Predictive Modeling and Validation of Cutting Tool Parameters in Various Machining Processes: An Industrial Study with Kennametal

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Abstract— ***Machining operations form the backbone of manufacturing industries, demanding optimization of cutting tool parameters to ensure product quality, cost efficiency, and sustainability. This study presents a predictive modeling and experimental validation framework for cutting tool parameters across various machining processes, including turning, milling, and drilling. In collaboration with Kennametal, cutting speeds, feed rates, and depths of cut were predicted, and experimental trials were conducted on AISI 4140 steel using carbide tools on a 5-axis DMU CNC machining center. Results show that optimized tool geometry, rake angle, and feed significantly impact surface finish, cutting forces, and tool wear. The developed model bridges the gap between theoretical predictions and practical performance, offering a reliable method for intelligent machining optimization in real-world manufacturing environments.***

Keywords— Machining processes; Cutting tool parameters; Predictive modeling; AISI 4140 steel; Kennametal; Surface roughness; Tool wear; CNC machining

I. INTRODUCTION

Manufacturing industries have continuously evolved, with machining processes such as turning, milling, and drilling playing a pivotal role in shaping and finishing components with high precision. Central to these operations is the selection and optimization of cutting tool parameters, including tool material, geometry, cutting speed, feed rate, and depth of cut. Optimizing these parameters ensures not only superior surface quality but also prolonged tool life and improved production efficiency.

Cutting tool parameters directly influence machining outcomes such as chip formation, cutting forces, temperature generation, tool wear, and surface finish. Improper parameter selection can result in excessive vibrations, poor dimensional accuracy, and premature tool failure. With the emergence of high-strength materials such as hardened steels and titanium alloys, the traditional trial-and-error method for tool selection has become increasingly inadequate.
Modern manufacturing demands require predictive, data-driven models to forecast tool behavior and machining performance accurately. Predictive modeling leverages historical data, simulation, and empirical experimentation to pre-emptively determine the outcomes of machining operations. This shift allows industries to reduce operational downtime, minimize material waste, and enhance product quality.

While theoretical models and tooling handbooks offer general guidelines for cutting parameters, they often fall short in real-world applications where machining conditions are highly variable. This project aims to develop a predictive and validated framework for optimizing cutting tool parameters across multiple machining operations, minimizing the gap between theory and industrial practice.

II. LITERATURE SURVEY

Pham Minh Duc, Le Hieu Giang, Mai Duc Dai, and Do Tien Sy. "An Experimental Study on the Effect of Tool Geometry on Tool Wear and Surface Roughness in Hard Turning."
This study investigates the influence of tool geometry (cutting edge angle, rake angle, and inclination angle) on tool wear and surface roughness in hard turning of AISI 1055 (52HRC) hardened steel using TiN-coated mixed ceramic inserts. The results show that the inclination angle is the major factor affecting tool wear and surface roughness. The optimal cutting tool angles in the research led to significant improvements in the hard machining process, with surface roughness and tool wear decreasing by 8.3% and 41.3%, respectively, compared to standard tool angles.

Joseph Emmanuel and Rahul Davis. "An Experimental Study of the Effect of Control Parameters on the Surface Roughness in Turning Operation of EN 353 Steel."
This paper investigates the effect of cutting parameters such as cutting speed, feed rate, and depth of cut on surface roughness in the turning operation of EN 353 steel. The Taguchi method is employed to determine the optimum cutting conditions for minimizing surface roughness. The study highlights that the Taguchi design of experiments helps identify the best quality parameters, and the selected predictive equations were verified with confirmation tests that showed their accuracy within the measurement limits.

Mustafa Ozdemir, Abidin Sahinoglu, Mohammad Rafighi, and Volkan Yilmaz. "Analysis and Optimisation of the Cutting Parameters Based on Machinability Factors in Turning AISI 4140 Steel."
This experimental study evaluates the machinability of AISI 4140 steel using coated carbide inserts, focusing on cutting forces, surface roughness, and other machinability factors. The study used the Taguchi L9 orthogonal array at three different cutting speeds, feed rates, and cutting depths. The depth of cut was found to have the highest impact on sound intensity, while cutting speed and feed rate affected the other output parameters.

