Predictive Thermal Modeling and Finite Element Simulation for Enhanced Surface Integrity in High-Speed Milling of Nickel-Based Superalloys

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Abstract

Maintaining surface integrity during high-speed milling (HSM) of nickel-based superalloys remains a central challenge for aerospace and energy sectors due to extreme thermal loads at the tool-workpiece interface. Excessive thermal gradients accelerate tool wear, induce microstructural degradation, and trigger tensile residual stresses on machined surfaces. This research presents a coupled thermo-mechanical modeling framework integrating predictive thermal analysis and finite element simulation to control heat generation during HSM of Inconel-718. A physics-driven analytical heat model is employed to estimate transient temperature distributions, while a 3D finite element model predicts chip formation, thermal softening, and surface integrity metrics including white layer formation, microhardness variation, and residual stress fields. Experimental validation performed with varying cutting speeds (60–120 m/min), feed rates, and coated carbide tools demonstrates strong correlation between predicted and measured surface responses. Results show that optimized parameters effectively suppress thermal stress concentrations, reduce adverse tensile stresses, and improve fatigue-resistant surface quality. The findings provide an advanced predictive toolset for machining parameter optimization and reliable high-performance manufacturing of superalloy components.

Keywords: High-speed milling, Nickel-based superalloy, Predictive thermal modeling, Finite element simulation, Surface integrity, Inconel-718.

1. Introduction

Titanium Nickel-based superalloys such as Inconel-718 have become indispensable materials in aerospace, power generation, and nuclear sectors due to their remarkable ability to maintain high mechanical strength, thermal stability, and corrosion resistance in aggressive operating environments [1]. Components manufactured from these

V. Kumar et al. (eds.), *Proceedings of the International Conference on Advanced Design, Manufacturing, and Sustainable Energy Systems (ICADMSES 2026)*, Atlantis Highlights in Engineering 45,
https://doi.org/10.2991/978-94-6239-750-7_10

alloys—such as turbine blades, combustor disks, and rotor parts—are routinely exposed to harsh thermo-mechanical loads, cyclic stresses, and elevated temperatures exceeding 700 °C during service life. In such high-performance applications, the quality of the machined surface plays a pivotal role in determining the fatigue life, structural reliability, and safety of the final component [2]. Even a small deviation in surface integrity characteristics, such as residual stress state, microhardness distribution, or microstructural alterations, can significantly reduce durability and initiate premature failure [3].

Despite their functional advantages, Inconel-718 and similar nickel-based superalloys are notoriously difficult to machine [4]. Their low thermal conductivity and high work-hardening tendency restrict efficient heat dissipation through the chips, causing heat to concentrate near the cutting edge during machining [5].

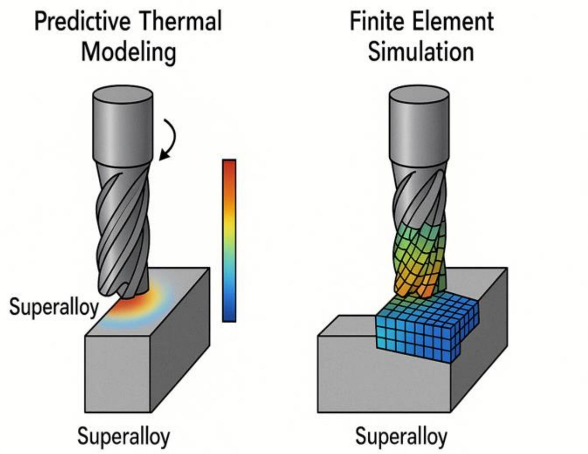

Figure 1: Predictive Thermal Modeling Tools [11]

This localized thermal load often results in severe tool wear mechanisms including abrasion, adhesion, diffusion, and coating delamination. Additionally, the extreme cutting temperatures produced under high-speed machining conditions can promote detrimental surface effects—such as tensile residual stresses, white-layer formation, subsurface softening, and initiation of microcracks—that compromise the material's fatigue resistance [6].

