the effective rake angle combines the inclination of the tool holder with the rake built into the insert. The lead or entry angle is formed between the cutting edge and the feed direction of the tool, whereas the tool nose radius describes the rounded point of the tool, which may be large for improved strength or sharp for fine-radius turning. Because sharp cutting edges are comparatively weak and susceptible to fracture, inserts are often strengthened through edge preparations such as honed radii, chamfers, lands, or combinations of these features.

II. LITERATURE SURVEY

Markopoulos, Angelos & Karkalos, Nikolaos & Vaxevanidis, Nikolaos & Manolakos, Dimitrios et al. Finite element simulations of orthogonal cutting were employed for the determination of the influence of large negative rake angles on the friction coefficient in the tool-chip interface. The qualitative and quantitative analysis of the tool-chip friction gives an insight on the mechanism of chip formation in processes like machining with chamfered tools, grinding and micromachining. Cutting conditions were selected in order to apply for the aforementioned processes. Negative rake angles varying from -10o to -55o and Coulomb friction with constant friction coefficient were considered in the analysis. The results indicated that friction coefficient is greatly affected by the negative rake angle, exhibiting values well above 1 for the high extreme of the negative rake angle [1].

H.A. Soliman, A.Y. Shash, T.M. El Hossainy, M. Abd-Rabou et al. The cutting force in orthogonal cutting of steel AISI 1045 was predicted by applying 2D finite element analysis (FEA) using two methods; (i) Lagrangian (LAG) and (ii) Arbitrary Lagrangian Eulerian (ALE). Johnson-Cook (J-C) models were used for defining plastic and failure properties of simulated materials. The predicted force was validated experimentally by using dynamometer. Comparison held between the simulation methods and experimental work in terms of results accuracy, reading stability, and chip morphology. Furthermore, this study adopted new modeling idea to control the excessive distortion of mesh elements along chip separation line by defining nearly zero damage criterion for these elements. The results demonstrated that LAG and ALE methods could predict the cutting force but with different accuracy, as LAG and ALE results deviated from experimental results with minimum error percentage 3.6% and 0.14% respectively. As well, ALE method showed stable force readings and continues smooth chip during simulation, while LAG method showed unstable force readings and discontinuous realistic chip [2].

Menezes, P.L., Avdeev, I.V., Lovell, M.R. et al. A fundamental understanding of the tribology aspects of machining processes is essential for increasing the dimensional accuracy and surface integrity of finished products. To this end, the present investigation simulates an orthogonal metal cutting using an explicit finite element code, LS-DYNA. In the simulations, a rigid cutting tool of variable rake angle was moved at different velocities against an aluminum workpiece. A damage material model was utilized for the workpiece to capture the chip separation behavior and the simultaneous breakage of the chip into multiple fragments. The friction factor at the cutting tool–workpiece interface was varied through a contact model to predict cutting forces and dynamic chip formation. Overall, the results showed that the explicit finite element is a powerful tool for simulating metal cutting and discontinuous chip formation. The separation of the chip from the workpiece was accurately predicted. Numerical results found that rake angle and friction factor have a significantly influence on the discontinuous chip formation process, chip morphology, chip size, and cutting forces when compared to the cutting velocity during metal cutting. The model was validated against the experimental and numerical results obtained in the literature, and a good agreement with the current numerical results was found [3].

Storchak M, Stehle T, Möhring H-C et al. Determination of the shear angle by experimental and analytical methods, as well as by numerical simulation, is presented. Experimental determination of the shear angle was performed by analyzing the chip roots obtained by the method of cutting process quick stop through purposeful fracture of the workpiece in the area surrounding the primary cutting zone. The analytical determination of the shear angle was carried out using the chip compression ratio and was based on the principle of a potential energy minimum. Measurement of the shear angle in the numerical simulation of orthogonal cutting was performed using the strain rate pattern of the machined material at the selected simulation moment. It was analyzed how the parameters of the Johnson–Cook constitutive equation and the friction model affect the shear angle value. The parameters with a predominant effect on the shear angle were determined. Then the generalized values of these parameters were established with a software algorithm based on identifying the intersection of the constitutive equation parameter sets. The use of generalized parameters provided the largest deviation between experimental and simulated shear angle values from 9% to 18% and between simulated and analytically calculated shear angle values from 7% to 12% [4].