A. Kriyadeesh, P. Srinivas Rao, and C. Labesh Kumar. "Optimization of Input Parameters with Carbide Inserts and HSS Tool on CNC Turning of EN19 Steel."
This study compares carbide inserts and HSS tools for CNC turning of EN19 steel. The results show that carbide inserts offer better performance in terms of surface quality, material removal rate, and tool wear. The study found that the surface roughness increased with higher feed rates, while spindle speed and depth of cut positively affected material removal rate. Tungsten carbide inserts experienced more wear compared to cemented carbide inserts.

Ogur Iynen, Abidin Sahinoglu, Mustafa Ozdemir, and Volkan Yilmaz. "Optimization of the Effect of Cutting Parameters on the Cutting Force in the Gradual Turning Process by Taguchi Method."
In this paper, AISI 4140 steel was subjected to machining experiments to investigate the effect of cutting parameters on cutting forces (radial force, tangential force, and feed force). The study used a Taguchi L9 orthogonal array to analyze three cutting speeds, feed rates, and cutting depths. The results showed that the feed rate primarily affected the radial and tangential forces, while the depth of cut influenced the feed force. The optimization was successful, with confirmation experiments showing significant improvements.

Geeta, Mukesh Kumar, and Kushal Goel. "Tool Life Comparison and Optimization on Different Cutting Tool Parameters on CNC Turning for Coated & Uncoated Cutting Tool Insert."
This paper compares the tool life of coated and uncoated cutting tool inserts in CNC turning. Three cutting parameters—cutting speed, feed rate, and depth of cut—were parameterized using Taylor's life equation. The study concluded that the optimized tool parameters enhance tool life, reduce manufacturing costs, and improve machining efficiency.

Nexhat Qehaja and Fitore Abdullah. "Mathematical Modeling of the Influence of Cutting Parameters and Tool Geometry on Surface Roughness During Drilling Process."
This study examines the influence of drilling parameters, including cutting speed, feed rate, drill diameter, and drill point angle, on the surface roughness of EN 1.0038 steel during wet drilling using TiN-coated HSS drills. The findings suggest that cutting speed and drill diameter are the primary factors affecting surface roughness.

Bhushan Nikam, Avinash Khadtare, and Raju Pawade. "Machinability Assessment of AISI 4140 Hardened Steel Using CBN Inserts in Hard Turning."
This paper investigates the machinability of AISI 4140 steel using CBN inserts, focusing on tool life, cutting forces, and surface roughness. The results show that cutting speed and feed rate significantly impact the cutting forces, with the lowest cutting force observed at a cutting speed of 200 m/min and feed rate of 0.15 mm/rev.

Pradeesh A. R., Mubeer M. P., Nandakishore B., Muhammed Ansar K., Mohammed Manzoor T. K., and Muhammed Raees M. U. "Effect of Rake Angles on Cutting Forces for a Single Point Cutting Tool."
This study explores the effect of rake angle on cutting forces during machining. It was found that increasing the rake angle reduces cutting forces and improves surface finish, while negative rake angles increase forces and heat generation. The feed rate and depth of cut also play critical roles in determining cutting forces.

M. Sivaramakrishnaiah, P. Nanda Kumar, and G. Ranga Janardhana. "Prediction of Cutting Forces in Turning of AISI-4140 Steel Using FEA and Experimental Validation."
This paper discusses the use of Finite Element Analysis (FEA) to predict cutting forces in turning AISI 4140 steel. The study integrates experimental data with simulations using the Johnson–Cook model to predict temperature, stress, strain, and force distributions during machining. The results highlight the reliability of FEA in predicting machining outcomes and improving process optimization.