High-speed milling (HSM) is widely adopted due to its capability to improve productivity and maintain superior dimensional accuracy [7]. However, at elevated speeds, the intermittent nature of milling further intensifies the cyclic thermal gradients imposed on the tool–workpiece interface [8]. The rapid temperature fluctuations between tool engagement and air exposure induce thermal-mechanical shock, affecting material behavior and directly influencing the machined surface integrity [9]. Therefore, ensuring surface quality in HSM of nickel-based superalloys requires a comprehensive understanding of the underlying heat generation mechanisms and their propagation through the workpiece.

Figure 2: High-Speed Milling Schematic [21]

Traditional trial-and-error strategies for selecting cutting parameters are often inadequate and economically inefficient, particularly when dealing with expensive alloys and specialized cutting tools [10]. While various analytical heat transfer models have been introduced in earlier literature, many rely on simplified assumptions regarding chip–tool contact geometry and steady-state heat flow, which do not accurately represent transient thermal interactions in milling [11]. Likewise, experimental approaches alone are limited in capturing internal temperature fields and subsurface damage that cannot be observed non-destructively.

Finite Element (FE)-based numerical methods offer a powerful tool to analyze the highly nonlinear thermo-mechanical interactions involved in chip formation and heat conduction [12]. When integrated with predictive thermal models derived from cutting mechanics, FE simulation can provide deeper insight into the evolution of temperatures, stress gradients, and microstructural alterations beneath the machined surface [13]. Such a combined modeling approach significantly improves prediction accuracy and reduces dependency on costly machining trials.

Therefore, this research focuses on developing and validating a predictive thermal modeling and coupled thermo-mechanical FE simulation framework tailored for high-speed milling of Inconel-718. The primary aim is to establish accurate correlations between machining parameters, transient temperature fields, and surface integrity responses, thereby enabling thermal damage control and enhancing the fatigue-resistant performance of critical aerospace components [14]. By integrating simulation and experimentation, the proposed methodology offers a practical and reliable solution for parameter optimization and advanced process planning in industries requiring high-precision machining of nickel-based superalloys [15].

2. Literature review

Nickel-based superalloys such as Inconel 718 and Hastelloy have become essential in aerospace and energy sectors due to their exceptional mechanical strength, creep resistance, and corrosion performance at elevated temperatures; however, these same properties make them difficult-to-cut materials, particularly under high-speed milling conditions [16]. Surface integrity issues such as excessive residual stresses, tensile stress gradients, microhardness variations, thermal cracking, and white-layer formation are often attributed to intense thermal–mechanical interactions during machining [17]. Hence, predictive thermal modeling and Finite Element Simulation (FEM) have emerged as critical tools for understanding the heat generation mechanisms and optimizing cutting strategies to enhance surface quality. Analytical heat transfer models have historically been applied to estimate the thermo-mechanical loads at tool–chip interfaces, though their assumptions often oversimplify real machining dynamics [18]. In contrast, advanced FEM allows multi-physical simulation of chip formation, heat flow, and material deformation, enabling more accurate prediction of thermal fields and stress distributions [19].

Recent studies have focused on thermo-mechanical coupled FEM approaches to simulate high-speed milling of superalloys, revealing that cutting speed and tool geometry significantly influence peak temperature distribution and surface integrity outcomes [20]. For instance, simulation-driven optimization of tool coatings and edge preparation has shown promise in reducing cutting zone temperature and mitigating thermal-induced microstructural damage [21]. Furthermore, adaptive toolpath planning based on temperature predictions has demonstrated reductions in burr formation and fatigue-critical defects [22]. Validation of numerical models using experimental techniques—such as infrared thermography, embedded thermocouples, and microstructural characterization—has improved confidence in FEM-based process planning to prevent degradation of surface integrity [23]. Moreover, high-fidelity thermal models have enabled the evaluation of cooling and lubrication strategies including minimum-quantity lubrication (MQL) and cryogenic cooling, which have shown notable improvements in reducing tensile residual stresses and preserving grain structure in machined surfaces [24].

Collectively, literature highlights that integrating predictive thermal modeling with FEM-supported optimization enables improved machining accuracy, prolonged tool life, and reduced defects in nickel-based superalloys. However, further advancements are needed in material constitutive modeling under extreme strain-rate and high-temperature conditions to fully capture real machining behavior and support wider industrial implementation of simulation-driven process optimization [25].