Ritesh Patidar, Dr. Suman Sharma et al. The process of orthogonal metal cutting is analyzed using the Academic FEA package ANSYS/Explicit 14.5. The focus of the results presented in this paper, effect on tool by different rake angles and depth of cuts in orthogonal metal cutting process. A number of finite element simulations have been done with the ANSYS/Explicit Dynamics 14.5 to initiate the stress variations on tool during orthogonal metal cutting process. A tool rake angle varying from 20^{o}, 25°, 30^{o} and a friction coefficient is constant 0.4 mm and constant cutting speed 2.54 m/s with depths of cut are 0.05, 0.1, 0.15 mm has been considered in the simulations. The results of these simulations provide insight how stresses are influenced by rake angle and depth of cuts [5].

III. METHODOLOGY

The cutting model employed in this study is based on a dual-zone approach to represent the contact between the chip and the tool along the rake face. In this model, originally proposed by Zorev, the contact region is divided into two distinct zones: a sticking region and a sliding friction region. The sticking region experiences plastic contact conditions due to the high normal pressure exerted on the tool, whereas the sliding region is characterized by elastic contact behavior governed by sliding friction. Two different friction coefficients are defined on the rake face: the apparent friction coefficient (μ_a), which accounts for the total cutting forces acting on the rake face, and the sliding friction coefficient (μ), which is associated only with the forces acting within the sliding region. To formulate the cutting forces, the normal pressure distribution along the rake face is considered, using a distribution that has been widely adopted and validated in several previous studies. In this formulation, l_e represents the total contact length, x denotes the distance from the tool tip along the rake face, and ζ is an exponential constant representing the pressure distribution, taken as 3 in the present study based on split-tool test analyses. The model further assumes that the shear stress on the rake face equals the material shear yield stress (τ_1) throughout the sticking region of length l_p, while in the sliding region the shear stress follows Coulomb's friction law and is equal to the product of the sliding friction coefficient and the normal pressure.

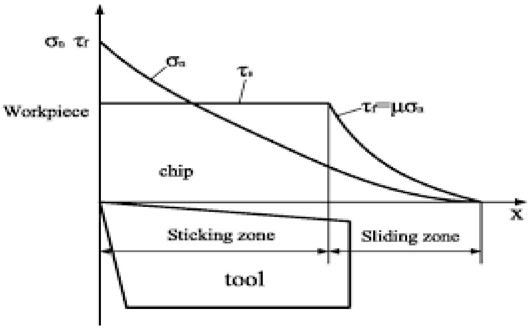


Fig. 1: Stress distribution on the rake face of the tool

The proposed rake contact model can be integrated with any primary shear zone model, provided that the shear stress at the exit of the shear zone is accurately determined. In this work, a thermo-mechanical primary shear zone model is adopted for analysis and prediction purposes. The model assumes that the shear plane maintains a constant thickness and that no plastic deformation occurs before or after the shear plane up to the sticking region on the rake face. Additionally, the material behavior is represented using the Johnson–Cook constitutive model. As the material enters the primary shear zone, it experiences an initial shear stress, which evolves at the exit of the shear zone due to inertia effects. By assuming a constant shear-zone thickness and a uniform pressure distribution, the entrance stress within the shear band can be determined iteratively. Applying the equations of motion for steady-state cutting and continuous chip formation allows the shear stress at the exit of the shear plane to be calculated and subsequently incorporated into the rake contact analysis. The model also provides predictions for important machining parameters such as cutting forces, shear stress distribution, normal pressure distribution along the rake face, and the shear angle.

TAGUCHI METHOD

The Taguchi method defines the quality level of a product in terms of the total loss incurred by society when the product fails to perform according to its intended target performance. This concept of quality extends beyond manufacturing defects and includes costs related to poor product performance, increased operating expenses as the product ages, and additional losses caused by harmful side effects during product usage. According to this philosophy, quality should be measured not only by conformance to specifications but also by the overall impact of the product throughout its lifecycle.

Taguchi Methods: Taguchi methods assist organizations in improving quality by addressing the sources of variability within products and processes. These variations, referred to as noise factors, are undesirable effects that increase inconsistency in performance. The methodology emphasizes extensive problem analysis, the use of interdisciplinary teams, and the application of designed experiments to identify significant factors affecting quality. Experimental results are commonly evaluated using techniques such as Analysis of Variance (ANOVA) and signal-to-noise ratio analysis to determine optimal process conditions.