III. METHODOLOGY

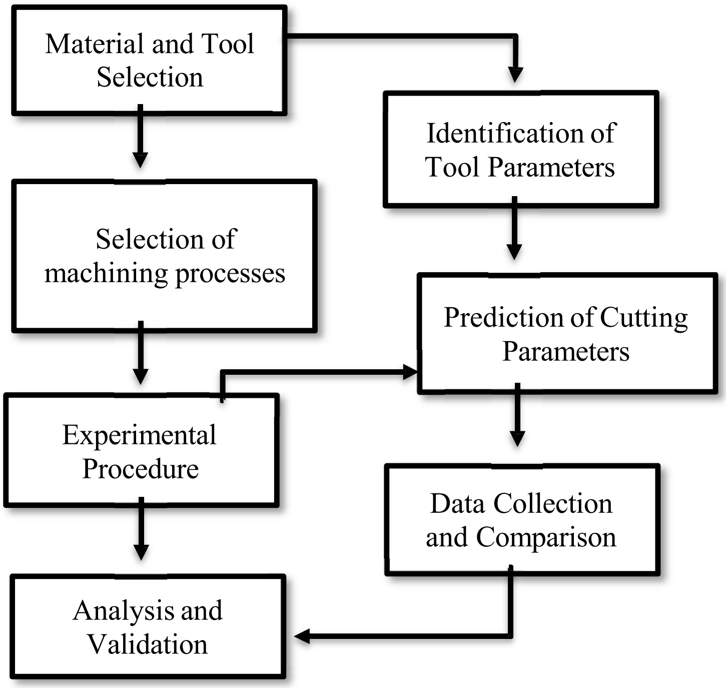

Fig.1 , The overview of our Project

Material and Tool Selection

AISI 4140 steel was selected as the workpiece material for its widespread industrial use, excellent machinability, and mechanical robustness. It offers a good balance between strength, toughness, and fatigue resistance, making it ideal for studying tool behavior under realistic machining conditions.
Cutting tools were selected from Kennametal's catalogue, comprising:

- Solid carbide end mills for milling operations.
- Insert-based carbide tools for turning and grooving operations.
- Specific tool geometries (rake angles, clearance angles, nose radii) were chosen to study their influence on machining performance.

Material and tool properties were confirmed through technical datasheets and validated through preliminary trial tests.

Identification of Key Tool Parameters

The following critical tool parameters were identified for investigation:

- Rake angle (positive and negative)
- Clearance angle
- Tool nose radius
- Tool material and coatings

Additionally, cutting process parameters were considered:

- Cutting speed (Vc) (m/min)
- Feed rate (f) (mm/rev)
- Depth of cut (ap) (mm)

These parameters were selected based on their dominant influence on tool wear, cutting forces, surface roughness, and chip formation behavior.

Selection of Machining Processes
Three core machining processes were studied:

- Turning: For cylindrical component shaping.
- Milling: For flat surfaces and complex profiles.
- Drilling: For hole-making operations.

Each process allowed different aspects of tool performance to be tested under controlled conditions.

Prediction of Cutting Parameters
Initial cutting parameters were predicted using:

- Manufacturer recommendations (Kennametal product guides).
- Standard machining handbooks.
- Empirical formulas considering workpiece hardness and tool material capabilities.

The general predictive formula used for cutting speed, for instance, was:
Vc=πDN1000V_c = \frac{\pi D N}{1000}Vc=1000πDN
where:

- VcV_cVc = Cutting speed (m/min)
- DDD = Workpiece diameter (mm)
- NNN = Spindle speed (RPM)

Feed rate and depth of cut values were initially set based on previous successful machining data of AISI 4140 and adjusted for each tool geometry.

Experimental Procedure
Machining trials were performed on a DMU 65 monoBLOCK 5-axis CNC machining center, equipped with:

- Automatic Tool Changer (ATC)
- Integrated probing systems for tool offset and part alignment
- Coolant systems for controlled temperature environments

For each test:

- New inserts were used to eliminate pre-existing wear.
- Tool offsets and workpiece coordinates were precisely calibrated.
- Machining parameters (cutting speed, feed rate, depth of cut) were varied systematically.
- Tool wear, surface roughness, and cutting forces were recorded.

Instrumentation included:

- Dynamometer for cutting force measurement.
- Surface profilometer for surface roughness (Ra) evaluation.
- Coordinate Measuring Machine (CMM) for dimensional accuracy checks.

Data Collection and Analysis
During and after machining trials, the following data was collected:

- Radial, tangential, and axial cutting forces.
- Tool wear patterns (flank wear, crater wear).
- Surface roughness values (Ra).
- Chip morphology observations.

Statistical analysis tools were employed to:

- Compare predicted and actual machining results.
- Evaluate significance using Analysis of Variance (ANOVA).

IV. FUNDAMENTALS

Basics of Machining

Machining is a material removal process wherein unwanted material is removed from a workpiece to achieve the desired shape, dimension, and surface finish. The material removal occurs primarily through the formation of chips, generated by the relative motion between the cutting tool and the workpiece.