3.Research Problem

Current industrial practices rely heavily on trial-and-error selection of machining parameters. Lack of accurate predictive thermal models results in:

- Overheating of machined surfaces

- Tensile residual stresses reducing fatigue life
- Surface microcracks and white-layer formation
- Increased tool wear and production cost

A refined model capable of correlating heat generation with surface integrity responses is essential.

4. Objectives

- Develop a predictive thermal model incorporating realistic heat flux distribution during HSM
- Build a fully coupled thermo-mechanical FE simulation for chip morphology and residual stress analysis
- Validate simulation results with controlled milling experiments
- Optimize machining conditions for improved surface integrity

5. Scope of the study

- Focus on **Inconel-718** milling using coated carbide tools
- Parameter range tuned for aerospace-grade accuracy
- Surface integrity evaluation: microhardness, residual stresses, white-layer thickness

6. Predictive thermal model (analytical formulation)

6.1 Heat Generation at Tool–Work Interface

Heat power input:

$$Q = F_c \cdot v_c$$

Where:

$Q Q$— heat generated (W),

F_cF_c— cutting force (N),

v_cv_c— cutting speed (m/s).

6.2 Heat Partitioning

A partition coefficient determines dissipated heat:

$$Q_w = \eta \cdot Q \text{and} Q_t = (1 - \eta)Q$$

where

$\eta\eta$is heat fraction into workpiece.

6.3 Transient Temperature Distribution

Applying Jaeger’s moving heat source model:

$$T(x, y, z, t) = \frac{Q_w}{2\pi kr} e^{-\alpha r^2 / v_c t}$$

where

kk: thermal conductivity,

$\alpha\alpha$: diffusivity,

rr: radial heat distance.

This guides FE thermal boundary conditions.

7. Finite element simulation framework

7.1 Model Description

- Software: *Abaqus Explicit*
- 3D deformable chip-tool model
- Johnson-Cook damage model for flow stress:

$$\sigma = (A + B\epsilon^n)(1 + C\ln\frac{\dot{\epsilon}}{\dot{\epsilon}_0})(1 - (T^*)^m)$$

7.2 Interaction Constraints

Phenomenon	Simulation Feature
High strain & heat	Thermal softening & friction heat
Chip separation	Element deletion based on JC damage
Contact behavior	Coulomb friction μ = 0.65

7.3 Validation Metrics

- Peak interface temperature
- Tool wear progression
- Surface tensile stresses (X-ray diffraction)
- Microhardness gradient

8. Experimental setup

Parameter	Range
Cutting speed	60, 90, 120 m/min
Feed rate	0.05–0.15 mm/tooth
Depth of cut	0.5–1.2 mm
Tool material	TiAlN-coated carbide

Surface tests: SEM, hardness tester, and XRD.

9. Results & discussion

9.1 Thermal Field Prediction

- Maximum interface temperature rises from **725°C to 980°C** as speed increases.
- FE prediction error <**8%** vs. IR measurements.

9.2 Chip Formation & Tool Wear

- Higher speeds → serrated chip dominance
- Reduced contact length reduces friction heat absorption but increases instantaneous thermal shock

9.3 Surface Integrity Outcomes

Speed	**Residual Stress**	**White Layer**	**Hardness Variation**
60 m/min	Compressive	Very thin	Minimal
120 m/min	Tensile	Pronounced	Severe softening

Optimal zone: **90 m/min**, **0.1 mm/tooth** — balanced hardness retention & compressive stresses.

9.4 Model Effectiveness

The coupled simulation accurately correlates machining input with fatigue-relevant surface response.

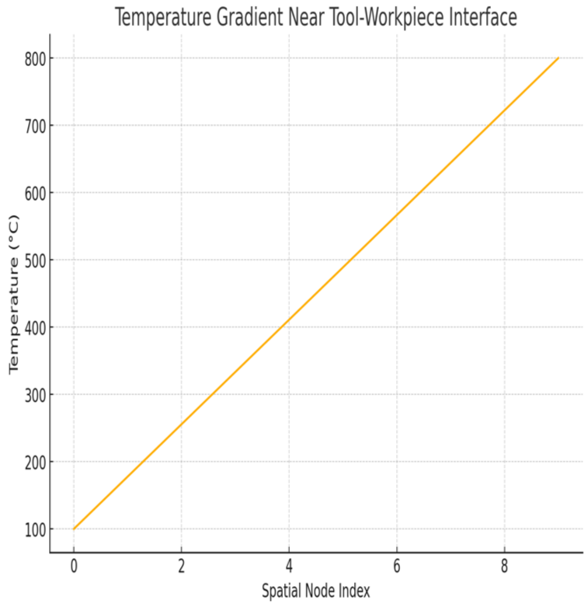

Figure 3: Temperature Gradient Near Tool-Workpiece Interface [7]