Defining the Taguchi Approach: The Taguchi approach recognizes that functional variation in products and processes is mainly caused by noise factors. These noise factors are classified into three categories: outer noise, inner noise, and between-product noise. Outer noise includes environmental conditions affecting product performance, inner noise refers to deterioration occurring during the product's lifetime, and between-product noise represents variations occurring from one product unit to another. By understanding and controlling these sources of variation, products can be designed to perform consistently under different operating conditions.

Three Levels of Design: Taguchi proposed three levels of design, namely system design, parameter design, and tolerance design. System design focuses on innovation and the application of scientific and engineering principles to develop new ideas, techniques, materials, and processes. At this stage, tentative parameter values are selected to create an initial product or process concept.

Parameter design is concerned with identifying the best operating conditions for process parameters so that the system becomes less sensitive to noise factors. The primary goal is to develop robust products and processes that maintain high quality without significantly increasing production costs. This stage is considered one of the most important aspects of the Taguchi method because it enhances product reliability and consistency through optimization.

Tolerance design is regarded as the final improvement stage and is applied when further quality enhancement is required. In this stage, the parameters that most strongly influence output variation are identified, and their tolerances are tightened to reduce variability. Although effective, tighter tolerances generally increase manufacturing costs because they may require higher-quality materials, more precise equipment, or stricter production control.

Selecting Parameters for Study and Control: In Taguchi methodology, selecting suitable parameters for analysis is essential. The process begins with identifying the quality characteristic to be improved and defining an appropriate measurement technique. Independent variables are then identified and evaluated using methods such as brainstorming, Dorian Shainin's techniques, and Failure Mode and Effects Analysis (FMEA). Preliminary improvement studies also involve reviewing past performance, comparing current results with desired targets, preparing Pareto charts to identify major causes of problems, and developing process control charts to understand the relationship between control and noise factors.

Robust Design – The Taguchi Philosophy: Robust design is one of the fundamental concepts of the Taguchi philosophy. The approach aims to develop products and services that are inherently high in quality and resistant to variations caused by disturbances. These disturbances may arise from environmental conditions, internal wear and tear, or deviations during production. The Taguchi method uses Design of Experiments (DOE) techniques to determine the optimal combination of input factors that will produce the best performance under varying conditions.

The robust design methodology consists of three stages: concept design, parameter design, and tolerance design. Concept design involves evaluating competing technologies and creating a prototype capable of satisfying customer requirements under ideal conditions. Parameter design focuses on selecting optimal control factors and their levels to minimize the influence of noise factors. Tolerance design establishes specification limits for production variables and is implemented after parameter optimization has been completed.

Background of the Taguchi Method: The Taguchi method was introduced by Genichi Taguchi in the 1980s and became one of the most influential approaches in quality engineering, comparable to Statistical Process Control (SPC), the W. Edwards Deming approach, and Total Quality Control (TQC). One of the unique features of the Taguchi philosophy is its definition of quality and the introduction of the Taguchi Quality Loss Function (QLF). Unlike traditional quality concepts, which consider products acceptable if they remain within specification limits, the Taguchi approach states that any deviation from the target value results in quality loss. Therefore, ideal quality is achieved only when product performance exactly matches the target value throughout the product's intended life under normal operating conditions.

The Taguchi Quality Loss Function: The Taguchi Quality Loss Function explains that quality loss increases as product performance deviates from the target value, even if the product remains within specification limits. In contrast to traditional quality models that assume no loss occurs within tolerance boundaries, the Taguchi approach emphasizes continuous improvement toward the exact target. This philosophy highlights the importance of minimizing variability rather than merely satisfying specifications.

The Taguchi Process: The Taguchi process consists of several systematic steps beginning with problem identification. The objective is to locate the root cause of the problem rather than only addressing visible symptoms. This is followed by brainstorming sessions involving project leaders, workers, managers, and technical staff to identify critical process variables, factor levels, and possible interactions among factors. During this stage, objectives such as "smaller-the-better," "nominal-is-best," or "larger-the-better" are also established depending on the desired quality characteristic.

The next stage is experimental design, where suitable orthogonal arrays and experimental conditions are selected. Taguchi strongly advocates off-line experimentation instead of in-process experimentation to improve product and process design before actual production. After conducting the experiments, the results are analyzed using statistical techniques such as ANOVA and regression analysis. The optimal factor levels identified from the experiments are then verified through confirmation experiments, where all parameters are set at their predicted optimal values to validate the results.