Key elements influencing machining outcomes include:

- Workpiece material properties
- Cutting tool material and geometry
- Machine tool capabilities
- Cutting conditions such as speed, feed, and depth of cut
- Use of cutting fluids

Types of Machining Processes Studied

Turning: The workpiece rotates while the tool moves linearly to generate cylindrical shapes.
(e.g., shafts, bushings)

Milling: A rotating multi-point cutting tool removes material by advancing into the workpiece, producing flat surfaces, slots, and contours.

Drilling: A rotating tool with cutting edges at its tip creates round holes in the workpiece.

Each process demands different cutting mechanics and tool interactions with the material.

Machining Input Parameters

The primary input parameters that affect machining performance are:

- Cutting Speed (Vc):
  Speed at which the cutting edge engages the workpiece, typically measured in meters per minute (m/min).
- Feed Rate (f):
  Distance the tool advances into the material per revolution or per unit time.
- Depth of Cut (ap):
  Thickness of the material layer removed in one pass.
- Tool Geometry:
  Defined by rake angle, clearance angle, nose radius, and edge preparation.
- Tool Material and Coatings:
  Materials such as carbide, cermet, CBN (Cubic Boron Nitride), with coatings like TiN, AlTiN, enhance wear resistance and cutting efficiency.
- Coolant/Lubrication:
  Application of fluid reduces heat generation, lowers cutting forces, and improves surface integrity.

Machining Output Parameters

The critical outcomes measured in machining operations include:

- Cutting Forces:
  Radial (Fr), tangential (Ft), and axial (Fa) forces experienced during cutting. Tangential force is usually dominant.
- Material Removal Rate (MRR):
  Volume of material removed per unit time, a direct indicator of productivity.
- Surface Roughness (Ra):
  Fine irregularities left on the machined surface, critical for component performance.
- Tool Wear:
  Gradual degradation of the tool's cutting edge due to friction, heat, and mechanical stress.

V. EXPERIMENTAL SETUP

The experimental trials were conducted using a DMU 65 monoBLOCK 5-axis CNC machining center, selected for its high precision, flexibility, and ability to perform multiple operations such as turning, milling, and drilling within a single setup.

Machine Specifications:

- Max. X-axis travel: 735 mm
- Max. Y-axis travel: 650 mm
- Max. Z-axis travel: 560 mm
- Max. Workpiece diameter: 840 mm
- Max. Workpiece weight: 1000 kg
- Controller: Siemens

The machine was equipped with an Automatic Tool Changer (ATC) and touch probes for accurate tool offset and part alignment.

Workpiece and Tool Details

Workpiece Material:

- AISI 4140 alloy steel (annealed)
- Tensile strength: 655 MPa
- Hardness: 28–32 HRC
- Key elements: Chromium, Manganese, Molybdenum

Cutting Tools:

- Solid carbide end mills for milling.
- Kennametal carbide inserts for turning and grooving.
- Insert rake angles varied: 0°, 8°, 10°, 12°, 14°, 16°, 18°.

All tools used were new to maintain consistent initial conditions.

Cutting Conditions Range:

- Cutting Speed (Vc): 200–800 m/min
- Feed Rate (f): 0.3–0.5 mm/rev
- Depth of Cut (ap): 0.5–1 mm
- Coolant: Water-soluble coolant applied during all trials.

Design of Experiments (DoE)

A systematic Design of Experiments was employed:

- Each parameter (speed, feed, depth of cut) was varied while holding others constant.
- Machining trials were repeated for different rake angles to evaluate its impact on cutting forces and surface finish.
- Taguchi L9 orthogonal array was referenced for experimental combinations to minimize trial numbers while covering all key factors.

Data recorded during experiments included:

- Radial, tangential, and axial cutting forces using a dynamometer.
- Surface roughness (Ra) using a contact stylus profilometer.
- Visual inspection and measurement of tool wear.

Observations and Measurements

- Chip Morphology: Changes observed from discontinuous to continuous chip flow with increasing positive rake angles.
- Surface Roughness (Ra): Lower Ra values were achieved with higher positive rake angles and reduced feed rates.
- Cutting Forces: Tangential force dominated, followed by feed and radial forces. Higher rake angles reduced cutting forces significantly.
- Tool Wear: Lower wear rates observed with optimal rake angles and moderate feed rates, indicating less mechanical and thermal loading.