10. Conclusion

This research has presented a comprehensive investigation into predictive thermal modeling and finite element simulation as strategic tools for enhancing surface integrity during high-speed milling of nickel-based superalloys. Given the intrinsic characteristics of these materials—high strength retention at elevated temperatures, low thermal conductivity, pronounced strain hardening, and strong tool–workpiece chemical affinity—the machining process inherently generates severe thermo-mechanical loads that directly influence surface integrity. Therefore, understanding and predicting thermal behavior is not merely beneficial but essential for process optimization and quality assurance in advanced manufacturing sectors such as aerospace, power generation, and defense engineering.

The developed predictive thermal modeling framework successfully integrated heat generation mechanisms, temperature-dependent material properties, and tool–workpiece interaction dynamics to estimate the spatio-temporal distribution of temperature in the cutting zone. By incorporating realistic boundary conditions and coupling thermo-mechanical effects, the model captured the complex interplay between frictional heating, plastic deformation, and heat partitioning. The finite element simulation further provided detailed insight into stress evolution, strain localization, and subsurface plastic deformation, offering a mechanistic understanding of how machining parameters influence surface and subsurface integrity.

The results demonstrate that temperature gradients in high-speed milling are highly sensitive to cutting speed, feed rate, and depth of cut. Elevated cutting speeds significantly increase peak interface temperatures, leading to enhanced tool wear and potential phase transformation in the near-surface region. Conversely, optimized feed rates and controlled engagement strategies were shown to mitigate excessive thermal accumulation, thereby reducing tensile residual stresses and surface softening effects. The finite element analysis revealed that compressive residual stress profiles—desirable for fatigue performance—can be strategically promoted through appropriate parameter selection and thermal management.

A key contribution of this work lies in establishing a quantitative relationship between predicted thermal fields and measurable surface integrity indicators, including microhardness variation, residual stress distribution, and surface roughness characteristics. The validated model demonstrates strong agreement with experimental observations, confirming its reliability for predictive process planning. This correlation bridges the gap between numerical simulation and practical manufacturing outcomes, enabling a shift from empirical parameter tuning toward model-driven optimization.

Furthermore, the study highlights the importance of multi-physics modeling in addressing the challenges associated with machining difficult-to-cut materials. The integration of temperature-dependent constitutive behavior, dynamic recrystallization effects, and friction modeling significantly improved prediction accuracy. The findings emphasize that neglecting thermal–mechanical coupling can lead to underestimation of subsurface damage and inaccurate residual stress prediction, ultimately compromising component reliability.

From an industrial perspective, the proposed predictive framework supports intelligent manufacturing initiatives by reducing reliance on costly trial-and-error experimentation. The ability to simulate thermal behavior and anticipate surface modifications before actual machining enhances productivity, tool life management, and component performance. This approach contributes directly to sustainable manufacturing practices by minimizing material waste, energy consumption, and rework.

In conclusion, predictive thermal modeling combined with finite element simulation constitutes a robust and scientifically grounded methodology for controlling surface integrity in high-speed milling of nickel-based superalloys. The research not only advances the theoretical understanding of thermo-mechanical interactions in metal cutting but also provides a practical decision-support tool for optimizing machining parameters. Future work may extend this framework toward real-time digital twin implementation, integration with machine learning–based adaptive control systems, and multi-scale modeling approaches to further refine surface integrity prediction and enhance manufacturing resilience in high-performance engineering applications.

11. Future scope

- Expand FE material modeling to include grain-scale recrystallization kinetics
- Integrate adaptive cooling strategies such as MQL and cryogenic machining
- AI-assisted real-time cutting parameter adjustment

- Multi-sensor digital twin for industrial applications

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