The Taguchi Approach to DOE: Traditional Design of Experiments mainly focused on understanding how design factors affect the average response of a process. In contrast, the Taguchi approach emphasizes reducing variation and improving robustness. Experiments are conducted by varying both controllable design factors and uncontrollable noise factors at different levels. For each combination of design variables, multiple experiments are performed under varying signal conditions to estimate both average performance and variability.

By analyzing these results, engineers can identify the combination of factor levels that minimizes sensitivity to disturbances and produces the most robust design. The experimental outcomes provide average response values as well as measures of variation, which serve as the basis for selecting optimal process settings capable of maintaining consistent product quality under diverse operating conditions.

Fig. 2: Experimental Setup 1

Experimental Investigation: The experimental results and analysis of the friction behavior for work piece material aluminium and cutting tool materials Uncoated Carbide and Coated Carbide are presented .Cutting tool materials-Uncoated Carbide and Coated Carbide
Work piece material – aluminium
Feed – 0.16 mm/rev
Cutting speed – 600 m/min to 1200 m/min
Depth of cut – 2mm.

Fig. 3: Experimental Setup 2

IV. RESULTS

Friction Test Results: The apparent and sliding friction coefficients that are identified by the proposed model from the orthogonal tube cutting tests are presented with respected tables, and discussed for case; aluminium with different cutting tools is presented. All the cutting tests are conducted in orthogonal conditions with rake angle of 5° and without inclination and side edge cutting angles. Uncoated and coated carbide rods are used for the tests conducted in this study the depth of cut is selected as 2mm.

Table 1: Cutting Speeds and Apparent Friction Coefficients for Aluminium with Uncoated Carbide Tool

Cutting Speed (m/min)	Apparent Friction Coefficient
200	0.39
300	0.42
400	0.35
500	0.64
600	0.37
700	0.34
800	0.31

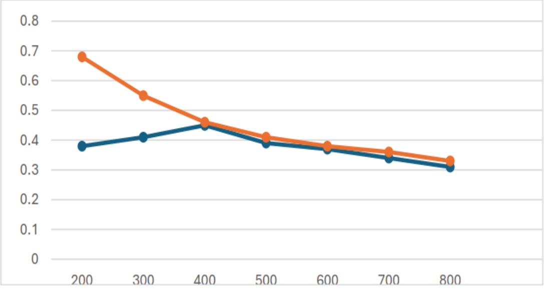


Fig. 4: Cutting speeds and apparent friction coefficients for aluminium with coated carbide tool

From the results presented in the graph, it can be concluded that the friction characteristics vary for different cutting tools. The sliding friction coefficient between the uncoated carbide tool and aluminium shows only a weak dependence on friction speed, although a slight reduction in the coefficient of friction is observed at moderate speeds. In contrast, the sliding friction coefficient between the carbide tool and Mild Steel decreases significantly as the cutting speed increases. Overall, the results indicate that the sliding friction coefficient decreases with increasing cutting speed for all cutting tools, which can be attributed to the rise in temperature at the tool–workpiece contact interface.

First Taguchi Orthogonal Array is designed in Minitab15 to calculate S/N ratio and Means which steps is given below:

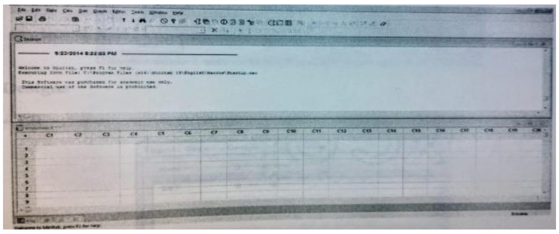
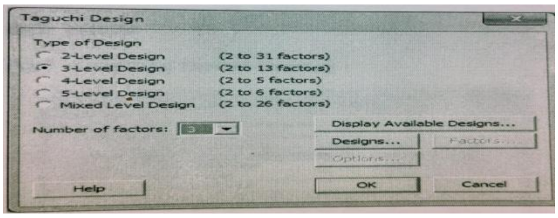


Fig. 5: Orthogonal Array Window

Start – DOE – Taguchi – Create Taguchi Design
Select 3 – Level Design
Number of factors – 3