VI. PROTOTYPING

Influence of Feed Rate

Feed rate showed a direct and significant influence on cutting forces and surface roughness:

- Higher feed rates led to increased cutting forces, especially the tangential and feed components.
- Surface roughness worsened with increasing feed, as larger feed values generated deeper feed marks on the machined surface.
- Higher feed rates also contributed to increased tool wear due to higher mechanical loading.

Key Observation:

Feed rate was the most dominant parameter influencing both cutting force magnitude and surface texture.

Effect of Rake Angle

Variation of rake angle profoundly impacted chip formation, cutting forces, and surface finish:

- Increasing the rake angle (making it more positive) significantly reduced cutting forces.
- Positive rake angles promoted smoother chip flow, reducing friction and cutting temperature.
- Surface roughness improved with positive rake angles, reaching minimum Ra values around 14°–18° rake.
- Tool wear decreased for positive rake angles due to better chip evacuation and lower heat buildup.

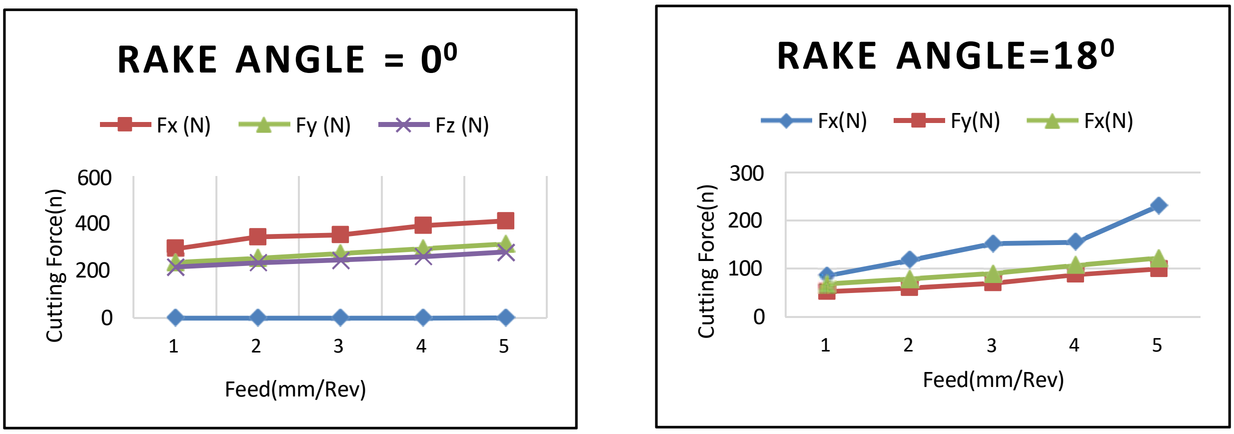

Fig.2 Variation of cutting forces with feed rate with different rake angle

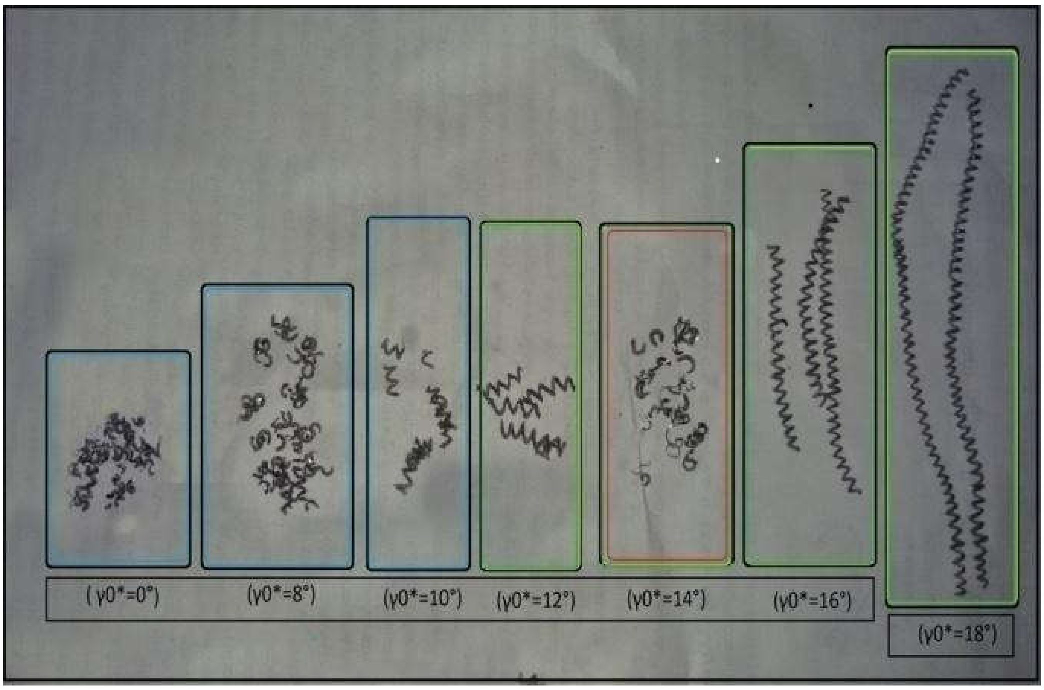

Fig.3 Variation of chip pattern with rake angle

Key Insight:
Optimizing the rake angle is crucial for balancing tool strength and cutting efficiency.

Impact of Cutting Speed
Cutting speed also influenced machining dynamics:

- Higher cutting speeds generally reduced cutting forces due to thermal softening of the workpiece material.
- Surface finish tended to improve at moderate cutting speeds but deteriorated at excessively high speeds due to thermal instability and tool wear acceleration.
- Tool wear mechanisms changed with speed — abrasive wear dominated at lower speeds, while diffusion wear became significant at higher speeds.

Key Trend:
Optimal cutting speeds (600–800 m/min for AISI 4140) offered the best balance between productivity and surface integrity.

Surface Roughness Analysis
Surface roughness (Ra) was strongly linked to feed rate and tool geometry:

- Low feed rates combined with positive rake angles produced surface roughness values below 2.0 µm, suitable for high-precision applications.
- At higher feed rates or with lower rake angles, Ra increased beyond 3.0 µm, indicating rougher finishes.

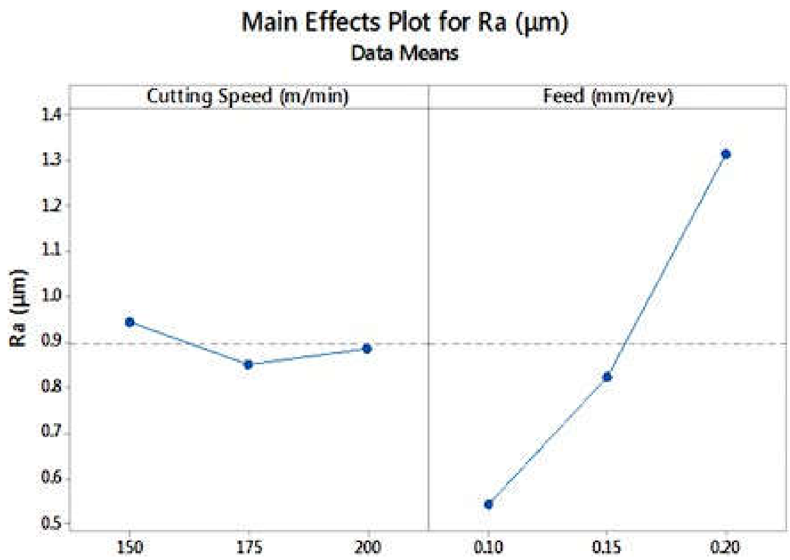

Fig 4:Main effects plot for surface roughness

VII. CONCLUSION

This study successfully developed and validated a predictive modeling framework for optimizing cutting tool parameters across various machining processes — turning, milling, and drilling — with a special focus on AISI 4140 steel.

Key conclusions drawn from the experimental investigation are:

Feed rate emerged as the most significant factor influencing cutting forces and surface finish. An increase in feed rate resulted in higher cutting forces and poorer surface quality.

Rake angle optimization played a crucial role in reducing cutting forces and improving surface roughness. Positive rake angles (14°–18°) provided the best balance between tool strength and machining efficiency.

Cutting speed had a secondary yet important effect: higher speeds reduced forces but required careful management to avoid excessive thermal wear.

Tool wear patterns indicated that flank wear was dominant and could be minimized through appropriate selection of rake angle and moderate feeds.

The predictive model built for cutting forces and surface roughness showed strong correlation with experimental data, confirming its practical reliability with error margins within ±10%.

Overall, the study demonstrates that a data-driven approach for tool parameter prediction, supplemented by real-world validation, can significantly enhance machining efficiency, tool life, and part quality.

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