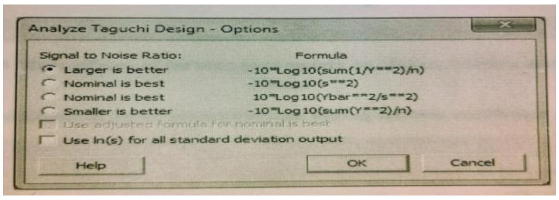


Taguchi Design

Type of Design
○ 2-Level Design (2 to 31 factors)
● 3-Level Design (2 to 13 factors)
○ 4-Level Design (2 to 5 factors)
○ 5-Level Design (2 to 6 factors)
○ Mixed Level Design (2 to 26 factors)

Number of factors: 3

Fig. 6: Taguchi design window



Analyze Taguchi Design - Options

Signal to Noise Ratio:	Formula
● Larger is better	-10*Log10(sum(1/Y**2)/n)
○ Nominal is best	-10*Log10(s**2)
○ Nominal is best	10*Log10(Ybar**2/s**2)
○ Smaller is better	-10*Log10(sum(Y**2)/n)

☐ Use adjusted formula for nominal is best
☐ Use ln(s) for all standard deviation output

Fig. 7: Analyzation of Taguchi design options

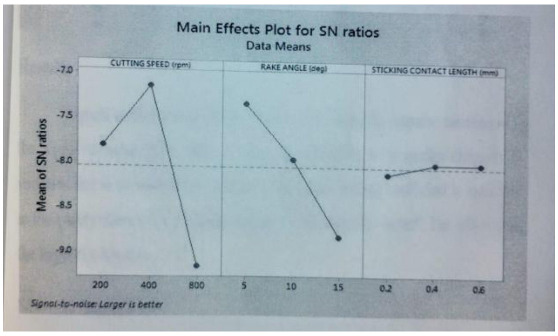
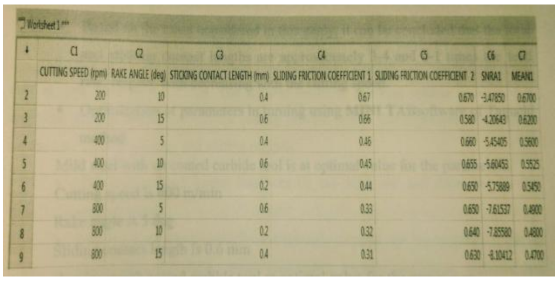


Fig. 8: Main effects of turning parameters on sliding friction co efficient for S/N ratio

The Taguchi method emphasizes the importance of analyzing response variation through the signal-to-noise (S/N) ratio in order to minimize variations in quality characteristics caused by uncontrollable factors. In this study, the sliding friction coefficient is considered as the quality characteristic under the "larger-the-better" criterion.



Worksheet 1 ***

↓	C1	C2	C3	C4	C5	C6	C7
	CUTTING SPEED (rpm)	RAKE ANGLE (deg)	STICKING CONTACT LENGTH (mm)	SLIDING FRICTION COEFFICIENT 1	SLIDING FRICTION COEFFICIENT 2	SNRA1	MEAN1
2	200	10	0.4	0.67	0.670	-3.47850	0.6700
3	200	15	0.6	0.66	0.580	-4.20643	0.6200
4	400	5	0.4	0.46	0.660	-5.45405	0.5600
5	400	10	0.6	0.45	0.655	-5.60453	0.5525
6	400	15	0.2	0.44	0.650	-5.75889	0.5450
7	800	5	0.6	0.33	0.650	-7.61537	0.4900
8	800	10	0.2	0.32	0.640	-7.85580	0.4800
9	800	15	0.4	0.31	0.630	-8.10412	0.4700

Fig. 9: The sliding friction coefficients and their corresponding S/N ratio values

The S/N ratio values were calculated using Minitab 15 software based on the experimental measurements obtained from each trial.

V. CONCLUSION

The study investigated the influence of rake angle on tool–chip friction behavior in orthogonal metal cutting through analytical and experimental methods. The results showed that increasing the rake angle reduces cutting forces, improves chip flow, increases the shear angle, and enhances chip formation, thereby improving machining efficiency and reducing energy consumption. Higher rake angles also decrease tool–chip friction and heat generation due to reduced contact area, which contributes to better tool life. However, excessively high rake angles may weaken the cutting edge, indicating that an optimum rake angle is necessary to balance machining performance and tool strength.

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